Combining Implicit and Explicit Communication in Object Manipulation Tasks Between Two Robots

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Abstract

The number of automated environments where multiple robots must cooperate with one another and humans on object manipulation is increasing. From the rapidly expanding automated warehouse industry, to research investigating search and rescue applications, the need for effective and robust communication between agents is essential to facilitate cooperation.

Human cooperative mechanisms, such as Joint Action, are known to enable effective cooperation between humans. In particular, humans are able to use a combination of explicit communication (the direct transfer of information, such as speech) and implicit communication (the indirect transfer of information, where information is inferred through an action, such as force-feedback) to cooperate on tasks. This behaviour could be used as inspiration for a robotic mechanism that improves communication between two robots when manipulating an object together.

This thesis presents a hybrid system that combines explicit and implicit communication in object manipulation tasks between two robots. The system combines communication strategies for explicit communication and implicit communication, which use wireless messaging and force information, respectively, using a weighted sum. In a Leader-Follower configuration, the Follower uses the hybrid system to coordinate its movements with the Leader, and the two robots jointly move an object along a pre-determined trajectory. The hybrid system presented in this thesis is found to capitalise on the advantages of both strategies that have been identified by evaluating their performances when operating in isolation. In addition, different weightings for the hybrid system are identified that offer the best compromise in performance and robustness across four experimental environments.

Contents

Acronyms

EST Expansive-Space Tree 4

OMPL The Open Motion Planning Library 27

SE Simple Environment xv

LF Line Following Environment 47

RE Randomly Generated Environment xv

CE Cluttered Environment xv

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Declaration

I declare that this thesis is a presentation of original work and I am the sole author. This work has not previously been presented for an award at this, or any other, University. All sources are acknowledged as References.

Aspects of the work presented in this thesis have been published and are as follows:

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Chapter 1

Introduction

Humans have evolved as social creatures to coordinate together effectively on a variety of tasks from dancing to carrying a box between two individuals. In the field of psychology, our ability to coordinate with others is referred to as *joint action* (Sebanz et al., 2006), and arises from several underlying mechanisms (detailed in Chapter 2).

Joint action is an advantageous social process that enables us to work efficiently and effectively with others. A fundamental facilitator to joint action is how we communicate with one another using both explicit and implicit communication. Explicit communication involves the direct, deliberate transfer of information, whereas implicit communication occurs when information is inferred in an indirect fashion, such as through an action.

The two forms of communication can be differentiated from each other through intent. In explicit communication, the transfer of information is deliberate through an established form of communication, where an individual has intent to share that information (Breazeal et al., 2005). For example, verbal communication such as speech and even non-verbal communication, like codified gestures such as a thumbs up or a wave, serve no purpose to a human performing a task except as a way to communicate with another human. Humans thus only perform explicit communication deliberately with the intent to share information with others.

In contrast, implicit communication is where an action or behaviour can act as a message in itself, and information is inferred from that action or behaviour by another human or agent (Castelfranchi et al., 2012). In this scenario, intent is not necessarily required. A human can be acting independently performing a task, with no intent or even ability to directly communicate with others, and another human can infer information from their behaviour. This can be achieved through a variety of mechanisms, such as observation or force feedback.

In cooperative tasks between humans, implicit communication often manifests itself in the form of force feedback, where an individual measures the force being exerted by the person they are cooperating with and uses that information to coordinate their joint movements

(Reed et al., 2006).

Tangentially, humans have been used as inspiration for robots for decades, from the way we walk (Ames, 2014) (HONDA, 2018), to how we learn (Degallier et al., 2008). Since effective cooperation and communication between robots is essential for the completion of many tasks, particularly object manipulation, joint action presents itself as an attractive source of biological inspiration. By applying joint action to object manipulation in cooperative robotic systems, its advantages – such as increased efficiency in task execution and robustness – can also be translated to the robotic implementation. An autonomous cooperation mechanism based on human behaviour would be beneficial for a wide range of applications where robots must effectively cooperate with one another, as well as humans, such as in the growing industry of automated warehouses.

This thesis proposes a novel hybrid system that employs a combination of explicit and implicit communication in cooperation between two robots using a weighted sum algorithm, inspired by joint action in humans. The system enables two robots in a Leader-Follower configuration, where one robot, the 'Leader' specifies the trajectory that the other robot, the 'Follower', must follow (Loria et al., 2015), to effectively manipulate different objects through a range of environments.

The task used to test the systems described in this thesis is a simple object manipulation task, where the robots must jointly move an object from one location to another across an environment. This task was chosen to best investigate how implicit communication using force feedback can be combined with explicit communication to emulate joint action, as the forces being exerted on the object during task execution can be used to infer information. It also provides a test bed to evaluate whether this kind of hybrid system could be beneficial in potential applications discussed above, like automated warehouses, where object manipulation is common. The environments used varied in composition, to investigate the systems' ability to manipulate the object around obstacles. Two kinds of path following were also used by the Leader in different environments, to investigate how the systems' performance with different navigation methods.

In addition to the hybrid system, this thesis provides a novel contribution to understanding of explicit and implicit communication when used in isolation in simple object manipulation tasks, providing comparative analysis and performance profiles of the two forms of communication.

1.1 Hypothesis

This thesis is guided by the following general hypothesis:

Hypothesis: Humans' innate ability to coordinate when moving objects together can be mimicked in object manipulation tasks between two robots by creating a system that employs a combination of explicit communication, in the form of wireless message transfer, and implicit communication, in the form of force sensing. The hybrid system will capitalise on the advantages that are found in both forms of communication when employed in isolation.

This hypothesis can be supported by achieving the following research goals:

1. To implement communication strategies employing explicit communication and implicit communication in isolation in an object manipulation task between two robots, as a foundation for comparison.

2. To deepen understanding of how the two strategies perform in isolation within different environments and with different objects, and how they perform in comparison with each other.

3. To develop performance profiles and robustness profiles on the strategies to a greater level of detail than currently present in existing literature.

4. To combine the two strategies into a hybrid system that employs a combination of explicit and implicit communication

5. To examine how the hybrid system performs in comparison to the two strategies operating in isolation in the same experimental test beds.

1.2 Thesis Contributions

This thesis makes the following contributions to research in object manipulation tasks between two robots:

- The following contributions can be categorised as contributions to knowledge and understanding:
  - Two communication strategies for a two robot Leader-Follower configuration. One strategy employs wireless messaging to allow explicit communication to occur between robots, the other strategy employs Newtonian physics to use force as a form of implicit communication. The contribution is made in Chapter 4, and achieves Research Goal 1.
  - Performance profiles for the two communication strategies operating in isolation that is more detailed than existing analysis. These profiles describe the strategies' advantages and disadvantages when manipulating different object types across four different environments. The contribution is made in Chapters 4 and 5, and achieves Research Goals 2 and 3.

- Fault tolerance profiles for the two communication strategies operating in isolation that is more detailed than existing analysis. These profiles describe the robustness of the strategies when manipulating objects in the presence of two simple faults across four different environments. The contribution is made in Chapter 6 and achieves Research Goal 3.

- The following contributions can be categorised as novel contributions:
  - A novel hybrid system that combines the implicit and explicit communication strategies into one system using a weighted sum algorithm. The contribution is made in Chapter 7, and achieves Research Goal 4.
  - A performance profile of the hybrid system, which demonstrates: that the hybrid system capitalises on the advantages identified in both strategies operating in isolation, that different weightings offer a compromise between the performances of the two strategies, and that the hybrid system shows better performance with different object shapes than either communication strategy working in isolation. The contribution is made in Chapters 7.2 and 8, and achieves Research Goal 5.
  - A fault tolerance profile of the hybrid system, which demonstrates that different weightings offer a compromise between the performances of the two strategies and for certain fault types work to reduce the error more effectively than either strategy working in isolation. The contribution is made in Chapters 9, and achieves Researchg Goal 5.

1.3 Thesis Structure

This thesis is structured as follows:

Chapter 2 provides a literature review of joint action in humans and between humans and robots, which acts as the biological inspiration to this thesis. It also explores previous work in explicit and implicit communication within robotic applications. Limitations of previous work that compare implicit and explicit communication are also outlined.

Chapter 3 describes the experimental test bed used throughout this thesis to test the systems within simulation. Four environments are described: a line following environment where the robots move along a pre-drawn path using vision sensors, and Expansive-Space Tree (EST) path planning in simple, cluttered and randomly generated environments. Design requirements deemed vital for successful task execution in object manipulation tasks, such as reliability, efficiency and smoothness are explored by measuring associated metrics within these environments.

Chapter 4 describes the two communication strategies for explicit and implicit communication that are used throughout this thesis, and the configuration of the two robots that employ these strategies in object manipulation tasks. This chapter also details the initial comparison of the performance of explicit communication and implicit communication when used in isolation in object manipulation tasks. Design requirements deemed vital for successful task execution in object manipulation tasks, such as reliability, efficiency and care for the object are explored by measuring associated metrics within four experimental set-ups: line following along a pre-drawn path using vision sensors, and EST path planning in simple, cluttered and randomly generated environments.

Chapter 5 presents the results for experiments exploring consistency in performance, which details how the two communication strategies handle objects of different size and shape when operating in isolation. The same metrics are measured as in Chapter 4, in order to compare results.

Chapter 6 presents the results for experiments exploring fault tolerance, which evaluate how the two communication strategies perform in the presence of two simple fault types, in order to investigate how the strategies may perform in imperfect environments. The same metrics are measured as in Chapter 4, and the results are statistically compared to the strategies' performance in the absence of faults.

Chapter 7 presents the new hybrid system that combines implicit and explicit communication using a weighted sum algorithm, and evaluates the performance of the hybrid system, for three different weightings, when manipulating the original object from Chapter 4. The results for the hybrid system are compared to the performance of explicit communication and implicit communication operating in isolation.

Chapter 8 describes a series of experiments that investigate how the hybrid system handles objects of different size and shape. The performance of each weighting of the hybrid system with different sized and shaped objects is compared to its performance with the original object. The hybrid system's performance is also compared to that of the explicit and implicit communication strategies operating in isolation.

Chapter 9 presents the results for a series of experiments that invesitage how the hybrid system performs in the presence of three simple fault types. The performance of each weighting of the hybrid system in the presence of the faults is compared to its performance with the original object in the absence of faults. It is also compared with the performance of the explicit and implicit strategies operating in isolation.

Chapter 10 concludes the thesis by providing a summary of the findings of each chapter and comparing them against the hypothesis stated at the beginning of this chapter. Suggestions on how the work presented in this thesis can be developed further are also outlined.

Appendix B provides a list of videos of simulations to be used as visual reference.

Appendices C to H provide the experimental data results in full for all the experiments performed in this thesis.

Chapter 2

Motivation & Related Work

This chapter provides an overview of the biological inspiration for this thesis, by discussing joint action in humans, and the types of communication that are facilitators to this behaviour and are employed in this thesis within object manipulation tasks. The discussion then moves onto exploring existing robotic applications, that aim to employ these types of communication within object manipulation and coordination. Focusing specifically on the use of force consensus as an effective form of implicit communication within object manipulation tasks.

Additionally, the limitations of previous work comparing implicit and explicit communication are outlined, which form the motivation for rich comparative analysis and the development of a combined communication system, and the limited existing work that combines explicit and implicit communication within robotic systems is discussed.

2.1 Communication

This thesis aims to present a hybrid system that mimics biological behaviour by combining two forms of communication within an object manipulation task, to allow two robots to coordinate their movements. It is thus important to first define the biological cooperation behaviour this thesis attempts to mimic, as well as the nature of the forms of communication employed to coordinate movement and cooperate on tasks together.

2.1.1 Joint action in humans

The social interactions that occur whilst humans cooperate together on task are known collectively as joint action, and comprise of various underlying mechanisms, including our ability to: direct our attention to the same place as another's, predict future actions of others, and to alter our own actions to compensate for another's by making assumptions about their capabilities (Sebanz et al., 2006). Most of these mechanisms are implicit social processes, where information is inferred from an action rather than explicit communication, where information is directly communicated via speech or codified gestures. As an example of an implicit social process, Driver IV et al. (1999) showed that humans often follow the gaze of others, which can improve response time in certain tasks as it allows humans to pre-empt outcomes. The implicit process of gaze following similarly plays into joint attention, in which humans' attention is aligned by attention cues. In Feinman et al. (1992), it was found when joint attention was occurring, small children would base their responses on those of their mothers whilst learning to approach or avoid objects they had not encountered before.

Another implicit cue humans use to coordinate their movements when cooperating on a task is force. Reed et al. (2006) conducted a study where two humans had to cooperate to jointly move a cursor on a screen by sensing the force being exerted on a lever and coordinating their movements using that force information, rather than via verbal communication. The results showed that subjects were able to non-verbally devise complementary strategies, and completed the task faster when cooperating with each other than when performing the task alone.

Sawers et al. (2017) investigated the role interaction forces play in motor experience between dance partners by measuring the magnitude and direction of these forces during a partnered stepping task. The participants of mixed dancing ability were blindfolded and wore headphones to prevent them using visual or auditory cues to coordinate movements. The results demonstrated that the small interaction forces between partners were sufficient to enable partners to successfully coordinate movements in a dancing task absent of other sensory cues, and that the interaction forces could communicate movement goals and act as guiding cues.

In fact, humans frequently use forms of haptic feedback in joint motor tasks to communicate information. Ganesh et al. (2014) showed that physical interaction with an active partner, caused by explicit reactions to behaviours and haptic feedback, allowed an individual to acquire additional information from their partner, which increased task performance. It has also been demonstrated that limb stiffness extracted from haptic feedback can be used to implicitly infer and communicate the intended movement direction of a limb (Mojtahedi et al., 2017b).

Another implicit social process, known as the *Chameleon Effect*, refers to the sociological phenomenon wherein humans imitate each other's movements and gestures while communicating (Chartrand & Bargh, 1999), to the point where it can even interfere with our own task performance (Sebanz et al., 2003). However, Sebanz et al. (2006) showed that when humans perform an action together, such as carrying an object, participants perform complementary actions in order to implicitly align their goals, rather than simply imitating each other. For example, whilst manipulating an object, one human will move backwards as the other moves forward, as shown in Figure 2.1. These behaviours are even observed in children as young as 18 months old (Warneken & Tomasello, 2006), indicating that implicit social processes could be intuitive rather than learned.

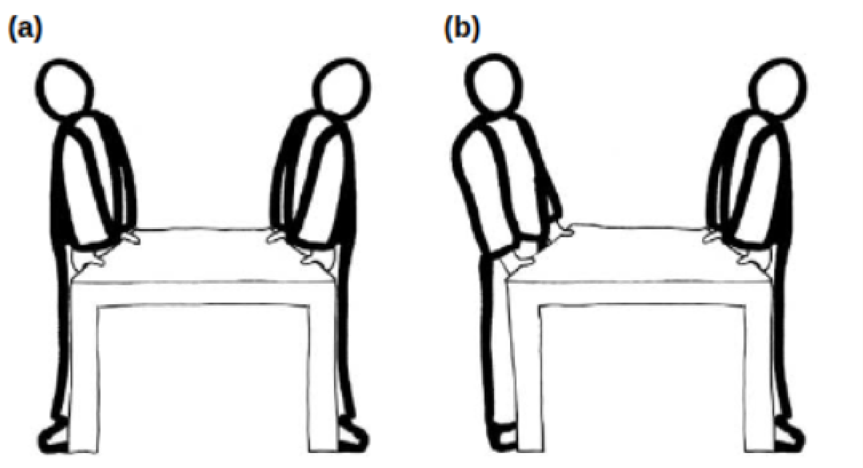

Figure 2.1: An example of goal-directed joint action. Rather than imitating the other's actions (a), people must sometimes perform complementary actions (b) to reach a common goal. Drawing by Ellie Langenhuizen. Taken from (Sebanz et al., 2006)

Some of the literature listed above have also identified joint action as an attract inspiration for robotic applications, and have suggested how their research into these coordination features can be used in human-robot and robot-robot interactions, particularly in the field of human rehabilitation (Ganesh et al., 2014; Sawers et al., 2017; Mojtahedi et al., 2017a, b).

2.1.2 Implicit and Explicit Communication within Joint Action

A fundamental facilitator to joint action in humans is the way we communicate with one another using a combination of implicit and explicit communication. For example, when humans cooperate on tasks such as carrying a box together, one might issue a verbal instruction and then apply force to the object to reinforce that instruction. Effective cooperation between robots could arise from focusing on this specific form of human cooperation in object manipulation.

As first postulated in Gildert et al. (2018), this combination of the two forms of communication has the potential to be faster and more efficient than current systems that only employ one form of communication. For example, in a situation where a human is carrying a box with another person, a verbal 'Stop!' command to communicate an instruction is likely to be interpreted differently depending on whether or not the person shouting also makes an attempt to stop. Using two forms of communication would also be more fault-tolerant, as a combined system could enable robots to cope with faults in one of the communication forms by compensating with the other.

For robotic applications in shared autonomy places, such as manufacturing or robotic warehouses, to be successful and effective, robots must be able to manipulate objects in a range of configurations, either individually or through cooperating with humans and other robots.

If we are able to mimic the behaviour exhibited when two humans cooperate on an object manipulation task, it could have wide-ranging benefits in this growing field of application.

In this section explicit and implicit communication are defined in their wider contexts as well as defined more specifically in the context of automated object manipulation tasks.

Explicit communication

Breazeal et al. (2005) define explicit communication in humans as a deliberate form of communication "where the sender has the goal of sharing specific information with the collocutor". To account for technical systems and applications, in this thesis explicit communication is defined to be: a direct, deliberate form of communication, where there is a clear associated intent for the transmitted information to be received by another agent or system over an established channel.

In biological examples, explicit communication typically involves verbal communication, such as speech in humans, or vocal calls in animals. Explicit communication can also relate to gestures or body language that have developed an explicit meaning over time, such as the 'okay' hand sign. It is important to not mistake non-verbal explicit cues with implicit communication.

In robotic applications, explicit communication relates to the direct transfer of information from one robot to another. This can occur over numerous conventional channels such as Wi-Fi, Bluetooth, or even synthesised speech and voice recognition software. Since the use of direct, explicit communication is such a ubiquitous channel of communication within robotics and wider electronic systems, literature discussing explicit communication has not been included in this overview.

Implicit communication

When discussing the interaction between smart environments and humans, Castelfranchi et al. (2012) stated that a form of communication exists outside of direct or explicit communication, which they called "behavioural implicit communication". This form of communication involves an action (or practical behaviour) representing as a message in itself, rather than a message being conveyed through language or codified gestures (such as a thumbs-up or a head nod).

While explicit communication requires associated intent, implicit communication differs in that pertinent information is independently inferred by another agent or system, rather than transferred purposefully. For example, a robot programmed to observe fellow robots and imitate them can infer information about an observed robot's programmed behaviour in order to copy it, without the observed robot needing to explicitly engage in the interaction(Winfield & Erbas, 2011).

Similarly, a robot can implicitly infer information about the environment and how it should adjust its behaviour through its interactions with other robots, for example through collisions, without being explicitly told by another robot to adjust its behaviour (Liu et al., 2007). Within swarm robotics, this implementation of implicit communication where information is inferred by how an agent interacts with its environment (known as *stigmergy*) has been frequently explored (Payton et al., 2001; Mir & Amavasai, 2007; Purnamadjaja et al., 2007).

As explained in Section 2.1.1, there are many examples where implicit communication and implicit cues play into joint action and interaction between humans. In the case of cooperative object manipulation, implicit communication could be achieved through methods such as force consensus (Wang & Schwager, 2016), or observation and imitation (Winfield & Erbas, 2011).

Passive Action Recognition

Within the field of robotics, passive action recognition is another communication technique often explored for evaluation communication and cooperation in dynamic and unreliable environments.

Passive Action Recognition refers to a communication technique where a given behaviour performed by one agent is observed and interpreted by another as an instruction or message. Within robotics research this technique typically takes biological inspiration from the 'waggle dance' of honey bees used to communicate the location of a food source. Passive Action Recognition provides an attractive solution to robot cooperation where other communication channels are unavailable due to environment noise, acoustic reflections, data packet loss or other communication failures, as well as within hostile environments where communication interception is undesirable (Huber & Durfee, 1995).

Novitzky et al. (2012) took direct inspiration from the behaviour of honey bees as a solution for Autonomous Underwater Vehicles (AUVs) to identify tasks and roles of other agents in a mine-clearing task. The UAVs would perform movements, similar to a honey bee performing a dance to indicate the location of a mine like object. Results showed potential for such a behaviour recognition system, particularly in underwater environments where typical acoustic communication can be affected by noise and reflections. The main limitations for the system were the time in which it took to fully observe the 'dance' compared to the speeds of traditional explicit communication channels.

Also inspired by the behaviour of honey bees, Das et al. (2016) present a multi robot communication system that uses passive action recognition to locate, identify and categorise patterns performed by another agent using an optical camera sensor and computer vision algorithms. Results demonstrated high sensitivity and good precision within both simulation and on AR Parrot Drones in a real world environment. This form of communication does not rely on any form of explicitly broadcast information, making the system more robust, unpredictable and secure, and suitable for search and rescue applications where other communication techniques are unreliable, unavailable or pose a threat to the security of the mission.

In the work presented by Ballagi et al. (2009), robots employ fuzzy signatures and decision trees within intention guessing to enable two robots to push a box together without communication. The robots, equipped with force sensors and light sensors to detect a goal sign, refer to a decision tree or 'codebook' to determine what scenario is occurring depending on what they are sensing. They then act accordingly based on that scenario to coordinate their movements with the other robot to push the box in the right direction. Results showed the fuzzy signatures and intention guessing allowed the robots to effectively cooperate without collaboration or communication.

Passive action recognition is often described in literature as a separate form of communication independent of explicit and implicit communication. It is the author's belief, however, that it shares similarities with both forms and can be categorised depending on the application. In Ballagi et al. (2009), for example, the communication technique employed is similar to how implicit communication is defined above, in that the robots are inferring information from an action rather than through a deliberate, established communication channel. The robots are not exerting force with the intention of communicating a message, the force is a by-product of them performing an action to try and move the object. The robots then use the 'codebook' to interpret information from that action in order to coordinate their movements accordingly.

For passive action recognition that mimics the waggle dance in honey bees, this application mimics explicit communication more closely. In this case, such as the work described in Novitzky et al. (2012) and Das et al. (2016), the robots performing a pattern or series of movements, were doing so in order to convey explicit information. The patterns have specific meanings which are known to both the performing robot and the observer, and thus it can said that information is explicitly being communicated over an established channel of communication through vision. In a human equivalent, the use of semaphore or smoke signals can be classified as an explicit form of communication because there is an established intent in both the sender and the receiver.

The Nature of Messages within Communication Types

It is a feature of all communication types that agents involved in the system must have an understanding of rules in which the communication type operates, or in other words, what is meant by a form of communication.

Within explicit communication, both agents have an understanding of the language being used in the channel, and how to parse that information. In the example of human verbal language, this relates to what a word means, for example a verbal instruction of 'left' relating to an instruction for a robot or agent to turn left. In serial data transmission this can relate to interpreting what a series of binary bits represent.

For implicit observation such as stigmergy, the robots are required to know what an observed affect on the environment means in terms of its required behaviour, for example in a foraging application, less food observed means they must stop foraging and return to their nest.

Within passive action recognition, the agents must have an understanding of what a behaviour they are observing means, in Ballagi et al. (2009) that is achieved with a code book to categorise the force they are measuring into a scenaro. In (Das et al., 2016), it involves employing a computer vision algorithm to perform pattern recognition on a video input recorded by a robot.

The nature of these messages vary in computational complexity. For example transmitting a velocity value is less computationally expensive than employing fuzzy logic on a decision tree in order to interpret a measured force value, and is less computationally expensive than a computer vision algorithm that tracks movement to identify a visual pattern.

However, explicit communication in the form of wireless messaging can increase exponentially, from a single integer being transmitted, to large xml files that must be parsed correctly, to audio files. Even simply transmitting strings in the form of human language involves a requirement for linguistic comprehension.

The hybrid system presented in this thesis provides an attractive novel contribution in this sense in that, in comparison to other applications presented throughout this chapter, it is quite simple in both types of communication it employs. The vocabulary required for explicit communication is limited to four instructions transmitted as strings: Left, Right, Back and Stop, where only four if statements are required to compare the strings and determine the appropriate action for a given message. For the implicit strategy, the follower takes measurements from its force sensor online throughout task execution and uses very simple mathematical operations to calculate velocities, allowing continuous implicit communication and cooperation.

2.2 Robotic Applications and Test-beds

This thesis aims to create a hybrid system that combines explicit, in the form of wireless messaging, and implicit communication, in the form of force consensus, within object manipulation tasks between two robots, by mimicking joint action. To contextualise this within existing literature it is important to discuss several application areas and test-beds.

Firstly robotic applications that also aim to mimic joint action will be discussed, to demonstrate how this application differs. Secondly, robotic applications that employ force consensus within object manipulation are explored to demonstrate how the force consensus implemented within the implicit component of the hybrid system relates to existing applications.

Thirdly, another aim of this thesis is to provide a contribution to knowledge and understanding for how explicit and implicit communication operate in isolation. It is therefore necessary to understand what comparative work exists in current literature, and how the work presented in this thesis will build on that.

Finally, this thesis provides a novel contribution in the hybrid system that combines explicit and implicit communication between two robots in an object manipulation task. Existing research investigating the combination of these two types of communication is explored to differentiate it from the contribution made in this thesis.

2.2.1 Mimicking Joint action in human-robot interaction

As robots continue to be developed for operation in shared autonomy spaces, human-robot interaction has become a necessary area of research. In previous work, the underlying mechanisms of joint action have been explored in a variety of applications to investigate using human behaviour to improve human-robot interaction. To illustrate this, the next section reviews examples that have investigated gaze following, prediction of future actions, and using force information to coordinate movements in human-robot interaction.

Gaze following to aid social human-robot interaction is a dense research area (Admoni & Scassellati, 2017). In terms of using gaze following during human-robot collaboration or cooperation, Breazeal et al. (2005) and Li & Zhang (2017) have studied gaze following as an implicit intention cue in the context of human-robot collaborative task performance, and in assistive robots, respectively. Breazeal et al. (2005) found that through non-verbal implicit cues, humans were able to pre-emptively address potential sources of error due to misunderstanding. This reduced the time it took to perform a task, increased efficiency and robustness to error, and increased the transparency and understandability of the robot's internal state.

Wang et al. (2013b) created a probabilistic movement model for "intention inference" in human-robot interaction, which mimicked humans' ability to predict future actions of others. The work modelled generative processes of movements that are directed by intention using Bayes' theorem. The system outperformed other existing algorithms that do not model dynamics, and was able to capture the causal relationship between intention and observed movements.

Regarding work exploring force information in human-robot interaction movement coordination, which is highly beneficial for cooperative object manipulation, studies by Magrini et al. (2015) and Rozo et al. (2015) relate more closely to creating a control system that uses force information to assure safety in human-robot interaction, rather than exploring the potential benefits of using force as an implicit cue in cooperation between humans and robots.

Crucially, previous research investigating joint action in human-robot interaction, like that of Breazeal et al. (2005) and Li & Zhang (2017), relies on humans' natural ability to communicate implicitly. Humans are able to collaborate more effectively with robots by either their natural implicit cues being interpreted by the robot, or being able to better understand a robot's behaviour. This thesis addresses the a need to investigate robot-robot algorithms that do not rely on a human 'expert' in implicit communication in the loop, to allow for communication protocols arising that are not inherently human in nature, and to better suit robot-robot interactions where no human expert will be present. While the inspiration for an improved robotic cooperation mechanism may be a human behaviour, it should not be constrained by its human limitations.

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2.3 Force Consensus in Robot-Robot Interaction

For cooperative object manipulation applications, which are often tightly coupled and involve robots being physically connected through an object, force consensus in particular provides an attractive option for incorporating implicit communication into cooperation mechanisms.

Force consensus is a manipulation technique that typically involves the movement or manoeuvring of objects by multiple robots, requiring agents to use force information to reach an agreement on the direction of movement for the object. Existing work that focuses on force consensus in robot-robot applications could provide valuable insights when developing cooperation mechanisms that employ a combination of implicit and explicit communication.

This section explores existing implementations of force consensus in robot-robot applications, where an expert in implicit communication (like a human in human-robot or human-human interactions) is not present.

Force consensus between two robots

A simple study was conducted by Aiyama et al. (1999) to investigate the use of implicit communication in cooperative transport of an object between two four-legged robots, without any explicit communication transfer between the two agents. This was achieved by applying very simple strategies separately to the front and rear robots, wherein the robots measured the force of the object being applied to their 6-axis force sensors, and changed their behaviour to ensure coordination by comparing the measured values to appropriate thresholds.

The work of Aiyama et al. (1999) was primitive in the sense that neither robot possessed any knowledge of where they were in relation to the goal location, nor did they utilise path planning algorithms that could have aided them in moving an object between two given locations. The robots were also only tested with two objects of similar thickness. As a result of this, although the system provides a mechanism for two robots to cooperate on carrying an object using implicit communication, the scope of the experimental configurations in which implicit communication is tested are limited and do not provide insight into how implicit communication performs with other objects or within other environments.

In further work investigating the same problem, Pereira et al. (2002) developed a methodology in which two robots, both in simulation and real hardware, were able to coordinate their actions when moving a box to a target location using implicit communication.

A follower robot measured the force and torque being applied by the leader onto the object and aimed to apply complementary force and torque to stabilise the object. The control configuration was based on a compliant linkage system that incorporated a *leadership-lending* mechanism, which enabled the two agents to coordinate themselves in an unknown environment where obstacles were present and had to be avoided.

The system's performance in simulation was compared to explicit communication being executed with an increasing number of errors in message transfer, in order to investigate whether implicit communication could be used as a valid means of communication between two robots. Pereira et al. (2002) concluded that although implicit communication could be used in a situation such as this to convey simple information – as results showed that performance of implicit communication was similar to that of using explicit communication in a reliable environment, as shown in Figure 2.2 – it might not be possible to convey more complex data through implicit communication channels alone.

The comparison provided in this work is limited in that it only tests both forms of communication within one environment and with one object. The fairness of the comparison can also be questioned. This work compares a faultless implicit communication strategy with an explicit system operating with errors occurring during message transfer, but does not investigate how implicit communication performs in the presence of faults or errors. It also performs this comparison under the assumption that the nature of these messages under these different channels are comparable. In addition, Pereira et al. (2002) form their conclusion after only comparing one quality: the completion time of the two communication types to execute the task.

There is a need for more in depth comparison of the types of communication to understand the advantages and disadvantages of both types, and explore their performance over a wider range of qualities than just completion time and whilst both performing in the presence of faults. Furthermore, whilst explicit communication has the ability to convey complex data through language, and numerical, binary and hexadecimal data, this does not mean that it's performance can not be supported or enhanced by implicit communication.

The work described above shows that force consensus is a form of implicit communication that can be used in object manipulation tasks, but is not sufficient in isolation. To the best of the writer's knowledge, there exists no work that focuses on using both implicit and explicit communication for object manipulation to exploit the advantages of combining them.

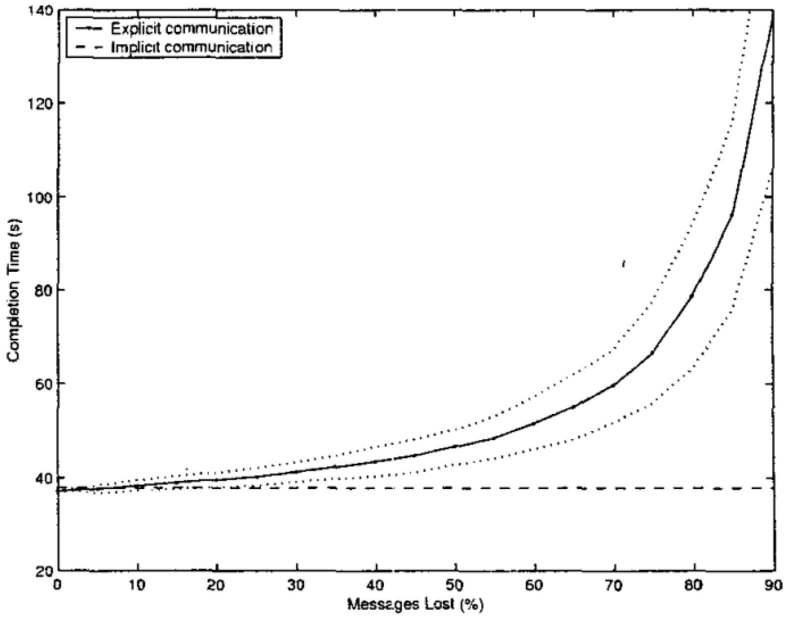


Figure 2.2: Mean completion time for implicit communication (dashed line) and explicit communication (solid line) and its variation (dotted lines), represented by the standard deviation. Taken from (Pereira et al., 2002)

Force consensus in multi-robot systems

Whilst the work described in this thesis focuses on object manipulation between two robots, research investigating similar tasks in multi-robot systems still provides useful insight on how object manipulation solutions can be implemented.

In shared autonomy spaces, robots may be required to manipulate large or heavy objects that cannot be handled by two robots, thus necessitating cooperation with numerous robots. Whilst the research field of multi-robot object manipulation is considerably dense, previous work typically does not involve using force information as an implicit form of communication in order to manoeuvre objects. Object manipulation strategies that do not employ force information include caging (Spletzer et al., 2001; Wan et al., 2012), ensemble control techniques (Becker et al., 2013), multi-agent consensus using local communication protocols (Jadbabaie et al., 2003), and leader-follower networks (Ji et al., 2006).

Groß & Dorigo (2004) and Groß et al. (2006) demonstrate that force measurements can be used by robots that either cannot sense, or have no knowledge of, the target destination in an object manipulation task to improve cooperative transport performance. In this sense, the forces exerted by knowledgeable robots implicitly communicates information to 'blind' robots, which they can then use to adjust their behaviour.

The work described in Wang & Schwager (2015; 2016), provides a way for robots to move objects far heavier than themselves using force consensus. The system is established as follows: there is a large group of simple robots, one of which is programmed to be the leader, whose collective goal is to move an object along a desired trajectory, as depicted in Figure 2.3. The leader can apply torque and measure the angle and angular velocity of the object. It has global knowledge of the position of the object and the desired location the object must be moved to. However, all other robots in the system have no global knowledge and can only apply a linear force in any direction. The forces from all robots have to be aligned in order to overcome the object's static friction and move it. It is therefore necessary for the robots to reach a consensus and apply the same force on the object to move the object along the desired trajectory.

In Wang & Schwager's research, control theory is used to enable the robots to always reach a consensus and always converge to the force applied by the leader robot. The robots periodically measure the force being exerted on the object and apply a force updating law that only uses locally known terms to adjust the amount of force being exerted by the individual robot. The force updating laws for each individual can be stacked into matrix form to create a stable linear system that converges, providing consensus without communication.

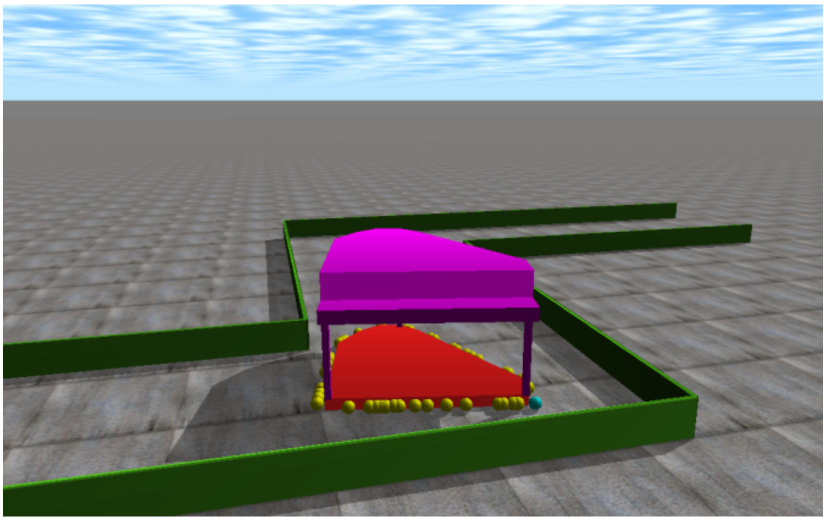


Figure 2.3: A group of small robots, denoted by spheres, grasp the base platform, where a grand piano is mounted, and apply forces to move the large piano together to the destination. Taken from (Wang & Schwager, 2015)

Similarly, Bechlioulis & Kyriakopoulos (2018) also investigated a multi-robot system using force information in a leader-follower scheme to manipulate an object without using explicit communication. In this work the leader robot was also the only robot with knowledge of the trajectory for the system and the goal region for the object. However the follower robots used locally measured position and velocity in addition to force and torque to estimate the trajectory of the object. The followers then used a prescribed performance methodology, causing the estimation error to converge to a predefined small residual set (Bechlioulis & Rovithakis, 2011).

2.3.1 Comparing Explicit and Implicit Communication

It is challenging to evaluate the performance of a system that combines implicit and explicit communication without fully understanding the performance of it's individual components. A thorough comprehension of the advantages and disadvantages of implicit and explicit communication that arise when the strategies operate separately is essential in determining whether advantageous design requirements are preserved when the strategies are combined.

Comparisons between explicit communication and implicit communication, where implicit communication occurs through stigmergy or observation, have been conducted in the field of swarm robotics (Rybski et al., 2004; McPartland et al., 2005), and in multi-robot systems (Rude et al., 1997; Wang et al., 2013a), for the past twenty years, but have not proved conclusive.

Whilst McPartland et al. (2005) boasted the performance of implicit communication, Rybski et al. (2004) concluded that the task completion times of explicit and implicit communication were not statistically significant in difference. Furthermore, Rude et al. (1997) and Wang et al. (2013a) both discussed that implicit communication through observation was either slower than explicit communication or caused motion delay, respectively. Previous research is yet to clearly conclude which form of communication is more advantageous.

Within robot-robot object manipulation tasks, as discussed previously, multiple researchers have investigated using force to communicate implicitly (Aiyama et al., 1999; Groß & Dorigo, 2004; Groß et al., 2006; Wang & Schwager, 2016). However in these bodies of work, no comparison to performance of explicit communication has been made, and the justifications for using implicit communication were primarily related to explicit communication being unreliable in some environments.

As detailed in Section 2.3, analysis comparing explicit communication and implicit communication in an object manipulation task between two robots was conducted by Pereira et al. (2002). Whilst the authors were able to conclude that performance of implicit communication was similar to that of using explicit communication in a reliable environment, the comparison was conducted in a simple environment and only investigated successful task completion, completion time and localisation error.

It can thus be argued that there has been insufficient comparison in existing literature of the performance of explicit communication and implicit communication within object manipulation tasks between robots that could be used to evaluate the performance of a combined system. Such a comparison is essential to explore the performance profiles and the advantages and disadvantages of the strategies individually to better understand how they might interact together. A thorough comparison of implicit and explicit communication separately would also be a beneficial asset to give greater insight into which strategy could be most suitable for different tasks and use-cases individually, when a combined strategy is not required or suitable.

2.3.2 Combining Implicit and Explicit Communication in Multi-Robot Systems

When exploring the novelty of this thesis' hypothesis, there is very little existing research that investigates the combination of implicit and explicit communication in multi-robot systems, to either capitalise on the advantages of both forms, or to aid in reliability if one form of communication becomes available.

In Nasroullahi (2012), a combination of implicit policy evaluations, stigmery and an explicit coordination mechanism were employed on a multi-robot system of rovers in an exploration task, where the rovers' goal was to find and identify as many points of interest (POIs) as possible. As the rover's observed points of interest, the POIs' 'values' decreased to mimic the visible change in the environment seen in natural stigmergy where animals can infer information through their interactions with the environment.

This provided a local environmental queue for the rovers and encouraged them to disperse and continue searching the domain when around POIs that had already been observed. Results showed that the combination of the complementary implicit and explicit mechanisms resulted in an improvement of up to 25% over using any of the mechanisms in isolation. It was also observed the combination of explicit and implicit communication was beneficial as when then the implicit mechanisms were less beneficial under limited observability by using the explicit mechanism.

Wang et al. (2013a) investigated the use of explicit and implicit communication within a multi-robot environment wherein a leader-follower system had to jointly manipulate an object whilst avoiding other robots moving within the environment, mimicking the dynamic environment that could be found within an automated warehouse.

The implicit communication strategy employed a sequence of reasoning, where the robots used a sensor network to observe the movement of other robots and make a prediction for their behaviour by using an inference engine. All robots in the environment were programmed to follow a list of 'traffic rules' when navigating around the environment, such as keeping to the left, prescribed speeds, and a sequence for encountering cross roads. The inference engine enabled the robots to predict the behaviour of the robots by observing the traffic rules they were enacting at any given time.

For explicit communication, the robots employed fuzzy logic to decode instructions from explicit messages sent by the robots. The messages could contain movement instructions like turn left, turn right, or stop, or the measured position of an obstacle in relation to the robot. The combination of these two mechanisms enabled the robots to cooperate on moving the object jointly whilst avoiding obstacles and other robots in the environment, and whilst reducing the overheads of explicit communication among the robots.

The work described above differs from the work presented in this thesis, in that neither of these implementations explore the use of force information as a type of implicit communication, but instead employ implicit communication that relies on observation. Additionally, neither of the two implementations explore the combination of the two forms as a cooperative mechanism for manipulating an object between two robots.

As discussed in Section 2.1.2, the combination of implicit and explicit communication within Joint Action between humans acts as an attractive inspiration for communication in a robotic system. When combined in human behaviour, cooperation is faster and more efficient than when using just one form of communication, force information can provide specific and accurate directional cues to the cooperator, and instructions can be re-enforced when applying both forms at the same time. The research question posed in this thesis asks whether, when such a behaviour is implemented onto robots, the advantages of the behaviour such as speed, efficiency and message re-enforcement translate.

In object manipulation tasks, both cooperators are in physical contact with the object they are manipulating and exert forces on the object naturally throughout task execution. Being able to measure these forces to interpret directional information makes force sensing an attractive form of implicit communication to use in such tasks. Additionally, improving speed and efficiency in object manipulation tasks within environments such as automated warehouses would increase performance and production for those businesses.

When exploring combined communication in human behaviour, there are no prevalent disadvantages or disadvantageous effects on performance. However, it is important to ensure when investigating a robotic system that combines both forms of communication that the combination does not negatively impact performance or hinder the robot's ability to successfully manipulate objects together.

Whilst this thesis focuses on the application of a combined system in object manipulation tasks, in the context of potential use in automated warehouses, a communication strategy that is fast and efficient by employing implicit and explicit communication could be useful in other robot tasks. For example in coordinated movement tasks between two robots where one is unable to navigate through the environment themselves, or in hostile environments where robots are required to cooperate with each other independently of humans, such as search and rescue applications after natural disasters, where robots are required to move debris, or in resource acquisition such as mining. Potential applications of a system that uses a combination of implicit and explicit communication is discussed in more detail in Chapter 10.

2.4 Conclusion

This chapter has provided an overview of the biological inspiration for this thesis: joint action in humans, as well as different communication types that help facilitate the behaviour. This chapter then reviewed implementations of these concepts within human-robot, robot-robot and multi robot applications to contextualise the aims of this thesis within exisitng research. This literature review highlights the shortcomings of existing research to be as follows:

- Applications employing implicit and explicit communication in human-robot interaction still rely on a human expert's ability to interpret implicit and non-verbal cues.
- Robotics research, both in robot-robot and human-robot systems, has yet to capitalise on humans' ability to cooperate on object manipulation task effectively using joint action, specifically the combination of implicit and explicit communication.
- There is insufficient comparative literature about the performance of explicit and implicit communication when used individually by robots in object manipulation tasks.
- No known existing literature has attempted to combine explicit and implicit communication in the form of forces consensus between two robots in an object manipulation task

This thesis presents a comparative analysis and performance profiles of explicit and implicit communication when used in object manipulation tasks between robots, to further understanding of the two forms of communication, as well as a two robot system that employs a novel combination of explicit and implicit communication using force information to manipulate objects through a range of environments.

The systems presented in this thesis are novel and interesting computational speaking because they are in reality quite simple. The form of explicit communication used, wireless messaging, is commonplace and only requires the transfer of simple data composed of a speed value and a string that is a verbal instruction. For implicit communication, the system does not rely on a human's expertise to interpret implicit and non-verbal cues and instead uses the tightly coupled nature of the object manipulation task to read forces in the x and y axis and uses simple Newtonian physics to calculate necessary velocity from those values. These two forms of communication are then combined through a weighted sum to investigate their performance in a hybrid system. The simplicity of the two strategies, and their combination, allows for a test bed where a thorough comparison can take place on a low level, reducing potential dependencies on other features. This comparison helps address the insufficiency present in current literature about the performance of both types of communication in object manipulation tasks between two robots, and provides a simple proof of concept that investigates combining explicit and implicit communication in the form of force consensus between two robots in an object manipulation task.

Chapter 3

Experimental Setup

The task chosen as a test-bed throughout this thesis was an object manipulation task between two robots in a Leader-Follower configuration that manipulate an object from one location to another across an environment.

The way in which the robots communicate with each other varies throughout the thesis, first in Chapters 4 and 5, the robots use exclusively explicit communication or implicit communication and their performance is compared. Then, in Chapters 7.2 and 8, when explicit and implicit communication is combined with a weighted sum. However, the physical configuration of the robots in a Leader-Follower configuration and the manner in which the Leader navigates through environments remain consistent regardless of the controllers being implemented.

Within this thesis several environments and object types are used to evaluate these communication strategies within simulation. This chapter outlines the experimental setup of all simulations performed in this thesis, and details the physical configuration of different environments and object types used. Additionally, the method is described for how the metrics used to evaluate performance were calculated from the raw data.

3.1 Simulator

All experimental configurations were designed and tested within the robotic simulator CoppeliaSim, (previously known as V-REP) a feature-rich commercial simulator. When choosing a simulator to test the systems it was crucial that the system could accurately simulate the physical interactions between the robots and the objects, due to the nature of the implicit strategy, which measures force in order to infer information from the Leader robot.

A simulator like ARGoS (Pinciroli, 2022), which is popular in the multi-robot community for simulating swarms, was not suitable as it's integration with physics engines was not well developed and it did not have a force sensor in its sensor library to use within simulations. This meant it lacked the functionality required to easily implement the strategies within a simulator test bed.

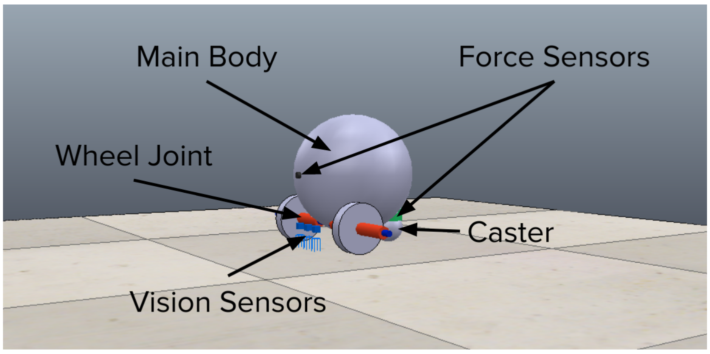
The simulator gazebo (Howard, 2022), offered much of the same functionality offered by CoppeliaSim, including access to multiple high performance physics engines, force-torque sensors in its sensor libraries, a graphical interface and a large online community with support to aid implementation.

Whilst gazebo could have been used to develop the same experimental test-bed, CoppeliaSim was ultimately chosen due to several advantages it possessed over gazebo. Firstly, it had the ability to combine basic objects and sensors easily within models encouraged the ability to quickly prototype and develop systems. Secondly, as a commercially available product, not only was it well documented, with a full user manual and forum, but its implementation of physics engines was industry standard and provided the functionality needed to implement the implicit strategy described in this thesis. Thirdly, the library of robot platform models available in CoppeliaSim was extensive, and offered attractive possibilities for future implementation of the strategies onto multiple platforms. Finally, CoppeliaSim's fundamental implementation allowed for the development of the physical system components within the graphical interface, and the development of the controllers as written Lua scripts. This enabled a faster development and prototyping process than other simulators, like gazebo and ARGoS, where entire simulation environments were written purely in code with no graphical counterpart.

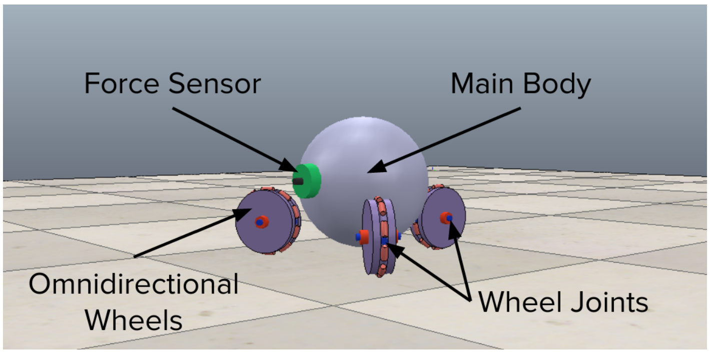
3.2 Robot Platform

The communication strategies used in this thesis were devised and implemented onto a variant of the BubbleRob robot platform (Coppelia Robotics, 2018a). As shown in Figure 3.1, the Leader robot used throughout this thesis was an unmodified BubbleRob platform. It's architecture comprised of a spherical main body, a caster for balance, three orthographic vision sensors for it to navigate through environments described in Section 3.3 and two wheels, whose speeds were controlled by two revolute wheel joints. The Leader also had two force sensors, one of which was positioned at the front to allow it to be rigidly connected to the Object, and another connected to the caster to rigidly link the caster to the rest of the robot. It is important to note that the only purpose of the force sensors were to enable the simulator to treat the system as a rigidly-connected system, throughout the experiments described in this thesis the Leader never read data off of the force sensors to manipulate the object. The vision sensors, joints and force sensors were all standard components available in the CoppeliaSim component library

The Follower robot, as shown in Figure 3.1 was modified to have three omnidirectional wheels adapted from the robot referenced in Liyanage (2018). The wheels were equally spaced around the robot and were oriented tangential to the robot's body, as shown in Figure 3.2. The wheels had two revolute wheel joints each, whose velocities were controlled by three velocity equations that are detailed in Section 4. The Follower was also equipped with a force sensor at the front of the robot, which it used to measure forces exerted by the Leader onto the object in the implicit communication strategy and the hybrid system described in this thesis.



(a) The Leader robot architecture



(b) The Follower robot architecture

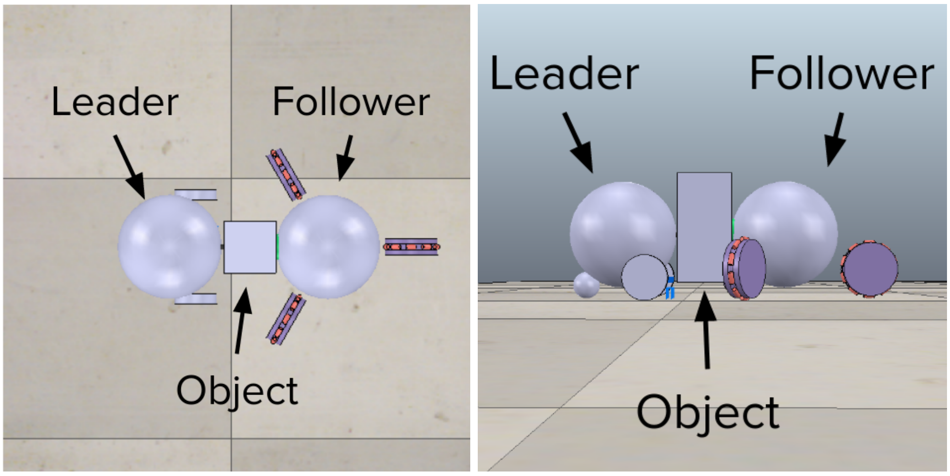
Figure 3.1: The Leader robot and Follower robots and their architectural and mechanical parts.

The BubbleRob platform was chosen for its simplicity, which allows for a comparison of the two communication strategies to occur at a low level. The simplicity of the platform also enabled the rapid prototyping of the systems described in this thesis, as the simple morphology of the two robots meant controllers were easy to develop and code. Additionally, it allows the results from the experiments to be translatable to multiple platforms, as the strategies only have a few dependencies: sensors for line following, omnidirectional wheels that have similar wheel equations to those described in Chapter 4, and memory to load a path found by the Expansive-Space Tree (EST) path planner, which can be found online or offline.

In all experimental environments, the Leader robot was the only robot that had knowledge of its location in relation to the goal location and the path it is following. The Follower robot had no ability to sense the path or to gain knowledge of its position. The Follower robot used information from the Leader either communicated explicitly, implicitly or through a combination of the two, to calculate the velocities it had to apply to it's wheels in order to manipulate the object jointly with the Leader.

The robots were rigidly connected to the object, whose size and shape changed depending on the experiment and are detailed in Section 3.4. The object was suspended in the air between the two robots, distinguishing this manipulation task from a Box-Pushing task, where robots manipulate an object by pushing it along a surface. By having the object suspended, frictional forces from the arena surface could be ignored when deriving velocity. Additionally, rigid attachment at a fixed point in the centre of the robots also meant the object formed a fixed part of the system's dimensions through task execution. Dimensions such as distance between robots remained constant and helped simplify the strategies used to derive velocity through implicit communication, as described in Chapter 4.

The robot-robot configuration shown with the Original Object can be seen in Figure 3.2. The mass and dimensions of the two robots are shown in Table 3.1.



(a) top view (b) side view

Figure 3.2: The Leader robot and Follower robot configuration. In both images the Leader is on the left and the Follower is on the right.

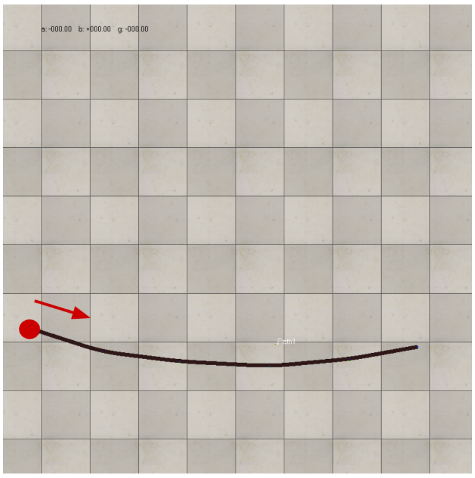
Table 3.1: Dimensions and mass of the Leader and Follower robots

Robot	Mass (kg)	Dimensions (x by y by z) (m)
Leader	6.321	0.21 x 0.22 x 0.23
Follower	8.061	0.34 x 0.38 x 0.22

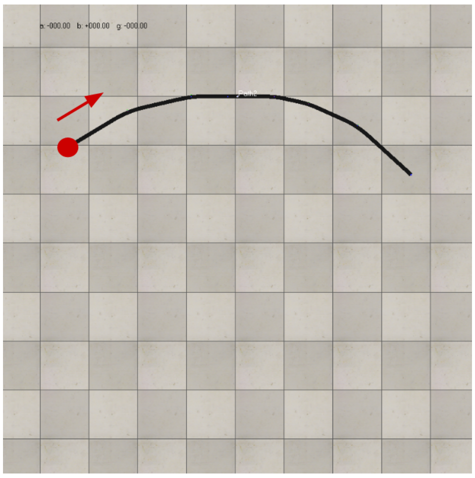
3.3 Environments

The objective of the experiments was for two robots to jointly move an object from a start location to a target location, or 'goal region' in four different experimental setups in simulation, using the two different communication cooperation strategies described in Chapter 4.

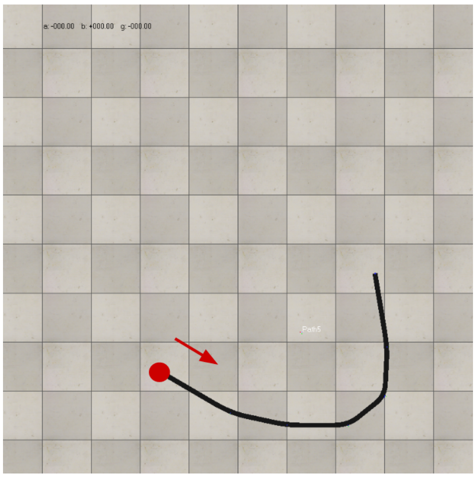
In the first setup the robots moved the object along a range of predetermined paths drawn on the ground, all three paths in this setup are shown in Figure 3.3. The Leader navigated along the path using three vision sensors.



(a) Line Following Path 1



(b) Line Following Path 2



(c) Line Following Path 3

Figure 3.3: Line Following environmental setups. The red dot indicates start point, and the arrow indicates the starting direction for each path.

The remaining three experimental setups involved the robots moving from a start position to a target position, using Expansive-Space Tree (EST) path planning, calculated using the The Open Motion Planning Library (OMPL) CoppeliaSim plug-in (Kavraki Lab, 2019). EST path planning uses random sampling to extract connectivity information in a configuration space to create a road-map from one location to another, and is well suited for single query path planning problems (Hsu et al., 1997), like the one employed in the experimental setups described in this thesis. It is also well suited for 2D problem spaces. Ultimately, the decision to use EST was arbitrary as path planning was not the focus of these experiments, but merely a necessary component to evaluate the ability for the two robots in the configuration to jointly move an object from on location to another. Other efficient tree search algorithms such as a Rapidly-exploring Random Tree planner (RRT) would have also been suitable as the path planning problem in this case was single query in a simple 2D problem space. EST planning was employed as it was a planner available in the OMPL library with a well supported API, and could thus be quickly used to create paths within the environments.

In one environment, the robots moved across an empty room (the ‘simple environment’), as shown in Figure 3.4, in another environment the robots navigated along a corridor into an office style room where the goal region was situated, (the ‘cluttered environment’), as shown in Figure 3.5. The final environment contained a mixture of cuboids and cylinders in a variety of sizes, positions and orientations that were randomly generated, (the ‘randomly generated environments’), shown in Figure 3.6.

The paths were generated prior to the experimental runs and stored in .csv files. The Leader read a path from a .csv file and then attempted to follow it as closely as possible using a simple algorithm derived from the one employed in Kummer (2019). Paths were stored rather than generated online in order to keep data collection consistent, as the plug-in is not guaranteed to generate the same path when scenes are run multiple times.

For the ‘simple environment’, only one path was generated as the presence of no collision objects meant the path planner generated the same path each time, the path can be seen in Figure 3.4.

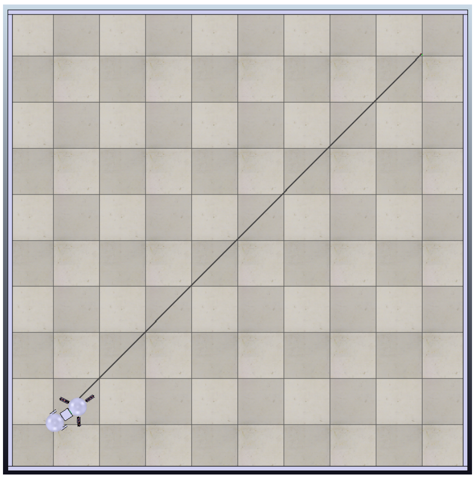
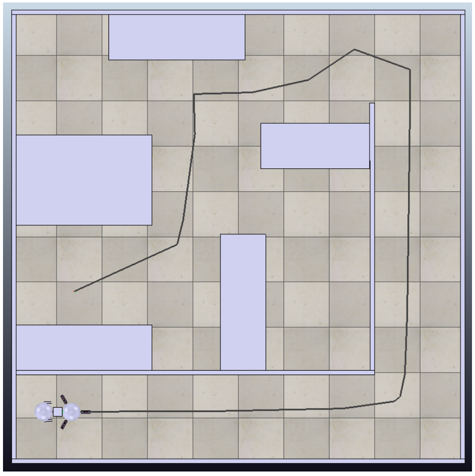


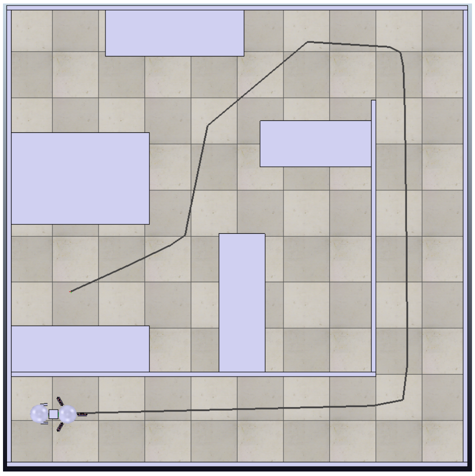
Figure 3.4: The Simple Environment setup for path planning

For the ‘cluttered environment’, three paths were generated to provide more data for how the strategies handled different path curvatures around the obstacles present in the environment, all three paths are shown in Figure 3.5.

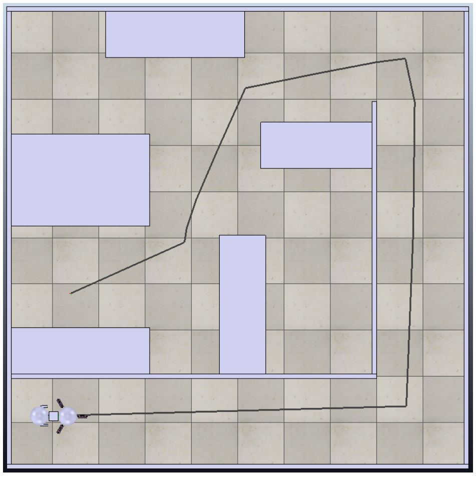
For the ’randomly generated environments’, three environments and associated paths were generated to evaluate how the strategies handled different path curvatures and obstacle configurations. The environments’ parameters were were randomly generated using a Python script first and then paths were generated in the constructed environments. The script generated the number of obstacles to appear within the environment, their size, their orientation within the environment, and the x and y coordinates for the end point and the



(a) Cluttered Environment Path 1



(b) Cluttered Environment Path 2



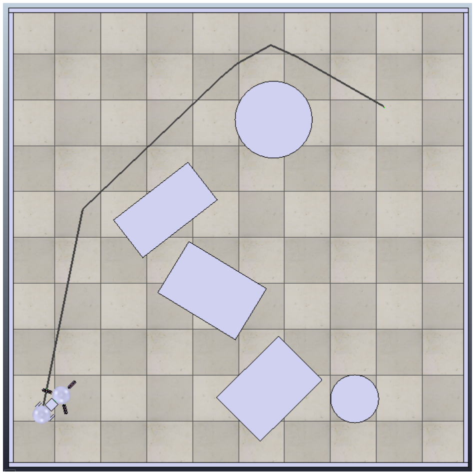
(c) Cluttered Environment Path 3

Figure 3.5: Cluttered Environment setups.

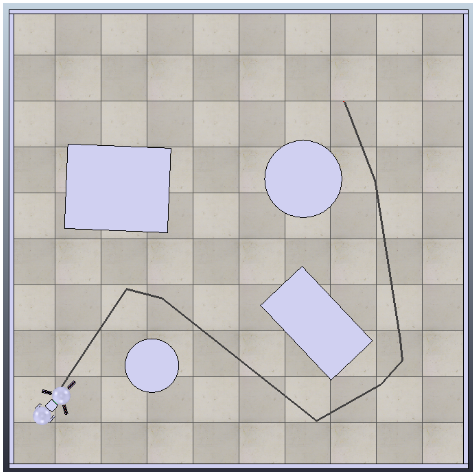
obstacles to be placed in the arena. The number of obstacles present was randomly selected from a range of 2 and 5 for both cuboid and cylinder obstacle types. The width and depth of the cuboid obstacles were randomly generated between the bounds of 0.5m and 1.5m, and the diameters of the cylinder obstacles were within the bounds of 0.5m and 1m. The height of the obstacles were kept constant at 1m. Finally, the orientations of the cuboid obstacles were randomly generated between zero and 360°. The python script used to generate these environments can be found in the code repository provided to support this thesis [1].

The environments were then constructed in such a way that ensured that the following conditions were met: the end point was not located underneath an obstacle or in a location that was reachable from the start location by a straight line, and no obstacles were positioned such that they were on top of the robots or overlapping each other.

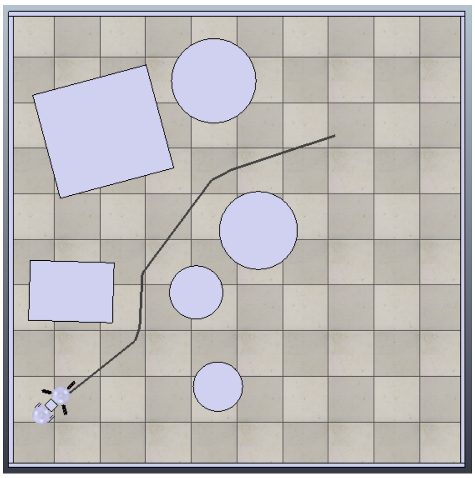
The three environments and their associated paths can be seen in Figure 3.6.



(a) Randomly Generated Environment Path 1



(b) Randomly Generated Environment Path 2



(c) Randomly Generated Environment Path 3

Figure 3.6: Randomly Generated Environment setups.

[1]https://github.com/naomigildert/NGildertThesis (Accessed: 21/04/2022)

In all environments noise was injected into the system in the Leader's wheel velocities to ensure variability in the simulation runs, this was achieved by randomly generating a different number between 0 and 1 in each experimental run using CoppeliaSim API functions and adding this number to the Leader's wheel velocities. In the line following set-up, the starting positions for the robots for each path were manually chosen to ensure the Leader robot's vision sensors were on the line and the alignment of the robots was congruent with the initial trajectory of the path. The target location and associated 'goal region' were set at the end of the line.

In the path planning set-ups the starting positions for the robots ensured the Leader was placed on the start location for the pre-planned path. The target locations were placed on the other corner of the environment for the simple set-up, in the middle of the office for the cluttered set-up, and were randomly generated in the randomly generate environments. The starting positions and target locations were kept the same for every experimental configuration.

The experiments were run headlessly, within a console and without a graphical interface, which enabled the computer to complete simulations more quickly, as computational power was not required for rendering the graphical environment. The experiments had a maximum simulation run time of 800 seconds, which was determined to be a sufficient amount of time for the robots to complete all tasks. Each experimental environment was run 100 times.

When running headlessly, if the robots completed the task, i.e. if the Leader's position was within the 'goal region', the Leader robot would log that the task had been completed and the simulation would stop. Every half second the Follower robot logged the simulation time, x and y coordinates of the object's position, and the object's velocity along the x and y axes, using CoppeliaSim API functions (Coppelia Robotics, 2018b).

Within the research field of robotics, the term 'reality gap' coined by Jakobi et al. (1995), refers to the difference between simulation and the real world. This gap can encompass several features, from the difficulty in simulating an environment that mimics the complexities of the physical world, to the discrepancies in electronics that can often create inaccuracy or noise in sensors and actuators that are not present in simulators.

Regarding the gap between a simulated environment and the real world, the simulator used throughout this thesis, CoppeliaSim, is feature-rich and is often used throughout research and industry to accurately simulate real robotic models, it also employs multiple physics engines to accurately simulate physical interactions between components within the simulation. It is used frequently and reliably within robotics research as a simulator before controllers developed within CoppeliaSim are employed in the real world.

In the environments discussed within this Chapter, whilst the randomly generated environments remain quite abstract and the line following environments and the simple environment are over simplified, the Cluttered Environment was based upon a real life office environment to provide some realism to the simulations.

Jakobi et al. (1995) stated that the introduction of noise within a simulation makes the simulation more realistic and reduces the reality gap, as sensors and actuators in real life are likely to be noisy. As discussed above, within the experiments described in this thesis noise was injected onto the Leader's wheels, however, no noise was injected into the sensor readings of either of the robots. This thesis provides a proof of concept of a novel system, thus it was important to investigate it's performance without inaccuracies in the sensor readings, so that it was clear the results were only correlated to the performance of the system, and not on the performance of it's sensors.

Whilst this thesis aims to minimise the reality gap with the factors mentioned above, the lack of noise present on the vision or force sensors, or in the wireless messaging used as explicit communication between Leader and Follower, are all explored in Future Work in Chapter 10, whilst discussing closing the reality gap, and evaluating performance of the system on robots in the real world.

3.4 Size and Shape of the Object

The size and shape of the object being manipulated by the robots varied in different experiments. The 'Original Object' was used in the simple comparison experiments conducted in Chapter 4 and in the experiments testing the hybrid system in Chapter 7.

The 'Original Object' was a cuboid box of uniform mass and density. The box weighed 0.5kg and was 10cm wide, 10cm deep and 20cm high. The 'Original Object' is depicted in Figure 3.2.

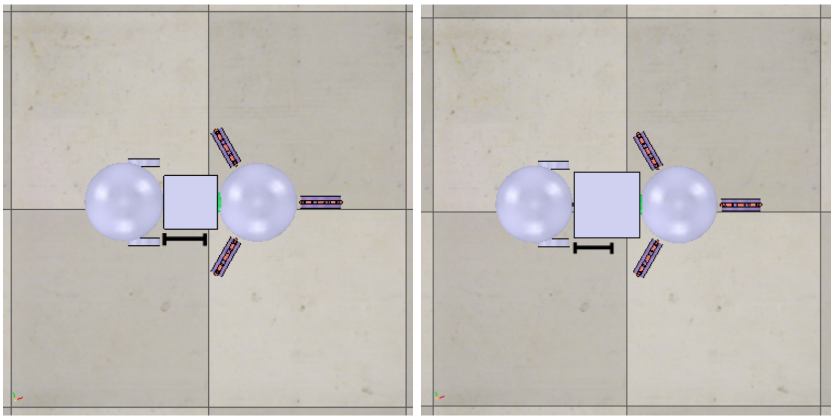
In Chapters 5 and Chapters 8, objects of different size and shape were used to test the sytems' abilities to manipulate different object types.

In these experiments, the robot-robot configuration remained the same, but the objects being manipulated by the robots were adjusted in size and shape. For different objects, the values for object mass and moments of inertia required by the implicit strategy to calculate its wheel speeds were modified accordingly. These values for each object type, including the original object were calculated offline.

3.4.1 Size

When investigating the performance of the strategies in relation to object size, the 'Original Object' cuboid box used in the experiments in Chapter 4 was proportionately scaled to two different object sizes.

Its original dimensions, and associated experimental results found in 4 were taken as the baseline small sized object. The range of sizes were limited by the morphology of the Leader robot as the Leader's wheels protrude forward from its main body, meaning any object larger than the 0.2m diameter of the robot did not fit between the Leader's wheels. An object width of 0.17m was chosen for the largest object size, and a midpoint value of 0.135m was chosen for the medium size. The different sized objects and their size in relation to the robots can be seen in Figure 3.7, their mass and full dimensions can be seen in Table 3.2



(a) Medium Sized Object (b) Large Sized Object

Figure 3.7: The medium and large sized cuboids to test consistency in performance with different object size. The included marker is equal to the length of the original object, and is provided for visual comparison. The dimensions and mass of each size are listed in Table 3.2

Table 3.2: Dimensions and mass of different sized cuboids

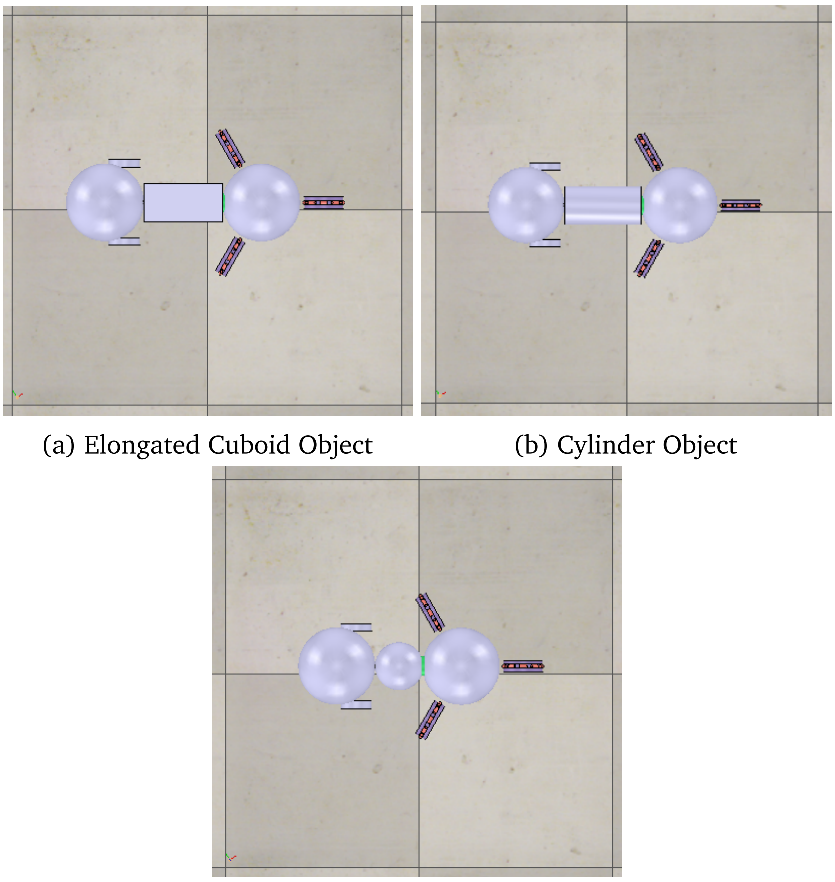
Size	Mass (kg)	Dimensions (x by y by z) (m)
Medium	0.91	0.135 x 0.135 x 0.2
Large	1.45	0.17 x 0.17 x0.2

3.4.2 Shape

In order to investigate performance with different shape types, three shapes were chosen from CoppeliaSim's library of primitive, pure shapes. A cuboid, that was elongated in the global x axis to differ from the original cuboid, a horizontally orientated cylinder and a sphere were chosen to provide a range of object sizes in length, and a variety of object surfaces at point of attachment to the robots. The different shaped objects and their size in relation to the robots can be seen in Figure 3.8, their mass and full dimensions can be seen in Table 3.3.

Table 3.3: Dimensions and mass of different shaped objects

Size	Mass (kg)	Dimensions (x by y by z) (m)
Cuboid	1	0.2 x 0.1 x 0.2
Cylinder	1.57	0.2 x 0.1 x 0.1
Sphere	1.02	0.125 x 0.125 x 0.125



(a) Elongated Cuboid Object (b) Cylinder Object

(c) Sphere Object

Figure 3.8: The three object shapes used to test consistency in performance with different object shapes. The dimensions and mass of each shape are listed in Table 3.3

3.5 Evaluating Performance

In order to evaluate performance, design requirements deemed vital for successful task execution in object manipulation tasks, such as reliability, efficiency and smoothness are explored by measuring associated metrics, which are shown in Table 3.4.

Table 3.4: An overview of the design requirements investigated in this work and the metrics measured during experiments to evaluate these qualities

Design Requirements	**Metric Measured**
Reliability	Task completion
Efficiency	Time taken Total distance travelled by object
Smoothness	Maximum displacement of object Path Fidelity
Fault Tolerance & Robustness	Fault tolerance to sensor fault Fault tolerance to motor fault

For all metrics aside from Task Completion, the mean and standard deviation were taken in order to make comparisons in performance. The method in which these metrics were calculated using the raw data taken from the experimental simulations, to determine the mean and standard deviation, is described below.

3.5.1 Reliability

To explore the reliability of the two communication strategies, task completion was measured. This metric gives an indication of the likelihood a strategy will complete the task and successfully manipulate the object from start location to end location. Task completion was calculated as a percentage of how many runs in the experiment the Leader logged a task as complete.

3.5.2 Efficiency

The two metrics used to gain an understanding of the efficiency of the strategies were time taken to complete the task and total distance travelled by the object. These design requirements are desirable as they demonstrate how quickly a strategy can complete a task, and also demonstrate how efficient the strategies are in the distance they travel when manipulating the object. These can give further indication of economical benefits such as lower power consumption, shorter run time of the system, less wear and tear of the system during task execution.

Time taken was determined as the simulation time recorded when the Leader logged the task as complete.

Total distance travelled by the object was calculated by performing a summation on the distances between consecutive x and y coordinates in the Follower's logged position data.

3.5.3 Smoothness

For object manipulation tasks, it can be important to consider if the system can cope with a wide range of object materials, including fragile items. To test the two strategies performance with different object types, the quality 'Smoothness' was considered and measured by the maximum displacement of object and path fidelity (ability to stick closely to the assigned path) during task execution. These metrics give an indication of how smooth the strategies are, and provide insight into whether or not the strategies could handle different object types.

The maximum displacement of the object for a single experimental run was calculated by comparing the x and y coordinates of the object from one time stamp to another to determine the displacement of the object during a single time step. The maximum displacement was stored for each experimental run and then averaged across all experiment runs for the data set.

Path fidelity was calculated by determining how many 'way-points' - theoretical circular zones with a radius of 0.02m - the object passed through along the trajectory. Control points, which lay along the trajectory, were exported from CoppeliaSim as x and y coordinates. The coordinates were compared with the logged x and y position of the object to determine whether the object had 'passed' through the way-point. Path fidelity was then calculated as the percentage number of way-points the object passed through during task execution and averaged over all experimental runs.

3.5.4 Fault Tolerance & Robustness

In order to evaluate the performance of any robotic system, it is beneficial to analyse the system's fault tolerance and performance in the presence of faults, to better understand it's robustness. In this thesis, understanding the communication strategies' fault tolerance when operating in isolation, and the fault tolerance of the hybrid system was crucial to understanding if the hybrid system proves a more attractive option than either strategy independently.

In this thesis, rather than using a singular metric to measure fault tolerance in the individual and hybrid systems, in the same manner the other design requirements are analysed, the evaluation of fault tolerance involved measuring the performance of the systems through the other metrics listed above when different simple faults had been injected into the system. That is to say the task completion, time taken, total distance travelled by the object, maximum displacement of the object and path fidelity were all evaluated to determine fault tolerance.

As fault tolerance in robotics systems is a vast research are in its own right, and this thesis aims to only provide a proof of concept for a hybrid system combining explicit and implicit communication, only two simple faults were considered when evaluating fault tolerance and robustness, to limit scope. The two faults injected were vision sensor faults and partial motor faults.

Vision Sensor Faults

This fault was only investigated within the line following environments, as those were the only environments in which the Leader used its vision sensors to navigate along the path. To inject a vision sensor fault occurring in simulation the Leader's controller was edited to continuously read the input of a given vision sensor as false, mimicking the behaviour of if the sensor had stopped functioning and taking readings in reality. The rest of the Leader's controller remained unchanged. This was done separately for each vision sensor: left, middle and right.

Partial Motor Faults

This fault was investigated across all environments. A motor fault was injected onto the Leader's left and right wheels, and all three wheels of the Follower. Only one wheel was injected with a fault at a time. The partial motor fault was emulated in simulation by editing the given robot's controller to reduce the speed of the specific wheel to fifty percent of it's velocity, mimicking if the motor had a partial failure in reality. The rest of the robot's controller remained unchanged.

3.6 Statistical Validity

In order to provide statistical validity to the comparisons in performance conducted throughout this thesis, Mann-Whitney U tests, also known as Wilcoxon rank sum tests, were used. These tests determine statistically significantly difference between data sets, and were thus used in order to accept or reject the null hypotheses.

The Mann-Whitney U tests returned a p-value, which if below 0.05 indicated statistically significant difference. This statistical test was used as it is able to calculate significant difference between data sets of different sizes, and thus could still provide statistical information for environments that did not have 100% task completion.

3.7 Conclusion

This chapter presents the experimental setup used throughout this thesis, detailing the four environments, which involve the robots using line following along a pre-drawn path or employing EST to move the object through simple, cluttered and randomly generated environments, and the six different object types used to investigate performance.

The qualities and metrics used to evaluate the performance of the communication strategies and the hybrid system are also described, as well as the methods used to calculate these metrics using raw experimental data.

Finally this chapter details the statistical test, the Mann-Whitney U Test, used to statistically compare and verify the performance of the communication strategies and the hybrid system.

Chapter 4

Comparing Communication Strategies in Simple Object Manipulation Tasks

In Chapter 2, the use of explicit and implicit communication between two robots in object manipulation tasks was discussed. In particular, the work of Aiyama et al. (1999), which employed an implicit strategy that used thresholds to ensure cooperative movements, and Pereira et al. (2002) whose implicit strategy involved a Follower robot making appropriate movements to keep a force summation null and allow cooperative object manipulation.

This chapter describes the two communication strategies for explicit and implicit communication that are used throughout this thesis, and the configuration of the two robots that employ these strategies in object manipulation tasks. The explicit strategy employs wireless messaging to transfer information from one robot to the other, whilst the implicit strategy employs Newtonian mechanics to use force information as a form of implicit communication.

This chapter also details the initial comparison of explicit communication and implicit communication. The design requirements of the two communication strategies are investigated within the four environments described in Chapter 3: line following along a pre-drawn path using vision sensors, and Expansive-Space Tree (EST) path planning in simple, cluttered and randomly generated environments.

4.1 The Communication Strategies

The cooperative system chosen for this configuration, as described in Gildert et al. (2019), is comprised of two robots: a Leader robot and a Follower robot, who are rigidly attached to an object they must manipulate from a start location to an end location. The Leader has knowledge of its location in respect to a path that it is programmed to follow, and the Follower must apply either an explicit or implicit communication strategy in order for the two robots to jointly move the object. The Leader travels forward across the environment, and the Follower travels backwards.

The only morphological and technological restraints imposed by the strategies are as follows:

- the Leader and Follower robots must have the ability to transmit and receive wireless messages whilst communicating explicitly
- the Leader must be equipped with the correct sensors and the computational ability to navigate across an environment from a start location to a desired end location, either using conventional path planning techniques, or sensors.
- the Follower must be equipped with a force sensor in order to measure and use force information whilst communicating implicitly
- the Follower must be equipped with omnidirectional wheels in order to transform force information measured in the x and y axis into lateral movement in any corresponding direction.

In both strategies the Follower interprets information it receives from the Leader, whether implicitly or explicitly, to determine its speed and direction in order for both robots to jointly move the box. The omnidirectional wheels of the Follower robot have three velocities associated with them: their translational velocities V_x and V_y along their x and y axes, and their rotational velocity around the centre of the robot, V_{rot}, which can be derived from the V_x and V_y velocities and the size of the robot.

The configuration of the omnidirectional wheels in relation to translational velocity along the x and y axis are shown in Figure 4.1. The equations for the velocities applied to each wheel, to allow movement and rotation in any direction, are described in Equations 4.2, 4.1 and 4.3, for Wheels 1, 2 and 3 respectively. For each strategy, the Follower calculates the three velocities using the information received from the Leader, and applies those velocities to the wheel equations. How it calculates the velocities is dependent on the communication strategy employed.

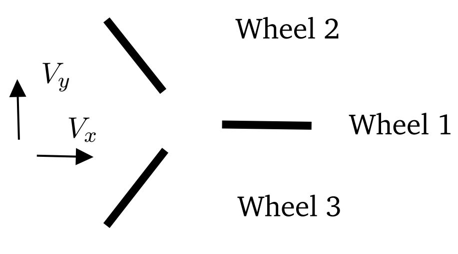


Figure 4.1: The wheel configuration for the omnidirectional wheels to enable movement of the Follower robot in any given direction, in relation to translational velocity along the x and y axis. The associated velocities for Wheel 1, 2 and 3 are described in Equations 4.2, 4.1 and 4.3, respectively

$$V_{Wheel2} = V_x + V_{rot} \tag{4.1}$$

$$V_{Wheel1} = -\frac{1}{2}V_x + \frac{\sqrt{3}}{2}V_y + V_{rot} \tag{4.2}$$

$$V_{Wheel3} = \frac{1}{2}V_x - \frac{\sqrt{3}}{2}V_y + V_{rot} \tag{4.3}$$

4.1.1 Explicit Communication

In the explicit communication strategy, the Leader transmits information to the Follower through an established wireless messaging channel.

The explicit communication strategy effectively acts as a feed-forward control loop, where the Follower performs a deliberative, corrective change in its movement to align with the transmitted instruction from the Leader. The Follower robot does not read any information from its force sensor, but solely uses the information received by the Leader to determine its movements. At every time step, the Leader robot transmits its desired forward velocity and, depending on its position on its trajectory to the desired end point, it also transmits the appropriate instruction from the set “Left”, “Right” and “Backwards”, to inform the Follower robot which direction to move or to continue backwards in a straight line. When the Leader robot’s position reaches the end of the path, or the ‘goal region’, the Leader transmits the message "Stop" and sets its desired forward speed to zero.

The Follower robot receives data from the Leader and adjusts the value of its wheel velocities, V_y, V_x and V_{rot}, depending on the message. For an instruction of “Left” or “Right” the Follower sets the values of V_x and V_{rot} to zero, and the value of V_y to the positive desired speed transmitted by the Leader for a “Left” instruction, and the negative of the desired speed for a “Right” instruction, in order to produce a deliberative movement in the appropriate direction. When the Follower receives a “Backwards” instruction it sets the value of V_x to be the negative of the desired speed transmitted by the Leader, the V_y velocity to equal $\frac{V_x}{\sqrt{3}}$, and the rotational velocity, V_{rot} to be the same value as V_x. These values are determined algebraically using the the equations shown in Figure 4.1, and correspond to an overall velocity vector in the direction of the wheel that points along the path. Upon receiving a “Stop” instruction, the Follower sets all wheel velocities to zero.

In the event of explicit communication failing, robustness cannot be guaranteed. As the Follower has no knowledge of where it is in the environment in relation to the goal location, it is not able to navigate across the environment without explicit instructions from the Leader. If explicit communication fails and the Follower stops receiving instructions from the Leader it will continue to apply the wheel velocities that correspond to the last transmitted instruction and the task will fail.

4.1.2 Implicit Communication

For the implicit case, no information is exchanged through wireless transmission. Instead, the Follower robot measures the force being exerted on its force sensor and uses this information to determine its wheel velocities as depicted in Figure 4.1.

Whilst the explicit communication strategy acts as a feed-forward control loop, the implicit communication strategy acts as an error rejection negative feedback loop. The Follower treats any change to the input, including the actions of the Leader, as a disturbance, which it rejects in order to correct its movement. This makes the strategy more reactive than deliberative.

The Follower, based on the force it measures, calculates what the Leader's expected velocity would be if the Leader was moving an object that was half the mass of the box by itself. This is under the assumption that the object is of uniform mass and density, and that the two robots should share the load equally whilst manipulating it together, thus at the point of connection each robot perceives the object to be half of its original mass. If both robots individually move at the expected velocity to move an object of half the mass, they equally share the load of the full mass and move the object jointly. The Follower uses the calculated expected velocity of the Leader to determine its own wheel velocities for its omnidirectional wheels to move at the same velocity.

The Follower measures the force being exerted along the global x-axis to determine the value of V_x and calculates the torque being exerted by the Leader to cause a moment in the y-axis, to determine a value of V_y. As the robots are rigidly connected in a fixed orientation for the movement of the box, the wheels' rotational velocities around its centre of rotation will always be zero.

Calculating V_x

When determining the value of the Follower's velocity along the global x-axis, the summation of the forces being exerted by the Follower and the Leader can be described using Newton's Second Law:

$$F_L + F_F = MA_F \tag{4.4}$$

where F_L is the unknown force being exerted by the Leader, F_F is the force being exerted by the Follower, as measured by its force sensor, M is the total mass of the object and the Leader and A_F is the acceleration of the box, which since the Follower is rigidly attached to the box is equivalent to the Follower's acceleration. For simplicity, the strategy does not estimate mass of Leader online, and the Leader's mass is a global known value.

In order for the Follower to determine it's desired velocity V_x, it must calculate the expected acceleration of the Leader pushing an object of half the mass as the expected object and integrate it. The expected acceleration of the Leader can again be described using Newton's Second Law as:

$$\hat{A}_L = \frac{F_L}{\hat{M}} \tag{4.5}$$

Where $\hat{M}$ is the mass of the Leader plus half of the mass of the object.

$\hat{A}_L$ can be determined by rearranging Equation 4.4 for F_L and substituting into Equation 4.5 to form the following:

$$\hat{A}_L = \frac{MA_F - F_F}{\hat{M}} \tag{4.6}$$

The Forces being exerted in the configuration used to derive the expected acceleration are shown in Figure 4.2.

The Follower integrates the value of $\hat{A}_L$ to determine the expected velocity, $\hat{V}_L$. It then takes this to be its value for V_x.

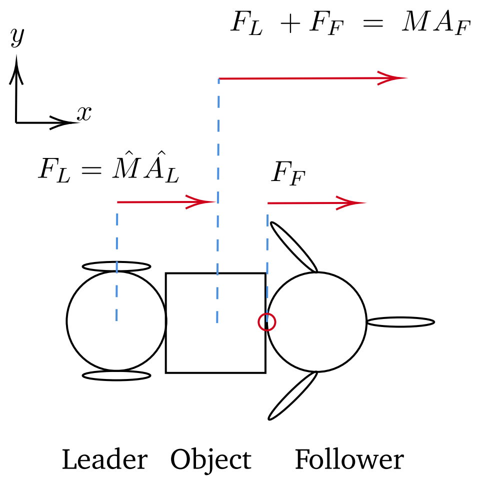


Figure 4.2: Diagram showing forces exerted by the Leader and Follower robots to calculate expected velocity from expected acceleration of the Leader along the global x-axis

Calculating V_y

In order to determine the Follower's velocity along the global y-axis, the torque being exerted by the Leader must be considered. Similar to the translational case it can be said the summation of the torque exerted by the Leader and the Follower is equal to:

$$T_L + T_F = J\ddot{\theta} \tag{4.7}$$

Where J is the moment of inertia of the Leader and the object as a coupled unit as measured from the centre of rotation of the Leader, and $\ddot{\theta}$ is the angular acceleration of the object and Follower. The moment of inertia is manually derived in advance as the summation of the moments of inertia of the shape components of the Leader and the Mass and is again is a known value to the Follower, rather than being derived online.

The torque exerted by the Follower can be expressed as the force its exerting along the y-axis, F_y, over the length from the point of connection with the box, in this case from the force sensor, to the centre of rotation of the Leader robot, L_s. Similarly, the angular acceleration of the Follower can be written in terms of its linear acceleration in the y-axis, A_y, around the centre of rotation of the Leader robot. The distance between the Follower's centre of rotation and the Leader's is L_T, for total length. Equation 4.7 can thus be written as:

$$T_L + \frac{F_y}{L_s} = J\frac{A_y}{L_T} \tag{4.8}$$

Which when rearranged for T_L gives:

$$T_L = J\frac{A_y}{L_T} - \frac{F_y}{L_s} \tag{4.9}$$

Using the same logic as for the translational case, the Follower must determine the expected angular acceleration of the Leader moving an object half its mass, and translate that to its desired linear velocity, V_y. The expected angular acceleration can also be written in terms of linear acceleration, where $\ddot{\theta}$ is equal to the linear acceleration in the y-axis over the total length. Thus the expected acceleration of the Leader along the y-axis, $\hat{A}_y$, can be written as:

$$\hat{A}_y = \frac{T_L L_T}{\hat{J}} \tag{4.10}$$

Where $\hat{J}$ is the moment of the inertia of the Leader around its centre of rotation, plus the moment of the inertia of an object of half the mass.

By substituting in the value of T_L from Equation 4.9, the Follower calculates the expected acceleration in the global y-axis of the Leader rotating an object of half the mass, and thus half the moment of inertia:

$$\hat{A}_y = \frac{T_L L_T}{\hat{J}} = \frac{(J\frac{A_y}{L_T} - \frac{F_y}{L_s})L_T}{\hat{J}} \tag{4.11}$$

The Follower again then integrates this acceleration value, to determine the expected velocity $\hat{V}_y$, which it takes to be its value of V_y for its wheel speeds.

The linear forces and torque being exerted in the configuration used to derive the expected acceleration along the y axis are shown in Figure 4.3.

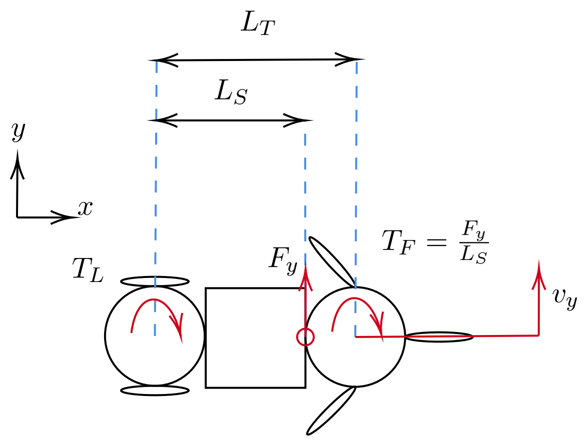


Figure 4.3: Diagram showing Torque and Linear forces exerted by the Leader and Follower robots to calculate expected velocity from expected acceleration of the Leader along the y-axis

The resulting behaviour of this strategy is that the Follower uses force information from its force sensor to move at such appropriate speeds and in directions to effectively share the load of the object with the Leader.

The controller code that implements these strategies can be found in the CoppeliaSim scene files used throughout the experiments described in this thesis. The scene files can be found within a repository. [1].

[1]`https://github.com/naomigildert/NGildertThesis` (Accessed: 21/04/2022)

4.2 Comparing the Performance of the Communication Strategies in Simple Object Manipulation Tasks

In Chapter 2, previous research comparing explicit communication and implicit communication and the limitations of those comparisons were outlined. Of particular interest was the work conducted by Pereira et al. (2002), which provided a narrow comparison of explicit communication and implicit communication in an object manipulation task between two robots, where only successful task completion, completion time and localisation error were measured in a simple environment.

As previously discussed, a more in depth comparative analysis is key to further understand the performance profiles of explicit and implicit communication when used individually in object manipulation tasks, as well as providing insight into how they might interact together in a combined system.

The null hypothesis used to analyse this comparison was as follows:

Null Hypothesis H_0: There is no statistical difference between the performance of the two strategies (rejected with a 95% tolerance).

This was formulated by taking into account Pereira et al. (2002)'s findings, which stated the performance of explicit and implicit communication were similar for simple environments and for conveying simple data. As described in Section 4.1, the explicit strategy only transmits simple data in the form of a string message and a numerical value corresponding to the desired backward speed of the Follower. Whilst the implicit strategy is more complex, the force data it senses from its force sensor can also be seen as simple numerical data, and the computational power required to calculate the desired wheel velocities is small as the Follower is only performing simple mathematical operations. It can thus be considered that the strategies are therefore 'conveying simple data' and will perform at a similar level to each other.

4.3 Results

As shown in Table 3.4, several metrics were measured associated with the design requirements being investigated in the four environments described in Chapter 3.

For all metrics aside from Task Completion, Mann-Whitney U tests, were conducted to determine whether the explicit and implicit data sets were distributions with equal medians or whether they were statistically significantly different, in order to accept or reject the null hypothesis.

How each metric is calculated using raw data taken from the experimental simulations is described in Section 3.5 in Chapter 3.

4.3.1 Reliability

To explore the reliability of the two communication strategies, task completion was measured.

Task Completion

The percentage task completion for both strategies across the four experimental environments is shown in Table 4.1.

The strategies for explicit communication and implicit communication achieved one hundred percent task completion for all paths in the line following and simple environments, with the exception of the implicit strategy which achieved 99% task completion in the third path in the line following environment. The explicit strategy proved to be less reliable in the cluttered environments and random environments, with a task completion of 93% in the third path of the random environment, and a task completion of 60% in the second path of the cluttered environment.

Table 4.1: Percentage Task Completion for Both Communication Strategies in the Four Experimental Environments

Type		Path		
		1	2	3
Simple Environment (SE)	Exp	100.00%	N/A	N/A
	Imp	100.00%	N/A	N/A
Line Following Environment (LF)	Exp	100.00%	100.00%	100.00%
	Imp	100.00%	100.00%	99.00%
Randomly Generated Environment (RE)	Exp	100.00%	100.00%	93.00%
	Imp	100.00%	100.00%	100.00%
Cluttered Environment (CE)	Exp	100.00%	60.00%	100.00%
	Imp	100.00%	100.00%	100.00%

Watching the graphical interface of CoppeliaSim it was observed that the explicit strategy has a tendency to overshoot around corners for higher values of noise injected into the system. In the specific case of the second path of the cluttered environment, this overshoot would then cause the robots to have difficulty navigating around the top corner of the arena, where the path lies close to the arena walls. This is viewable in Video 1a in Appendix B. The robots would collide with the walls and get stuck, preventing them from completing the task.

As the Leader is at the back of the configuration, there is an inherent offset error in the system because the directional information it is transmitting or implying to the Follower is related to its position on the path, not the Follower's. This offset results in the Follower colliding with objects or walls as it has often receiving information to turn too late, which affects overall task completion.

4.3.2 Efficiency

The two metrics used to gain an understanding of the efficiency of the strategies were time taken to complete the task and total distance travelled by the object.

Time Taken

The mean time taken by the strategies can be seen in Figure 4.4a for the line following environment, Figure 4.5a for the simple environment, Figure 4.6a for the cluttered environment and Figure 4.7a for the random environment.

The full numerical results can be found in Table C.1 in the appendices.

As is visually evident in Figures 4.4a, 4.5a, 4.6a and 4.7a, the results show that the Implicit strategy was consistently the fastest in every environmental configuration. For all three paths in the line following environment the implicit strategy was 40 seconds faster and in the simple environment the strategy was over 50 seconds faster, with a completion time of 118.84 seconds compared to the 170.98 seconds it took for the explicit strategy to complete the task on average. In the randomly generated environments, the implicit strategy was faster by a margin of over fifty seconds across all paths and in the cluttered environments, the implicit strategy was over 100 seconds faster than the explicit strategy.

The Mann-Whitney U tests showed that there was a statistically significant difference between explicit and implicit communication for every path in every environment.

The strategy's speed can be attributed to the fact that it continuously calculates velocities in both translational directions by measuring the force and torque. This enables the Follower to continuously move in an arbitrary direction. The Follower in the explicit strategy, however, only sets the value of V_y to a non-zero value when performing a corrective movement, or to a value that produces a velocity vector that is congruent to its own x axis when in backwards mode. This means the Follower is not continuously moving in both the x and y direction, which results in a 'stop-start' corrective behaviour that in turn causes a reduction of speed.

Total Distance Travelled by Object

The mean total distance travelled by the object can be shown in Figure 4.4b for the line following environment, Figure 4.5b for the simple environment, Figure 4.6b for the cluttered environment and Figure 4.7b for the random environment.

The full numerical results can be found in Table C.2 in the appendices.

In the line following, simple and cluttered environments, it can be seen that explicit communication is the most efficient strategy in that it produces the smallest total distance travelled by the object in six out of the ten environmental configurations. The implicit strategy outperformed the explicit strategy in the random environment and in the first path of the line following environment. Across the majority of the environments the differences in total distance travelled was small, in the range of 1cm to 3cm. In the cluttered environments the margin was larger and ranged from 3cm to 12cm.

When watching the strategies in CoppeliaSim it was observed that the implicit strategy would begin to oscillate in such a way that could be observed as a 'tremor', which gradually increased during task execution, indicating an instability in the system. This is viewable in Video 1b in Appendix B. Whilst the 'tremor' was evidently not substantial enough to affect task completion or path fidelity, as indicated by the strength of the implicit strategy's performance in these two metrics, the oscillation caused the object to move more across task execution than in the explicit strategy, resulting in an increase in total distance travelled by the object for the implicit strategy.

In the simple environment, and the first paths in the line following and cluttered environments, the Mann-Whitney U tests showed no significant difference between data sets, however the remaining 7 tests showed significant difference, again contradicting the hypothesis that the two strategies perform similarly.

4.3.3 Smoothness

The design requirement 'Smoothness' was considered and measured by the maximum displacement of object during task execution and path fidelity (ability to stick closely to the assigned path).

Maximum Displacement of Object

The mean maximum displacement of the object can be shown in Figures 4.4c, 4.5c, 4.6c and 4.7c for the line following, simple, cluttered and random environments respectively. The full numerical results can be found in Table C.3 in the appendices.

For the simple environment, the explicit strategy outperformed the implicit strategy with a smaller value for maximum displacement of object (0.018m compared to 0.031m for the explicit and implicit strategies respectively). Since the path in this environment was a straight line, with the robots beginning the task in line with the trajectory, the explicit strategy only ever had to communicate an instruction for the Follower to move backwards, as the next way-point on the path was always directly in front of the Leader. Conversely, as the implicit strategy constantly measures force and torque to calculate its wheel velocities, a small perturbation from the Leader could have caused the Follower to move simultaneously in both axes and thus cause a larger displacement between time steps than if it had been just moving backwards constantly. Effectively, the explicit strategy is noise-immune, whereas the implicit strategy will detect and attempt to mimic the noise injected on the Leader's motor speeds.

The explicit strategy also outperformed the implicit strategy in the cluttered and randomly generated environments. For every path the explicit strategy's mean maximum displacement of object was less than the implicit strategy's, with the smallest difference being in the first path of the random environment, where the explicit strategy had a mean maximum displacement of 0.019m compared to the implicit strategy's mean maximum displacement of 0.033m. The largest difference was in the second path of the cluttered environment, where the mean maximum displacement of the object for the implicit strategy was 2.2cm more than for the explicit strategy. The larger maximum displacement observed in the implicit strategy can also be attributed to the oscillation observed in the strategy. As mentioned previously it was observed this oscillation increased during task execution, causing larger values of maximum displacement observed in the cluttered environment, as those paths have the longest completion time.

The statistical tests showed that every environmental configuration had statistical difference.

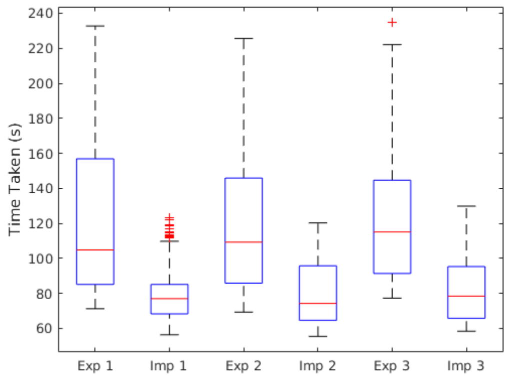
Path Fidelity

The results for path fidelity can be seen in Figure 4.4d for the line following environment, Figure 4.5d for the simple environment, Figure 4.6d for the cluttered environment and Figure 4.7d for the random environment.

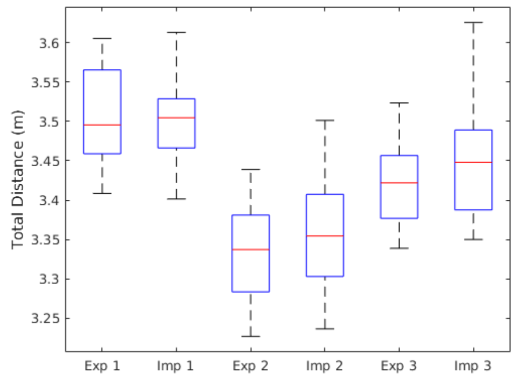
The full numerical results can be found in Table C.4 in the appendices, where LF, SE, CE and RE stand for the Line Following, Simple Environment, Cluttered Environment and Random Environment respectively.

In seven of the ten paths across the four environmental configurations, the implicit strategy proved to have the highest path fidelity, most noticeably in the random environments, where the difference in path fidelity ranged from 11.96% for the third path and 20.95% for the first path. Large standard deviations were also visible for the explicit strategy across the random paths of over 20% for every path. As mentioned previously, the explicit strategy was observed to overshoot around corners for large values of noise injected into the system before returning to the trajectory. Since the paths in the random environment are shorter than the cluttered environment, and contain more turns in that length in comparison, the low path fidelity for the explicit strategy can be attributed to it overshooting on the turns present in these paths and thus missing way points as it executed the task.

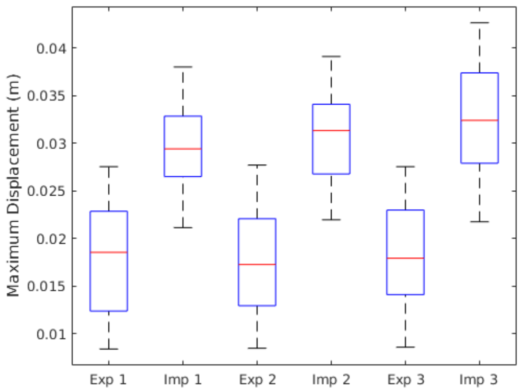
In the simple environment, the first and third path in the line following environment and the second and third paths in the cluttered environment the values for path fidelity were within 3% of each other, with the Mann-Whitney U tests showing no statistical difference for the third cluttered path or the first line following path. The other eight statistical tests showed statistical difference, opposing the hypothesis that the two strategies have similar performance.



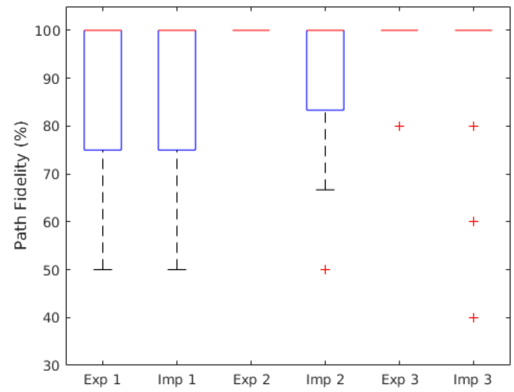
(a) Mean Time Taken and Standard Deviation



(b) Mean Total Distance Travelled and Standard Deviation

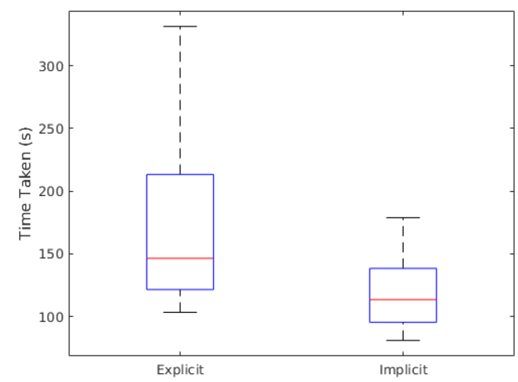


(c) Mean Maximum Displacement of Object and Standard Deviation

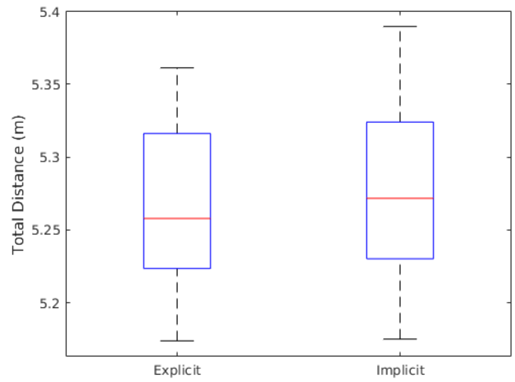


(d) Mean Percentage Path Fidelity and Standard Deviation

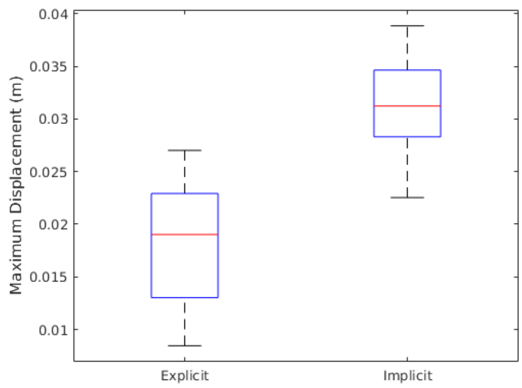
Figure 4.4: Performance of both communication strategies across all design requirement metrics in the Line Following Environment



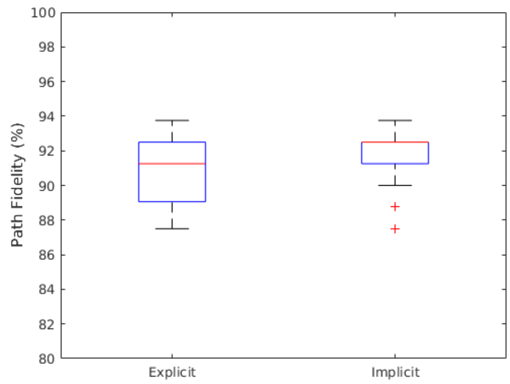
(a) Mean Time Taken and Standard Deviation



(b) Mean Total Distance Travelled and Standard Deviation

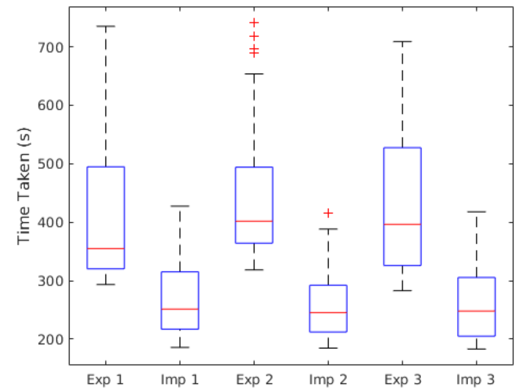


(c) Mean Maximum Displacement of Object and Standard Deviation

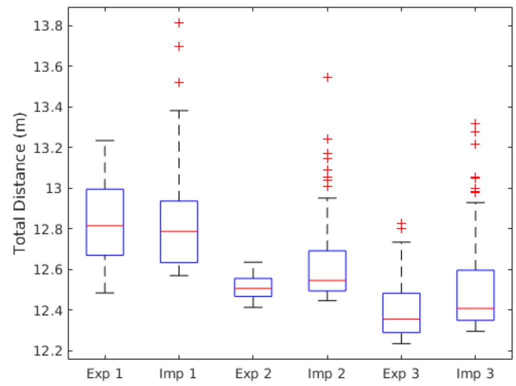


(d) Mean Percentage Path Fidelity and Standard Deviation

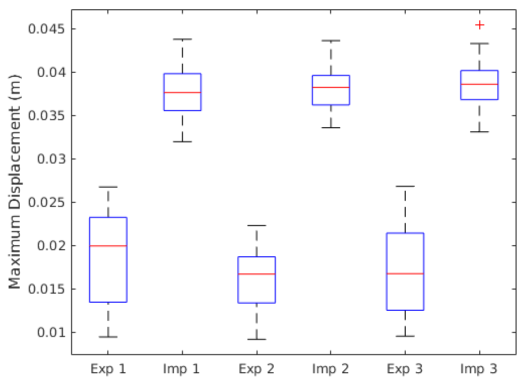
Figure 4.5: Performance of both communication strategies across all design requirement metrics in the Simple Environment



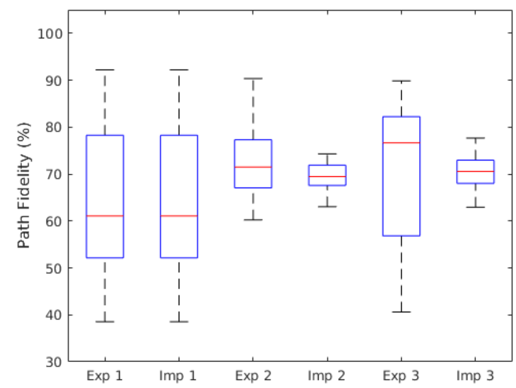
(a) Mean Time Taken and Standard Deviation



(b) Mean Total Distance Travelled and Standard Deviation

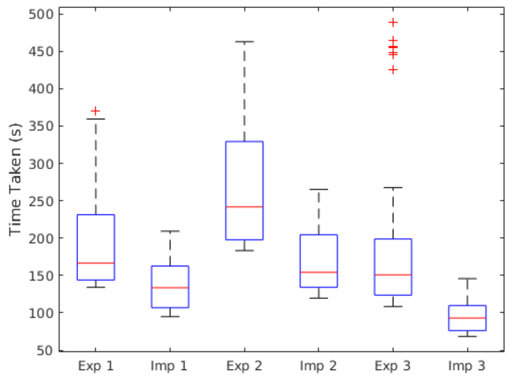


(c) Mean Maximum Displacement of Object and Standard Deviation

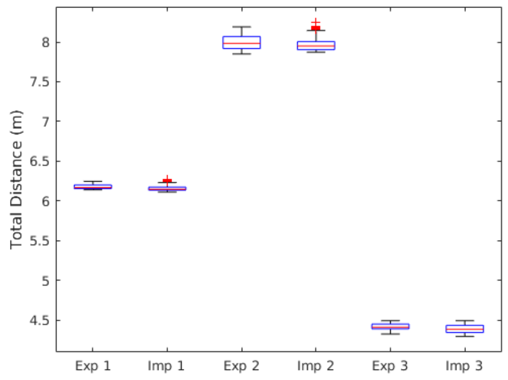


(d) Mean Percentage Path Fidelity and Standard Deviation

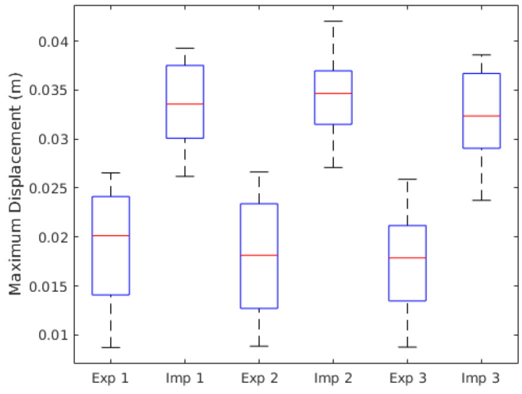
Figure 4.6: Performance of both communication strategies across all design requirement metrics in the Cluttered Environment



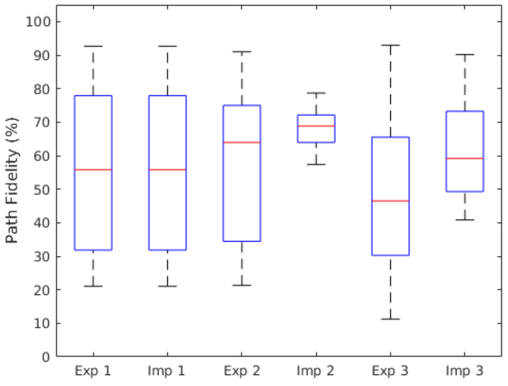
(a) Mean Time Taken and Standard Deviation



(b) Mean Total Distance Travelled and Standard Deviation



(c) Mean Maximum Displacement of Object and Standard Deviation



(d) Mean Percentage Path Fidelity and Standard Deviation

Figure 4.7: Performance of both communication strategies across all design requirement metrics in the Randomly Generated Environments

4.3.4 Conclusion

This chapter investigated the performance of explicit communication and implicit communication between two robots in an object manipulation task. Design requirements such as reliability, efficiency and smoothness were evaluated in four different environmental settings, by measuring metrics including task completion, path fidelity, completion time, total distance travelled by the object, and maximum displacement of objects.

The null hypothesis for this comparison stated at the beginning of this chapter was “There is no statistical difference between the performance of the two strategies". When analysing the Mann-Whitney U tests conducted to determine statistical similarity, the null hypothesis must be rejected. The statistical tests for the different metrics explored in this chapter show that the two communication strategies do have significant difference between the data sets and thus do not perform equally.

Nevertheless, as is evident in the results analysis, one strategy does not consistently outperform the other across all metrics: each strategy has it’s own characteristic behaviour that has both advantages and disadvantages relating to its performance in object manipulation tasks in different environments.

Thus, the results of this chapter provide an initial evaluation of the performance of both communication strategies and an insight into their advantages and disadvantages. It also presents a strong foundation for further comparative work.

Table 4.2 provides a matrix, which gives an overview of the strategies’ performance profiles. For each metric used to define design requirements deemed vital in task execution in Chapter 3, the matrix lists which communication strategy yielded the best results within each environment. This offers a clear profile of each strategy’s advantages and disadvantages, which can be used to inform design decisions by showing which communication strategy may be best suited for manipulation tasks for different design requirements. For example, if smoothness is to be prioritised over completion time.

It can be summarised from this matrix that the implicit strategy offers the most reliability, having outperformed explicit strategy in task completion within the cluttered and randomly generated environments, and offering equal task completion within the line following and simple environments.

In terms of efficiency, implicit communication again outperforms explicit communication, particularly when considering the time taken to complete a task, where implicit communication outperformed explicit across in every environments. As discussed in the analysis, this is due to the implicit strategy’s continuous movement in both the x and y direction as it calculates wheel velocities in both directions continuously throughout task execution, rather than just when performing a corrective movement. Explicit communication provides the most efficiency in distance travelled by the object, however, outperforming implicit communication in all environments except the randomly generated environments, due to an oscillation observed in the implicit strategy that caused the object to move more across task execution, increasing the total distance it travelled.

When considering smoothness as a design requirement both strategies offer different advantages. The explicit strategy showed the minimum displacement of the object across all environments, outperforming the implicit strategy. The larger displacement in the implicit strategy can be attributed to the oscillation observed in it's task execution which caused the object to move larger distances between time steps. However, the implicit strategy demonstrated smoothness by boasting the strongest path fidelity of the two strategies, outperforming explicit communication in the simple, cluttered and randomly generated environments. As the explicit strategy performed large corrective movements, it could overshoot corners causing it to miss way-points whilst performing turns.

It can thus be concluded that for simple manipulation tasks where speed, reliability and path fidelity are required, the implicit strategy offers greater advantages and a more attractive option. However if greater efficiency is required, particularly when considered distance travelled by the object, and smoothness in how the object is manipulated, the explicit strategy is the most attractive solution. These performance profiles of implicit and explicit communication provide a foundational understanding of the strategies' advantages and disadvantages in simple object manipulation tasks. The choice of communication strategy for each design requirement is informed by the performance of the strategies across a variety of environments that range in complexity, and across metrics that encapsulate and accurately measure those design requirements.

However, whilst the work presented in this chapter provides a good starting point for understanding the two strategies' performance, it ultimately offers a limited comparison and exploration of the performance of the two communication strategies. This comparison is limited by several factors: performance was only evaluated for one object type being manipulated by the strategies, and the strategies' performances were only evaluated in experiments that are faultless, within simulation, within one simple manipulation task and on only one type of robot architecture.

As discussed in the analysis of the results, an inherent offset error was observed in the system due to the Leader being at the back of the configuration, which resulted in the Leader transmitting delayed positional information related to it's position, rather than the Follower's. This could have impacted the analysis of the strategies, particularly for the task completion and path fidelity metrics. Another factor related to the robot architecture is that the robots are rigidly joined to the object, whilst this may have impacted the robot's abilities to move around corners flexibly and thus affected results for task completion and path fidelity, it is a design constraint on the system that is necessary for the implicit strategy to calculate wheel velocities.

The comparative foundation provided here is built on in Chapter 5, which investigates how the strategies perform with a variety of object shapes and sizes, and in Chapter 6, which investigates how the strategies perform when two faults are injected into the system separately. The limitations of the comparison only being conducted for experiments in simulation, within one manipulation task and only using one robot architecture are identified and explored as future work in Chapter 10, as they are out of scope for this thesis, which aims to provide a foundational comparison and proof of concept.

Table 4.2: Performance Profiles of Explicit and Implicit Strategies in Simple Object Manipulation Tasks

	Reliability	Efficiency		Smoothness	
	Reliable task completion	Shortest completion time	Shortest distance travelled by object	Minimum object displacement	Strongest path fidelity
Line Following in a Simple Environment	Explicit/Implicit	Implicit	Explicit	Explicit	Explicit
Path Planning in a Simple Environment	Explicit/Implicit	Implicit	Explicit	Explicit	Implicit
Path Planning in a Cluttered Environment	Implicit	Implicit	Explicit	Explicit	Implicit
Path Planning in a Randomly Generated Environment	Implicit	Implicit	Implicit	Explicit	Implicit

Chapter 5

Communication Strategies Manipulating Objects of Different Size and Shape

In the previous work discussed in Chapter 4, it was established that a wider range of experiments were required to form a comprehensive comparison of explicit and implicit communication within object manipulation tasks between robots. This information would not only allow for a more in depth comparison between the two forms of communication, but also a greater insight into the performance of a system that combines both forms of communication to manipulate objects.

Previous research that has investigated using implicit communication in object manipulation tasks, such as Aiyama et al. (1999), Pereira et al. (2002), Groß & Dorigo (2004) and Groß et al. (2006), have only explored simple experimental configurations, using only one object of uniform mass and shape. Thus, the findings of these works do not easily translate to real-life use cases where systems are able to manipulate to different object types.

In this chapter a series of experiments are described, which test the strategies derived in Chapter 4, when manipulating objects of different size and shape. The strategies were tested in the four environments described in Chapter 3 and the same design requirements detailed in Table 3.4 were used to evaluate the consistent performance of the two strategies with different objects when compared to the original object.

The only modifications made to the robot configurations were the changes to the objects being manipulated by the robots, which were adjusted in size and shape. The different object types used are shown in Chapter 3.

The strategies were not modified, except for the values for object mass and moments of inertia required by the implicit strategy to calculate its wheel speeds. The new values for each object type were calculated offline, as was done in the experiments in Chapter 4.

5.1 Size

The null hypothesis used to analyse the strategies' consistent performance with different object sizes was as follows:

Null Hypothesis H_0: The change in size of object has no effect on the system completing the task using either communication strategy. There is no statistical difference between the performance of the communication strategy with the new object size and the performance of the strategy with the original object size (rejected with a 95% tolerance).

This was formulated under the expectation that the object size should have no effect on performance as the object is attached to the robots in such a way that movement of the robots is unimpeded by object morphology.

In addition, the explicit strategy does not require any information about the object in order for the robots to manipulate the object, as the explicit messages transferred from the Leader to the Follower only indicate a desired direction and speed, which are completely independent of features of the object. The implicit strategy does require information about the object, as the desired speed and direction calculated by the implicit strategy uses mass and moments of inertia information, as described in detail in Chapter 4, to calculate wheel speeds. However, the Follower is provided with the mass of the object and the moments of inertia prior to the task commencing and thus has the correct information to calculate necessary wheels speeds to manipulate the new object size.

5.1.1 Expected Results

Using the null hypothesis stated above, and what is known about the performance of the strategies from Chapter 4 it is possible to form expectations of results for each of the five metrics used to evaluate performance. For task completion, it is expected that size should have no effect on either strategies ability to complete the task. As discussed above the implicit strategy should be scalable to object size when using appropriate mass and moments of inertia values, and the explicit strategy acts independently of object size, thus it is expected for the strategies to have similar completion rates as when manipulating the original object. Using the same reasoning it is expected both strategies will yield similar results for the time taken and path fidelity metric when comparing manipulating different sized objects to the original object.

Whilst it is expected that both strategies should be able to manipulate different sized objects with no impact on their performance, there is a possibility object size will impact the strategies performance for the metrics total distance travelled and maximum displacement of the object. This is due to the fact that as object size increases the distance between the Leader and the Follower will also increase, which may result in larger corrective movements within the explicit strategy producing higher maximum displacement values, and increasing the total distance travelled by the object.

5.2 Shape

The null hypothesis used to analyse the strategies' consistent performance with different object shapes was as follows:

Null Hypothesis H_0: The change in shape of object has no effect on the system completing the task using either communication strategy. There is no statistical difference between the performance of the communication strategy with the new object shape and the performance of the strategy with the original object size (rejected with a 95% tolerance).

This was formulated under the expectation that the object shape should have no effect on performance as neither strategy require the dimensions of the object in order to calculate desired wheel speeds and direction. Additionally, as was the case with object size, the object is attached to the robots in a way independent of the shape of the object.

The Follower is again provided with the mass of the object and the moments of inertia prior to the task commencing and thus has the correct information to calculate necessary wheels speeds to manipulate the new object shape.

5.2.1 Expected Results

It is again possible to form expectations of results for each of the five metrics used to evaluate performance using the null hypothesis, and what is known about the strategies' performance with the original object. The expectation remains that the implicit strategy should be scalable to object size and shape, and the explicit strategy should act independently of object size due to it not requiring any information of the object. It is thus expected that the shape of the object will have no effect on the time taken for the strategies to complete the task.

However, there is a possibility the morphology of the shapes may negatively affect task completion. The cuboid and cylinder shapes are considerably longer than the original object, and even the medium and large sized objects. This increase in length of the configuration of the two robots and the object will result in a larger turning circle, which may cause the strategies to struggle in environments with tight corners where they have previously gotten stuck, for example, for the third paths in the line following environment and the randomly generated environment, and the second path in the cluttered environment.

It is possible that this larger turning circle may also have an effect on path fidelity where a waypoint is missed a long the path as the robots perform a large, sweeping turn, or on maximum displacement, where the increased distance between Leader and Follower may result in a larger moment when performing a corrective move along the path, resulting in a larger displacement between time steps. As the total distance travelled by the object is calculating by summing the difference in x and y coordinates per consecutive time steps, larger displacement caused by a larger turning circle could also impact the total distance travelled by the object, resulting in a statistical difference in performance between the original object and different shaped objects.

5.3 Results

The same design requirements and associated metrics as shown in Table 3.4 in Chapter 4 were investigated when analysing the consistent performance of the communication strategies to different object sizes and shapes in the four environments.

Mann-Whitney U tests were performed on the data set for the new object and the data set for the original object used in Chapter 4 to reject or accept the null hypotheses formulated in this chapter.

Graphs showing the mean and standard deviation across all design requirement metrics for both communication strategies for different sized objects can be found in Appendix D.1 for the line following environment, and in Appendix D.2 for the simple environment. The corresponding graphs for different shaped objects can be found in Appendix D.1 for the line following environment, and in Appendix D.2 for the simple environment.

Graphs showing the mean and standard deviation across all design requirement metrics for both communication strategies in the cluttered and randomly generated environments can be found within this chapter for reference alongside their analysis.

In all graphs of the results for the Line Following, Cluttered and Randomly Generated Environments for different sized objects the labels 'O', 'M' and 'L' stand for Original, Medium and Large, respectively, and the numbers correspond to the path number. For different shaped objects the labels 'O', 'Cu', 'Cy' and 'Sp' stand for Original, Cuboid, Cylinder and Sphere, respectively, and the numbers corresponds to the path numbers.

5.3.1 Reliability

Reliability of the two communication strategies when manipulating different object shapes and sizes was evaluated by measuring task completion.

Task Completion

The task completion for the medium and large object sizes in line following environments are shown in Table 5.1. The task completion for the medium and large object sizes in simple

(SE), cluttered (CE) and randomly generated (RE) environments are shown in Table 5.2. The results for the original object size are also provided for reference.

The task completion for the cuboid, cylinder and sphere objects in line following experiments and in simple, cluttered and randomly generated environments are shown in Table 5.3 and Table 5.4 respectively. As can be seen in Table 5.2, the implicit strategy had a task completion of 0% for the cylinder object in path 2 of the cluttered environment, all figures for the different shape objects therefore do not contain a corresponding box plot for this path.

The strategies are shown to be reliable for almost all paths in the line following environment, the simple environment and the randomly generated environments for different object sizes and shapes, but with less reliability in the cluttered environments. This was particularly evident with the second path of the cluttered environment, where task completion ranged from 0% for the implicit strategy manipulating the cylinder to 84% for the implicit strategy manipulating the medium object.

The performance of both strategies this path in the cluttered environments is consistent with the results shown in Section 4.3 in Chapter 4: wherein the explicit strategy struggled with path 2, achieving a task completion percentages of 60% due to the tight corner at the top of the arena.

For the random environment the performance of both strategies with different sized and shaped object were consistent with the results for the original object in Chapter 4, with the strategies achieving 100% task completion for all configurations in the first and second paths. However, the implicit strategy had difficulties completing the task in the third randomly generated environment when manipulating the cuboid and the cylinder, with task completion percentages of 98% and 80%, respectively, compared to an original task completion percentage of 100%. A video of the implicit strategy exhibiting task failure in the third line following environment with the cylinder can be seen in Video 2a in Appendix B.

It was addressed in the Chapter 4 that there were situations where the robots would veer off and collide with walls or obstacles; these occurrences were still observed for the different object sizes and shapes. As discussed in the previous chapter, there is an inherent offset error in the system due to the Leader's position in the configuration: its position at the back of the configuration behind the Follower means the Follower receives information from the Leader about the Leader's position on the path, not the Follower's. The cause for such low task completion percentages in these paths is due to the fact that as object size increases, this offset error also increases. There is greater distance between the Leader and the Follower, and thus a larger disparity between the directional information the Leader is transmitting or implying about it's position on the path, and the Follower's own position.

For the cuboid and cylinder object shapes, this offset error was increased further as the objects were 20cm long. The object length also contributed to the low task completion percentage for

Table 5.1: Percentage Task Completion for Both Communication Strategies Manipulating Different Sized Objects in Line Following Environments.

Object Size	Type	Line Following Paths		
		1	2	3
Medium	Exp	100%	100%	100%
	Exp Original	100%	100%	100%
	Imp	100%	100%	99%
	Imp Original	100%	100%	99%
Large	Exp	100%	100%	100%
	Exp Original	100%	100%	100%
	Imp	100%	100%	92%
	Imp Original	100%	100%	99%

Table 5.2: Percentage Task Completion for Both Communication Strategies Manipulating Different Sized Objects in SE, CE and RE Environments..

Object Size	Type	Path						
		1			2		3	
		SE	CE	RE	CE	RE	CE	RE
Medium	Exp	100%	100%	100%	72%	100%	100%	100%
	Exp Original	100%	100%	100%	60%	100%	100%	100%
	Imp	100%	100%	100%	84%	100%	100%	100%
	Imp Original	100%	100%	100%	100%	100%	100%	100%
Large	Exp	100%	97%	100%	44%	100%	100%	100%
	Exp Original	100%	100%	100%	60%	100%	100%	100%
	Imp	100%	100%	100%	16%	100%	100%	100%
	Imp Original	100%	100%	100%	100%	100%	100%	100%

Table 5.3: Percentage Task Completion for Both Communication Strategies Manipulating Different Shaped Objects in Line Following Environments.

Object Shape	Type	Line Following Path		
		1	2	3
Cuboid	Exp	100%	100%	100%
	Exp Original	100%	100%	100%
	Imp	100%	100%	89%
	Imp Original	100%	100%	99%
Cylinder	Exp	100%	100%	100%
	Exp Original	100%	100%	100%
	Imp	100%	100%	53%
	Imp Original	100%	100%	99%
Sphere	Exp	100%	100%	100%
	Exp Original	100%	100%	100%
	Imp	100%	100%	100%
	Imp Original	100%	100%	99%

Table 5.4: Percentage Task Completion for Both Communication Strategies Manipulating Different Shaped Objects SE, CE, and RE Environments.

Object Shape	Type	Path						
		1			2		3	
		SE	CE	RE	CE	RE	CE	RE
Cuboid	Exp	100%	82%	100%	7%	100%	99%	100%
	Exp Original	100%	100%	100%	60%	100%	100%	93%
	Imp	100%	100%	100%	6%	100%	100%	98%
	Imp Original	100%	100%	100%	100%	100%	100%	100%
Cylinder	Exp	100%	71%	100%	4%	100%	92%	100%
	Exp Original	100%	100%	100%	60%	100%	100%	93%
	Imp	100%	88%	100%	0%	100%	100%	80%
	Imp Original	100%	100%	100%	100%	100%	100%	100%
Sphere	Exp	100%	98%	100%	73%	100%	99%	100%
	Exp Original	100%	100%	100%	60%	100%	100%	93%
	Imp	100%	100%	100%	70%	100%	100%	100%
	Imp Original	100%	100%	100%	100%	100%	100%	100%

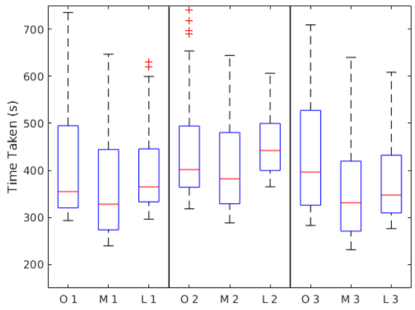
the first three paths in the cluttered environment. When examining the paths in Chapter 3, it can be seen that the turn into the 'office area' in the top right hand corner of the arena occurs closer to the top wall in paths 1, 2 than in path 3. With a longer object, the Follower would only receive information from the Leader to turn on this corner a few time steps after it had reached the corner itself, thus the Follower would collide with the wall before being able to turn or whilst turning.

In the randomly generated environments, the path through the third environment resembles a narrow corridor, thus the robots were likely to collide with obstacles due to the increased offset error.

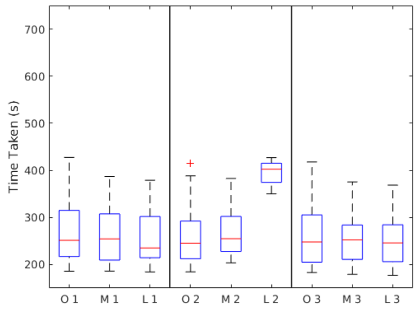
The low task completion percentages for the third path in the line following environments is a product of the path's close proximity to the arena walls of the environment. As object size increases, so too does the robots' turning circle, meaning the configuration had trouble clearing the sharp turn in path 3 that was close to the arena walls with the longer objects of the cuboid and cylinder. These results match our expected results for different shaped objects, and demonstrated that whilst the length of the different sized objects was considerably less than the cuboid and cylinder, the increase in offset error still impacted the results for task completion. A video of the implicit strategy exhibiting task failure in the third line following environment with the cylinder is viewable in Video 2b in Appendix B.

5.3.2 Efficiency

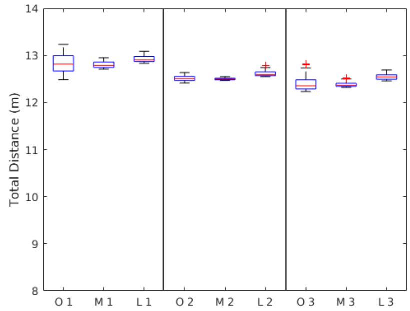
Efficiency of the strategies was measured by evaluating the time taken by the strategies to complete the task and the total distance travelled by the object during task execution.



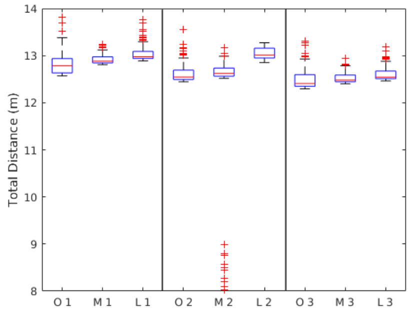
(a) Explicit: Mean Time Taken and Standard Deviation



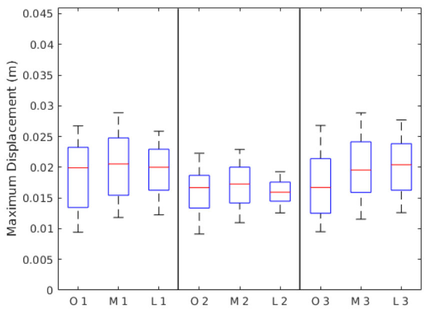
(b) Implicit: Mean Time Taken and Standard Deviation



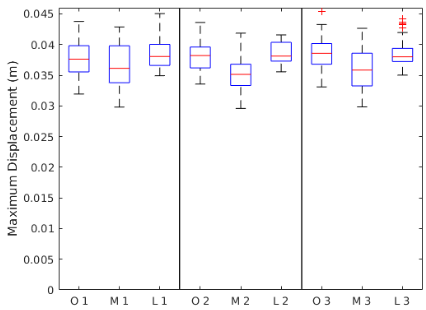
(c) Explicit: Mean Total Distance Travelled and Standard Deviation



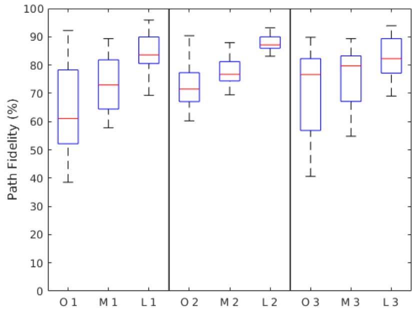
(d) Implicit: Mean Total Distance Travelled and Standard Deviation



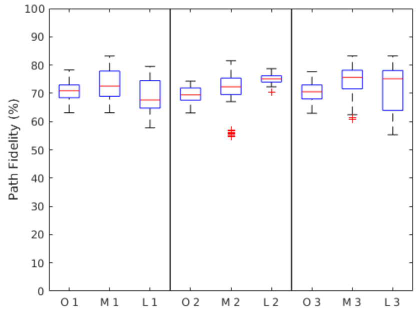
(e) Explicit: Mean Maximum Displacement and Standard Deviation



(f) Implicit: Mean Maximum Displacement and Standard Deviation

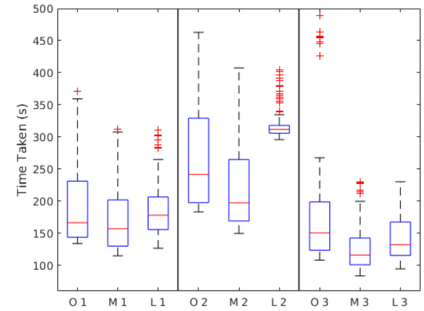


(g) Explicit: Mean Percentage Path Fidelity and Standard Deviation

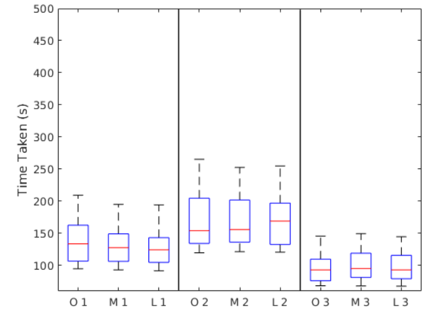


(h) Implicit: Mean Percentage Path Fidelity and Standard Deviation

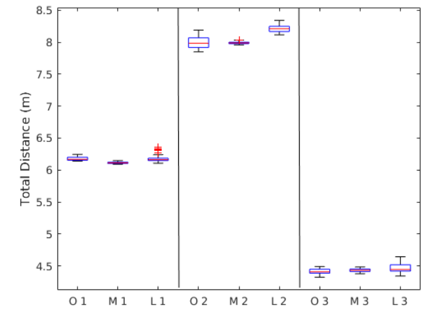
Figure 5.1: Performance of both communication strategies across all design requirement metrics in the Cluttered Environment for different sized objects



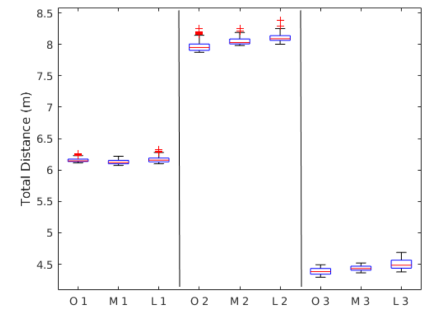
(a) Explicit: Mean Time Taken and Standard Deviation



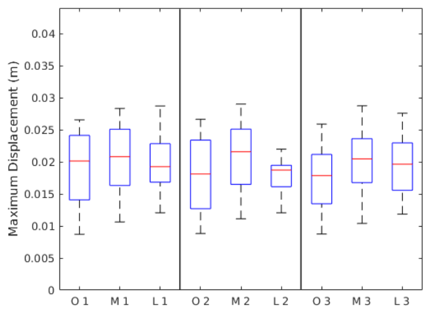
(b) Implicit: Mean Time Taken and Standard Deviation



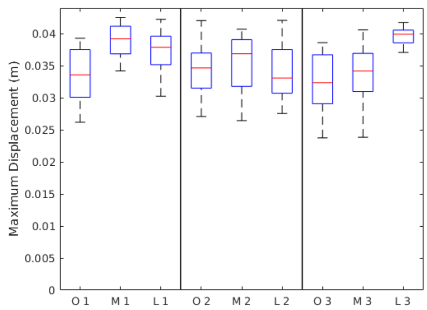
(c) Explicit: Mean Total Distance Travelled and Standard Deviation



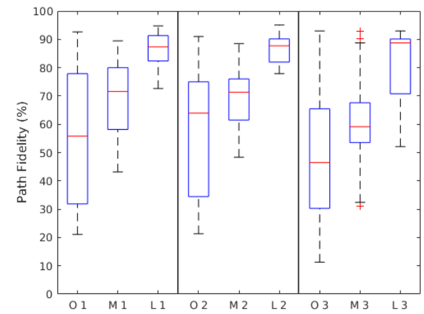
(d) Implicit: Mean Total Distance Travelled and Standard Deviation



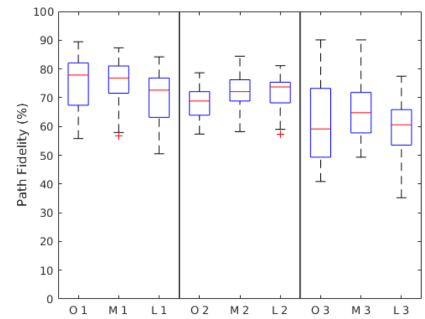
(e) Explicit: Mean Maximum Displacement and Standard Deviation



(f) Implicit: Mean Maximum Displacement and Standard Deviation

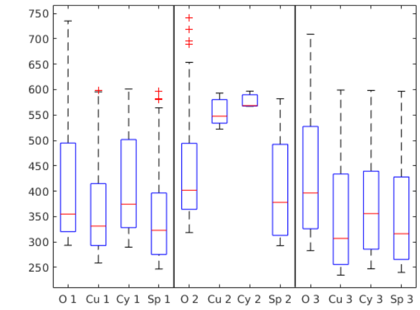


(g) Explicit: Mean Percentage Path Fidelity and Standard Deviation

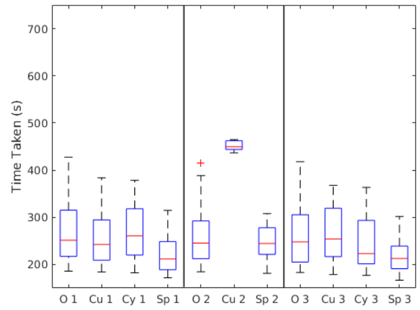


(h) Implicit: Mean Percentage Path Fidelity and Standard Deviation

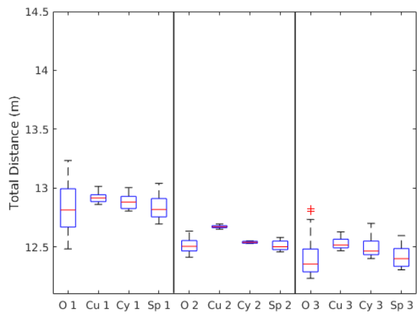
Figure 5.2: Performance of both communication strategies across all design requirement metrics in the Randomly Generated Environments for different sized objects



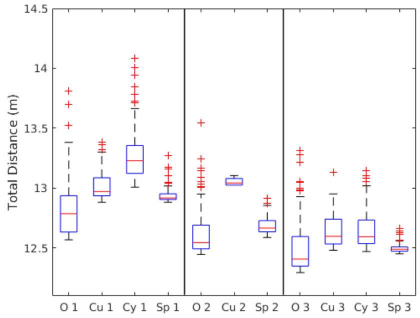
(a) Explicit: Mean Time Taken and Standard Deviation



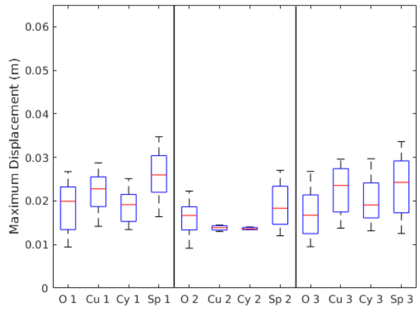
(b) Implicit: Mean Time Taken and Standard Deviation



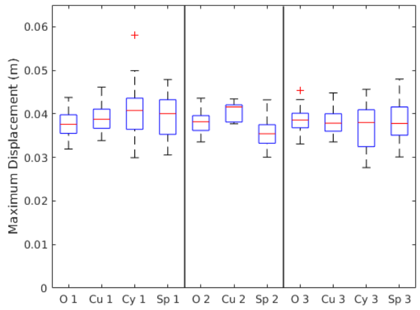
(c) Explicit: Mean Total Distance Travelled and Standard Deviation



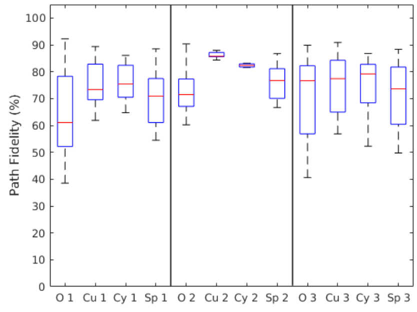
(d) Implicit: Mean Total Distance Travelled and Standard Deviation



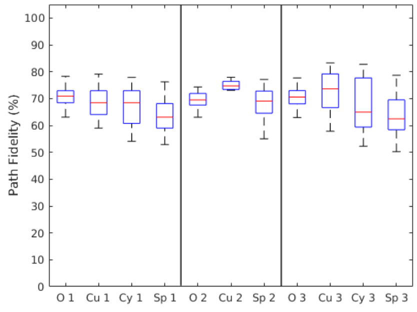
(e) Explicit: Mean Maximum Displacement and Standard Deviation



(f) Implicit: Mean Maximum Displacement and Standard Deviation

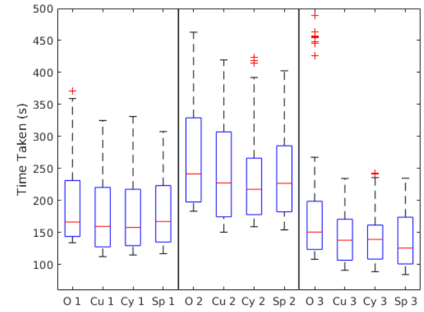


(g) Explicit: Mean Percentage Path Fidelity and Standard Deviation

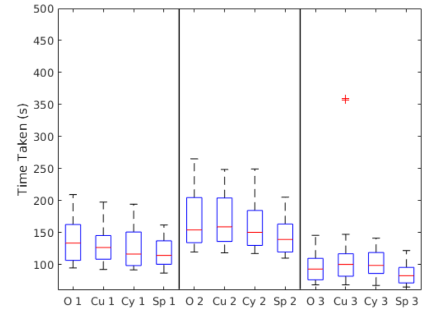


(h) Implicit: Mean Percentage Path Fidelity and Standard Deviation

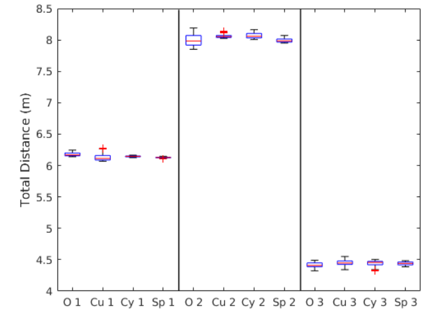
Figure 5.3: Performance of both communication strategies across all design requirement metrics in the Cluttered Environment for different shaped objects



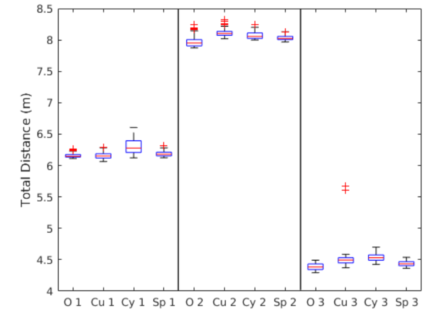
(a) Explicit: Mean Time Taken and Standard Deviation



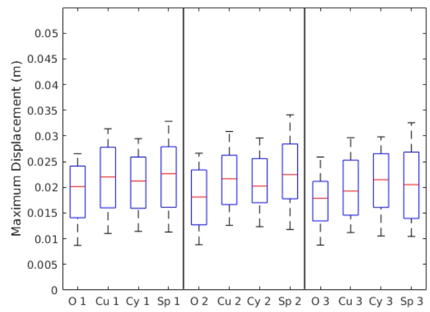
(b) Implicit: Mean Time Taken and Standard Deviation



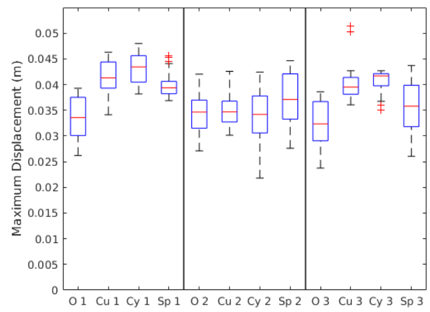
(c) Explicit: Mean Total Distance Travelled and Standard Deviation



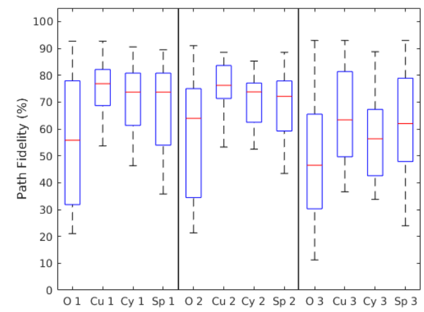
(d) Implicit: Mean Total Distance Travelled and Standard Deviation



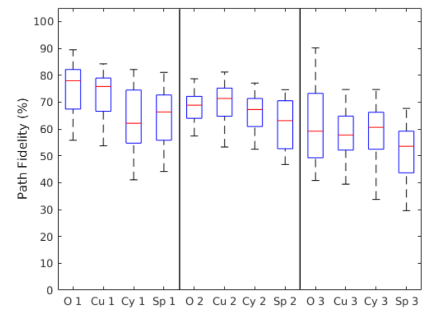
(e) Explicit: Mean Maximum Displacement and Standard Deviation



(f) Implicit: Mean Maximum Displacement and Standard Deviation



(g) Explicit: Mean Percentage Path Fidelity and Standard Deviation



(h) Implicit: Mean Percentage Path Fidelity and Standard Deviation

Figure 5.4: Performance of both communication strategies across all design requirement metrics in the Randomly Generated Environments for different shaped objects

Time Taken

The numerical results for the time taken to complete the task in seconds for the medium and large sized objects are shown in Tables D.1, D.2 and D.3 in the appendices.

The numerical results for time taken for the the cuboid, cylinder and sphere objects are shown in Tables D.4, D.5 and D.6 in the appendices.

The results indicate that the performance of the implicit strategy is consistent with different sized and shaped objects, and met our expected results for this metric. Across all environments for the medium object there was no significant difference when compared to the original, and the results for the large object also showed no significant difference in six out of the ten paths. Out of the 29 statistical tests conducted for the different shaped objects, 18 tests showed no significant difference when comparing the performance of the implicit strategy to its performance with the original object. The strategy showed the most consistent performance with the cuboid object with 9 out of ten tests showing no significant difference.

The explicit strategy indicated less consistency in performance: whilst in the simple environment there was no significant difference for all object shapes or the large object size when compared to the original object, for the remaining 45 tests only 14 showed no significant difference. This lack of consistency in performance is coupled to the lower task completion observed for this strategy with different shaped objects in the cluttered environments. As discussed previously it was observed that if a strategy had a low task completion it was due to the robots colliding with obstacles and walls or getting stuck. In the majority of cases the robots would be stuck permanently and fail the task as the simulation timed out, in some cases however, the robots would manage to eventually free themselves from the obstacle or wall, which would allow for the robots to complete the task but after a time often far longer than a collision free run.

Total Distance Travelled

The numerical results for total distance travelled in metres by the medium and large sized objects are shown in Tables D.7, D.8 and D.9 in the appendices.

The numerical results for total distance travelled for the cuboid, cylinder and sphere objects are shown in Tables D.10, D.11 and D.12 in the appendices.

It can be seen for 20 out of 50 statistical tests show there is no statistically significant difference between the data for medium and large sized objects and the original object, and between different object shapes and the original object for the explicit strategy. For the implicit strategy, 9 out of 29 tests show no significant difference for different sized and shaped objects. This indicates marginal consistency in performance with different object size and shape.

The results for total distance travelled, like time taken are coupled to task completion. For paths where low task completion and high time taken were observed, for example the first and second paths of the cluttered environments and the third path of the randomly generated environment showed an increase in total distance travelled for the object for both strategies, see figures 5.1, 5.2, 5.3 and 5.4. As discussed when analysing the results for time taken, in these difficult environments sometimes the robots would become stuck after a collision and later free themselves. Since their is nothing in their controllers to instruct them to stop when they have collided with an obstacle the robots still move, which enables them to in some cases work themselves free. This means the robots move minimal amounts every time step for the duration of them being stuck. As total distance is calculated as a summation of difference in x and y coordinates per consecutive time steps these minimal movements are included in the summation and add up to a larger total distance travelled.

5.3.3 Smoothness

The design requirement 'Smoothness' was used to give an indication of how smooth the strategies are, and provide insight into whether or not the strategies could handle potentially fragile objects. Smoothness was measured by the maximum displacement of object during task execution and path fidelity (ability to stick closely to the assigned path).

Maximum Displacement of Object

The numerical results for maximum displacement of the object in metres for the medium and large sized objects are shown in Tables D.13, D.14 and D.15 in the appendices.

In the appendices, Table D.16, Table D.17 and Table D.18 show the numerical results for maximum displacement of the object in metres for the different shaped objects.

Results show that neither strategy have consistent performance with objects of different size and shape in terms of maximum object displacement.

For the explicit strategy four out of 20 tests showed no statistical difference for different object sizes, and only seven out of 30 show no statistical difference for different object shapes. However, whilst they showed statistical difference the results were very numerically close to that of the original object differing by only a few millimetres across all environmental configurations.

For the implicit strategy, eight out of 20 tests across all environments show no statistical difference for different object sizes. For the different object shapes seven out of 29 data sets showed no significant difference. Similar to the explicit strategy, for the majority of the environmental configurations the numerical difference between maximum displacement for different sized and shaped objects and the original object was small. The largest differences between data sets was seen in the random environment, where the maximum displacement increased for different sized and shaped objects, see figures 5.2f 5.4f.Referring back to the figures of the path curvatures in Chapter 4, the robots in the random environment have a starting orientation of 45 degrees from horizontal. This means that the first move that the robots perform is a corrective movement towards the direction of the path, and as the object sizes increase this corrective movement also increases. Since the implicit strategy is faster this results in a large maximum displacement between time steps at the beginning of the task in the randomly generated environments. This behaviour is viewable in Video 2c in Appendix B.

Path Fidelity

The numerical results for path fidelity for the medium and large sized objects are shown in Tables D.19, D.20 and D.21 in the appendices.

The numerical results for path fidelity for the cuboid, cylinder and sphere objects are shown in Tables D.22, D.23 and D.24 in the appendices.

Whilst some results indicated consistency in performance in both communication strategies to different object sizes and shapes, the majority of Mann-Whitney U tests conducted on the results indicated statistical difference between the compared data sets. To be precise, out of a total of 20 tests comparing the explicit strategy's path fidelity with the original object to different sized objects, only four tests showed no statistical difference. The implicit strategy had the same result. When considering different shaped objects, only three out of 30 tests showed no statistical difference for the explicit strategy, and only nine out of 29 tests for the implicit strategy.

A higher path fidelity is observed in the cluttered environment and the random environment for the explicit strategy, as shown in figures 5.1c and 5.2c for different sized objects, and in figures 5.3c and 5.4c for different shaped objects.

This is a product of the distance between the Leader and Follower increasing with object size. In the explicit case the Leader transmits an instruction every time step, since time interval and desired speeds are kept constant throughout the task, the distance the Follower moves in either a left or right direction per time step is also constant. The Follower has no way of knowing how much it should move in a given direction, just that it should do so until it is given another instruction. This result in over-corrective behaviour and a slight oscillation with the original object. When the distance between the two robots is increased, the distance the Follower should move in order to completely correct it's position also increases, but the distance it can actually move per time step remains constant. This results in an overall smoother movement for both robots as the Follower is no longer able to accidentally over-correct for a given instruction.

The differences in path fidelity for the implicit strategy, whilst statistically significant, are close enough in value that a cause for these differences are not visible when observing the strategy in the graphical interface.

5.4 Conclusion

This chapter investigated the consistency in performance of explicit and implicit communication between two robots manipulating different object sizes and shapes. This was achieved by analysing the statistically significant difference between the performance of the strategies in Chapter 4 in relation to the design requirements described in Chapter 3 and the performance of the strategies in experiments using different sized and shaped objects.

Results showed that for multiple cases the time taken to complete the object manipulation tasks were not of statistically significant difference to the results for the original object used in the experiments described in Chapter 4. This indicates that the strategies have some consistency in performance with different object sizes and shapes. This conclusion can be easily consolidated into the understanding of the strategies, as the only assumption made about the object by either strategy is that the implicit strategy assumes uniform mass and density. The implicit strategy requires the mass and moments of inertia for the object, so it is inherently scalable to object size. The explicit strategy does not require any information about the object at all and can thus also be considered scalable.

Across the four metrics the implicit strategy showed the most consistency with different object sizes and shapes, with 32 out of 80 statistical tests comparing the implicit strategy's performance with the medium and large object to the original object showing no statistical difference compared to 22 tests for the explicit strategy showing consistency in performance. For the different shaped objects, 39 out of 116 statistical tests showed no statistical difference for the implicit strategy manipulating different shaped objects, compared to 30 for the explicit strategy.

However, since the majority of Mann-Whitney U tests conducted for both strategies showed that there was statistical difference between the different sized and shaped objects and the original object, the null hypotheses for size and shape must therefore be rejected.

Nonetheless, what must be considered when discussing the performance of the strategies is that this lack of consistency in performance can not purely be attributed to how the robots communicate within the different strategies, but in how the robots are physically configured.

It has been concluded that the results for many of the metrics are intrinsically linked to the distance between the two robots when manipulating larger objects and the effect this has on the offset error present due to the Leader being situated at the back of the configuration. The offset error affects task completion when present in an environment that has sharp turns to avoid obstacles, or paths that have turns close to the walls of the environments, and can also impact time taken and total distance travelled in these environments when robots collide with obstacles but eventually free themselves.

Reducing this offset error as an attempt to improve performance could prove a challenge. Whilst in the explicit strategy it could be possible for the Leader to transmit a prediction of what direction the Follower must move in based on where it predicts the Follower to be on the path, such an extrapolation would be harder to implement in the implicit case, which relies on real time force information. Even investigating switching the configuration and having the Follower lead, or even having the robots move side by side would still induce an offset error as in each configuration the Leader would still operate in a different space to the Follower and would thus transmit inaccurate positional data to them.

Thus the offset must be accepted as a feature of the system and be taken into consideration when employing the strategies in environments that contain multiple obstacles and specifically, where generated paths involve tight corners around obstacles or run close to the walls in the environment.

It is also important to note that whilst the Mann-Whitney U tests do not support the null hypotheses that the strategies have consistent performance with different object sizes and shapes, that does not mean the strategies are rendered completely ineffective with different object types. It is possible the strategies can still be used effectively for object manipulation tasks in simple environments, with trajectories that do not have tight corners or if it is deemed for an application that a particular metric, like path fidelity or maximum displacement of object, is not crucial for task success.

To summarise the anaylsis and conclusions drawn above, Tables 5.5 and 5.6 provide a matrix to describe the performance profiles of the two strategies when manipulating objects of different sizes and shapes. They are derived by determining which communication strategy demonstrated the least amount of statistical difference in the Mann-Whitney U tests for a given metric across the environmental set ups, when compared to its performance when manipulating the original object. These matrices indicate which strategy offers the most consistent performance across different object types. For example, in the Line Following Environment, the implicit strategy can be considered the most consistent strategy for the metric of time taken to complete the task as it showed no statistical difference in all three statistical tests for each or the paths when manipulating the medium sized object, compared to the explicit strategy, which showed significant difference for every path.

The work presented in this chapter builds on the analysis of the performance of explicit and implicit communication in simple object manipulation tasks by investigating the performance of the strategies with different object shape and sizes, in order to better inform the development of a system that combines the two forms of communication.

The analysis in this chapter provides a strong understanding of the performance profiles of both strategies. These profiles are used in Chapters 7.2 and 8 to inform the evaluation and analysis of a hybrid system that combines implicit and complicit communication to manipulate objects.

Table 5.5: Performance Profiles of Explicit and Implicit Strategies to Different Sized Objects in Simple Object Manipulation Tasks

Metric	Time Taken			Total Distance			Maximum Displacement			Path Fidelity		
Environment	LF	SECE	RE	LF	SECE	RE	LF	SECE	RE	LF	SECE	RE
Medium Object	Implicit	Implicit	Implicit	Explicit	Explicit	Explicit	Implicit	Neither	Implicit	Explicit	Explicit/ Implicit	Implicit
Large Object	Implicit	Explicit	Implicit	Explicit	Explicit	Implicit	Implicit	Implicit	Explicit/ Implicit	Explicit	Neither	Implicit

Table 5.6: Performance Profiles of Explicit and Implicit Strategies to Different Shaped Objects in Simple Object Manipulation Tasks

Metric	Time Taken			Total Distance			Maximum Displacement			Path Fidelity		
Environment	LF	SECE	RE	LF	SECE	RE	LF	SECE	RE	LF	SECE	RE
Cuboid	Implicit	Implicit	Implicit	Explicit	Implicit	Implicit	Neither	Explicit/ Implicit	Implicit	Neither	Implicit	Implicit
Cylinder	Implicit	Implicit	Implicit	Explicit	Explicit	Neither	Explicit	Explicit	Implicit	Implicit	Neither	Implicit
Sphere	Explicit	Explicit/ Implicit	Explicit	Explicit	Explicit	Explicit	Explicit/ Implicit	Implicit	Neither	Implicit	Explicit/ Implicit	Neither

Chapter 6

Fault Tolerance of Implicit and Explicit Communication in Object Manipulation Tasks

A limitation of the comparison of the two communication strategies performed in Chapter 4 was that the comparison was conducted in a faultless environment. In order to develop a more comprehensive understanding of the performance profile of the two communication strategies and their robustness it is essential to consider how tolerant the systems are to faults.

Previous research that has aimed to compare explicit and implicit communication in object manipulation, such as Aiyama et al. (1999), Pereira et al. (2002), Groß & Dorigo (2004) and Groß et al. (2006), did not investigate fault tolerance of the types of communication by purposefully injecting faults into the system. This chapter aims to provide further understanding of the performance of the two forms of communication in the presence of two simple fault types.

In this chapter the performance of explicit and implicit communication is compared through the injection of two simple types of faults: vision sensor faults and partial motor faults as described in Chapter 3, into the explicit and implicit strategies whilst they complete the simple manipulation tasks used throughout this thesis. The strategies' performance was measured using the same metrics described in Table 3.4, and their results were statistically compared to the results of the faultless comparison performed in Chapter 4.

The only modifications made to the robot controllers were those described in Chapter 3 to inject the fault within simulation. The rest of the controllers remained unchanged. The robots themselves remained unchanged in architecture, and the 'Original Object' was used throughout.

6.1 Vision Sensor Fault

The null hypothesis used to analyse the strategies' fault tolerance and robustness to a vision sensor fault is as follows:

Null Hypothesis H_0: The presence of a vision sensor fault in one of the Leader's vision sensors has no effect on the system completing the task using either communication strategy. There is no statistical difference between the performance of the communication strategy with a vision sensor fault and the performance of the strategy operating faultlessly (rejected with a 95% tolerance).

This null hypothesis was formulated in order to use statistical tests to measure the fault tolerance and robustness of the strategies whilst manipulating an object across different environments. The robot controllers employed in the two strategies assume faultless behaviour and have no way of determining if the inputs the Leader is receiving from the vision sensors are erroneous, thus there is no fault-tolerance purposefully implemented in their design. The comparison performed in this chapter aims to see how the strategies perform in the presence of faults, and if their characteristics, such as the feed-forward control loop nature of the explicit strategy, or the error correction negative feedback loop of the implicit strategy, are inherently fault tolerant.

6.1.1 Expected Results

As discussed above the strategies assume faultless operation and do not have any functionality encoded that is deliberately designed to mitigate the presence of faults. It is therefore expected that the presence of vision sensor faults will negatively impact performance, depending on which sensor demonstrates the fault.

A fault in the middle sensor is expected to have the smallest negative impact on performance. This is because the left and right sensors will still be operational and able to detect the edge of the path for the Leader to turn in the appropriate direction and communicate that instruction to the Follower explicitly or implicitly.

For the left sensor, it is expected to have the greatest impact in the first and third lines of the Line Following Environment, as both of these paths consist of a left turn, as shown in Figure 3.3, as the robot cannot sense the edge of the path to make a corrective movement in the left direction along the trajectory. Similarly, for the right sensor, it is expected to have the greatest impact in the second path, which consists of a right turn. This will likely dramatically affect task completion as the strategies will struggle to stick to the path, as well as path fidelity as if the strategies overshoot in one direction they will not be able to perform a corrective movement in the opposite direction.

6.2 Partial Motor Fault

The null hypothesis used to analyse the strategies' fault tolerance and robustness to a partial motor fault is as follows:

Null Hypothesis H_0: The presence of a partial motor fault in one of the Leader's wheels or one of the Follower's wheels has no effect on the system completing the task using either communication strategy. There is no statistical difference between the performance of the communication strategy with a partial motor fault and the performance of the strategy operating faultlessly (rejected with a 95% tolerance).

Once again, this null hypothesis was formulated in order to use statistical tests to measure the fault tolerance and robustness of the strategies whilst manipulating an object across different environments. The robot controllers have no way of determining if a given wheel speed is erroneous due to a motor fault, thus there is no fault-tolerance purposefully implemented in their design for partial motor faults. The comparison performed in this chapter aims to see if the strategies' characteristics are inherently fault tolerant.

6.2.1 Expected Results

Similarly to vision sensor faults, it is therefore expected that the presence of vision sensor faults will negatively impact performance.

The partial motor faults are emulated by reducing the motor speed for a given wheel to half of it's velocity. In experiments, it is expected this will cause a differential wheel speed that will affect the strategies' performance in both straight segments of paths and on corners.

A differential in wheel speeds caused by a partial motor fault will cause the system to turn in the direction of the faulty wheel, for example for a partial motor fault in the Leader's left wheel, will reduce the speed of motor by half causing the robot to turn to the left. When performing turns in the direction of the faulty wheel the turn will be tighter due to the increase in differential caused by the motor fault.

This behaviour will likely impact task completion and path fidelity as it may increase the likelihood of the robots veering off the paths in the different environments. It could also affect maximum displacement of the object if the larger differential in wheel velocity causes tighter turns. Typically turns have been observed to be large and sweeping, resulting in large values of maximum displacement, a tighter turn may reduce this displacement between time steps.

6.3 Results

The metrics as shown in Table 3.4 in Chapter 4 were use to investigate the performance of the system in the presence of faults, in order to evaluate how fault tolerant and robust the communication strategies were in the four environments.

Mann-Whitney U tests were performed on the data set for the systems performing with the original object in the presence of a fault and the data set for the original object in fault-less conditions used in Chapter 4 to reject or accept the null hypotheses formulated in this chapter. Graphs showing the mean and standard deviation across all design requirement metrics for both communication strategies in the presence of faults can be found in Figure 6.1, for vision sensors. The remaining graphs for the other faults can be found in Appendix E

In all graphs of the results for vision sensor faults the labels 'O', 'VSL', 'VSM', and 'VSR' stand for Original, Vision Sensor Left, Vision Sensor Middle and Vision Sensor Right, respectively, and the numbers correspond to the path number. For partial motor faults the labels 'LL' and 'LR' stand for Leader Left and Leader Right, respectively, and the labels 'F1', 'F2' and 'F3' stand for 'Follower 1', 'Follower 2' and 'Follower 3', and reference which wheel has the partial motor fault.

6.3.1 Reliability

Reliability of the two communication strategies when performing in the presence of faults was evaluated by measuring task completion.

Task Completion

The percentage task completion for both strategies in the presence of vision sensor faults can be seen in Table 6.1

The percentage task completion for both strategies in the presence of partial motor faults in Leader's wheels and Follower's wheels can be found in Appendix E in Section E.2.

Vision Sensor Faults

It can be seen that the reliability of both strategies' was negatively impacted by the presence of a fault in one of the vision sensors. For both the explicit and implicit strategy task completion dropped to zero percent in the third path in the presence of a fault in the left vision sensor, and in the second path in the presence of a fault in the right sensor. Additionally, the explicit strategy suffered from zero percent task completion in the first path of the line following environment in the presence of a fault in the left vision sensor. In the same path, the implicit strategy achieved a task completion of 52% compared to 100% in the presence of zero faults.

Table 6.1: Percentage Task Completion for Both Strategies in the Line Following Environment in the presence of Vision Sensor Faults

Vision Sensor Fault	Type	Line Following Environment Paths		
		1	2	3
Left	Exp	0.00%	100.00%	0.00%
	Exp Original	100.00%	100.00%	100.00%
	Imp	52.00%	100.00%	0.00%
	Imp Original	100.00%	100.00%	99.00%
Middle	Exp	100.00%	100.00%	100.00%
	Exp Original	100.00%	100.00%	100.00%
	Imp	100.00%	100.00%	98.00%
	Imp Original	100.00%	100.00%	99.00%
Right	Exp	100.00%	0.00%	100.00%
	Exp Original	100.00%	100.00%	100.00%
	Imp	100.00%	0.00%	99.00%
	Imp Original	100.00%	100.00%	99.00%

These results match the expected behaviour discussed in Section 6.1.1. In the paths featuring left turns, paths 1 and 3, a fault in the left vision sensor caused both strategies to veer off the path as the continuously false reading in the left sensor left them unable to detect the left edge of the path and thus form a corrective movement back onto the trajectory. The same was true in the second path, which features a right turn, in the presence of a fault in the right vision sensor as both strategies achieved zero percent task completion in this path.

Interestingly, the implicit strategy showed non zero task completion in the presence of the left sensor fault in the first path. When observing the strategy, however, it was clear this was not due to the implicit strategy demonstrating more fault tolerance, but due to coincidence. During task execution the robots would veer off the path as soon as it begin curving left, consistent with the behaviour of the explicit strategy in the presence of a left vision sensor fault, and the robots would continue in a straight trajectory until they collided with the far arena wall. This can be observed in Video 3a in the video repository in Appendix B.

It was observed that for some experimental runs the robots would hit the wall at an angle such that the follower's 'wheel 1' was the only wheel making contact with the wall . In this position, the leader would still be trying to move forward, and thus would still be exerting force on the force sensor, the follower would be measuring this force and applying velocities to it's three omniwheels. At certain angles this would cause the robots to move along the wall to the right until they reached the end zone that triggers a task completion recording. Thus, the implicit strategy was not demonstrating fault tolerance to the fault but 'failing the task successfully'. This behaviour impacts the results for the other metrics for the implicit strategy on this path, and will be discussed throughout this results section.

The strategies' reliability was less impacted by a fault in the middle sensor, as the the left and right sensors were still able to detect the edge of the path, enabling the Leader to apply the appropriate corrective movement and transmit the appropriate message to the Follower. As can be seen in the controllers of the two robots for the line following environments [1], the Leader begins the simulation by moving forward at the desired velocity and communicating that velocity to the follower to enable continuous movement throughout the experimental run, and then begins to send appropriate directional messages dependent on its position on the path, this allows the robots to continuously move backwards along straight segments even in the presence of a fault in the middle sensor.

Partial Motor Faults in the Leader's Wheels

It can be seen that as expected, a partial motor fault in one of the leader wheels has affected task completion in object manipulation tasks.

For the explicit strategy, task completion was lower across all environments than that recorded in the original faultless case in the presence of a fault in the leader's left wheel. In the simple path, the first and third line following paths and the first random environment, the difference between performance in the presence of a fault and in a faultless environment was small, varying from 1% to 15%. Task completion was most heavily affected in the third random environment, where zero percent task completion was achieved and in the first cluttered environment, where only 32% was achieved. For a right wheel fault, lower task completion was recorded in nine out of ten paths across all environments. In the simple environment, and the random environments this difference was again small, varying from 2% and 14%. A fault in the right wheel affected the second path in the cluttered environment the most with only 32% task completion recorded.

The implicit strategy fared slightly better, with eight out of ten paths showing lower task completion for a left wheel fault, and six out of ten showing lower task completion for a right wheel fault. For a left wheel fault the difference between performance in the presence of a fault and in a faultless environment was small across all line following environments, the second random environment and in paths 2 and 3 for the cluttered environments, with the lowest task completion falling to 85%. The worst performance recorded was 14% in the third random environment. For a right wheel fault, the worst performances recorded were 3% in the third line following path and 38% in the second cluttered environment.

When observing the strategies in the graphical interface, the low task completion observed in the third line following path for the implicit strategy in the presence of a right wheel fault was consistent with previously observed low task completion behaviour. The robots were observed to veer off the path during task execution and collide with an arena wall. The robots veered off the path to the right due to the wheel differential caused by the partial motor fault in the right wheel. This behaviour is viewable in Video 3b in Appendix B.

[1]`https://github.com/naomigildert/NGildertThesis` (Accessed: 21/04/2022)

When observing other low task completion instances in the path planning environment, a previously unseen failure scenario was observed. The robots navigated through the environment successfully, without any collisions with obstacles or walls, however, throughout task execution a 'drift' was observed in the direction of the motor fault. This drift caused the robots to move at an offset along the path, which meant when the robots reached the end of the path and the Leader transmitted the 'Stop' instruction and set it's wheel velocities to zero, the robots were not inside the 'end zone' to trigger the simulation to stop and the task to be marked as complete. This can be observed in Video 3c in Appendiz B.

Partial Motor Faults in the Follower's Wheels

In the presence of partial motor faults in the follower wheels, task completion was not impacted as heavily for either strategy as it was for faults in the Leader's wheels.

For the explicit strategy, task completion was impacted in the third random environment, and the first two paths in the cluttered environment. In the random environment the difference in task completion was less than 10% across all follower wheel faults. When observing the strategy task failure occurred due to the robots colliding with an obstacle, which was similar behaviour for the explicit strategy operating without faults. As most of the statistical tests for this environment produced no significant difference, we can say these results are consistent with known behaviour for the strategy. In the second cluttered environment task completion was observed to be slightly higher but when taking into account the strategies' performance across other metrics this behaviour remains consistent with faultless behaviour.

In the first cluttered environment, the task completion was affected the most, ranging from 22% for a fault in wheel 2 to 35% for a fault in wheel 1. For the remaining paths and across all faults in the follower wheel's task completion was unaffected. When observing the strategy, the same failure scenario as seen for faults in the leader's wheels was observed where the robots completed the task but failed to reach the end zone before the leader communicated the instruction to stop. This can be seen in Video 3f in Appendix B.

For the implicit strategy, task completion was only impacted for the first cluttered environment across all follower wheel faults, and for a fault in wheel 2 in the third line following path. For the line following path this difference was only by 4%. As all four statistical tests across the design requirement metrics showed no significant difference for this path and wheel fault, we can assume this behaviour is consistent with that of the strategy performing without faults.

In the cluttered path, task completion ranged from 75% for a fault in wheel 3, to 80% for a fault in wheel 1, demonstrating a smaller effect on the strategy than for explicit. When observing the strategy, the same incompletion behaviour was observed as in the explicit strategy, where the robots successfully followed the trajectory but failed to reach the endzone before the leader set it's wheel speeds to zero. The path fidelity for the implicit strategy in this path was consistent with faultless behaviour and considerably higher than for the explicit strategy. The implicit strategies higher task completion can be attributed to its higher path fidelity, as it meant the robots were less likely to be at an offset to the path such they were not in the end zone at the end of the task.

6.3.2 Efficiency

Efficiency of the strategies was measured by evaluating the time taken by the strategies to complete the task and the total distance travelled by the object during task execution.

Time Taken

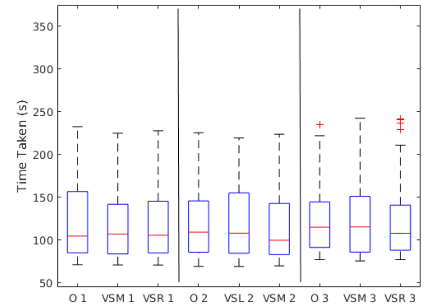
The numerical results for the time taken to complete the task in seconds in the presence of vision sensor faults can be found in table E.1 in Appendix E.1, and in the presence of motor faults in Section E.2 in Appendix J.

Vision Sensor Faults

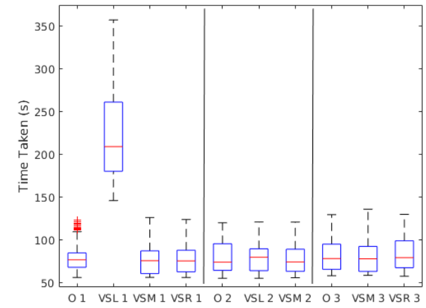
For the explicit strategy, all statistical tests for paths that achieved a non zero task completion showed no significant difference between the performance of the system with a fault and the faultless system for the time taken metric.

For the implicit strategy, six out of seven statistical tests showed no significant difference. The only test that showed significant difference was for the first path in the presence of a fault in the left vision sensor. This is linked to the behaviour observed for this path, in that the implicit strategy was able to reach the end zone ’by accident’ for some experimental runs. Within these runs the robots veered off the path and reached the end zone due to a collision with the rear wall at such an angle that allowed them to ’creep’ to the right to the end zone. This creeping movement was very slow, as the robots tried to continually move backwards into the wall, and the only movement being the small velocity vector in the right direction caused by the Follower’s omniwheels. This resulted in a long completion time for the robots to reach the end zone.

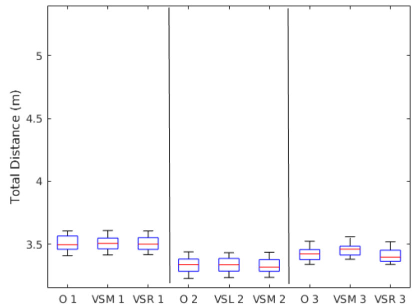
The results of the statistical tests the showed no significant difference indicate that, whilst the presence of a vision sensor fault can impact performance in environments that feature turns in the same direction as the fault, they do not impact performance in environments featuring turns in the opposite direction.



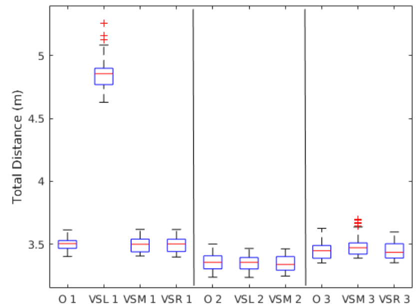
(a) Explicit: Mean Time Taken and Standard Deviation



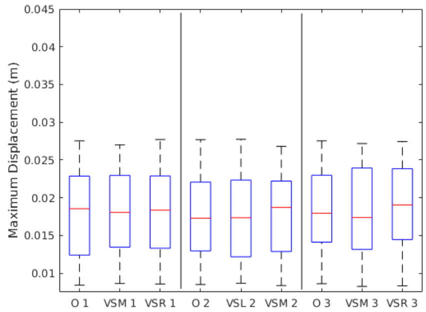
(b) Implicit: Mean Time Taken and Standard Deviation



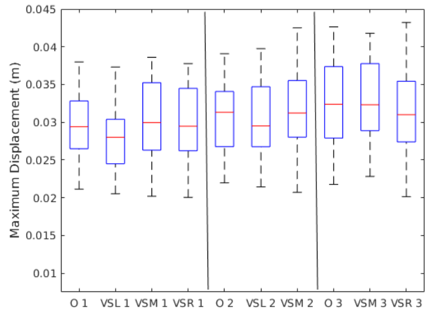
(c) Explicit: Mean Total Distance Travelled and Standard Deviation



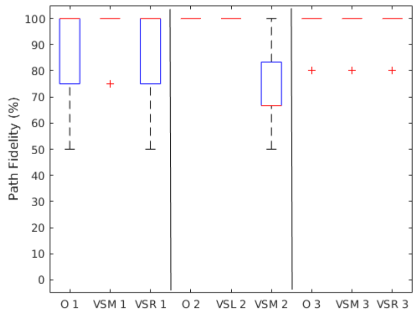
(d) Implicit: Mean Total Distance Travelled and Standard Deviation



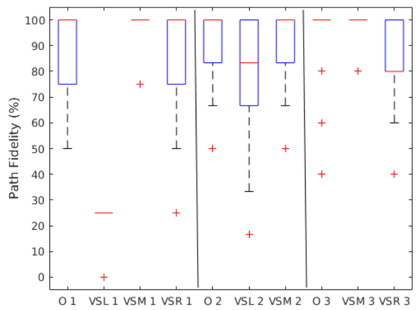
(e) Explicit: Mean Maximum Displacement and Standard Deviation



(f) Implicit: Mean Maximum Displacement and Standard Deviation



(g) Explicit: Mean Percentage Path Fidelity and Standard Deviation



(h) Implicit: Mean Percentage Path Fidelity and Standard Deviation

Figure 6.1: Performance of both communication strategies in the Line Following Environment for vision sensor faults

Partial Motor Faults in the Leader's Wheels

Very little fault tolerance was demonstrated for the metric of time taken in the presence of motor faults in the leader's wheels. For the explicit strategy, only one statistical test demonstrated no significant difference in the first path of the cluttered environment in the presence of a fault in the leader's left wheel. All other statistical tests showed significant difference for faults in either wheel. The implicit strategy showed significant difference across all tests for faults in either wheel. Across both strategies it was observed the time taken to complete the task was higher in the presence of a partial motor fault than when operating faultlessly.

For a partial motor fault on the leader's left wheel, the performance of the explicit strategy was affected more heavily than the implicit strategy in the simple, line following and random environments, with the time taken to complete tasks almost doubling on average. In the cluttered environment, the implicit strategy was affected the most with time taken increasing by up to 166 seconds. A similar pattern was observed for a partial motor fault on the leader's right wheel.

This is consistent with the expected behaviour for this fault type, as the motor fault reduces wheel speed by fifty percent in the affected wheel. This consequently reduces the speed of the entire system and causes time taken to increase. When observing the strategies in the simple environment, in one instance the explicit strategy took 490.65 seconds to complete the task whilst operating with a partial motor fault in the leader's left wheel. For the same noise value, the strategy only took 225.30 seconds to complete the task when operating without any faults. This supports the expectation that the motor fault reduces the speed of the strategies. The implicit strategy was impacted the least proportionally due to it being a faster strategy.

Partial Motor Faults in the Follower's Wheels

Considerable fault tolerance was demonstrated for the time taken metric for both strategies in the presence of partial motor faults in the follower's wheels.

For the explicit strategy 24 out of 30 statistical tests showed no significant difference when compared to the strategies performance in the absence of faults.

The implicit strategy demonstrated more robustness, with 28 out of 30 statistical tests showing no significant difference when compared to a faultless task execution.

Interestingly, in the cluttered environments, where significant difference was found, the time taken for the explicit strategy in the presence of a follower wheel fault was less than the original result for faultless task execution. This was most visible in the first cluttered environment where the difference was as large as 91.02 seconds, which was recorded in the first environment for a fault in wheel 1. When observing the strategy it became evident that the incompletion behaviour discussed above occurred for low noise values injected into the system for variability. The robots were able to complete the task successfully for higher noise values, which correlate to a higher speed. A faster time taken is observed in this case due to the data set for successfully task completion being skewed towards higher noise values.

The same behaviour was observed in the implicit strategy, although the difference between the time taken in the presence of a fault and without was lower, ranging from milliseconds to 14.25 seconds.

Total Distance Travelled By Object

The numerical results for the total distance travelled by the object in metres in the presence of vision sensor faults can be found in table E.2 in Appendix E.1, and in the presence of motor faults in Section E.2 in Appendix J.

Vision Sensor Faults

The two strategies showed less fault tolerance in the total distance travelled metric to vision sensor faults. For the explicit strategy, four out of six statistical tests showed no significant difference, with the total distance travelled by the object increasing on the second path in the presence of a left vision sensor fault, and on the third path in the presence of the middle vision sensor fault.

For the implicit strategy, 5 out of seven tests showed no significant difference, with increased total distance travelled in the first path in the presence of a left sensor fault, and in the third path in the presence of a middle sensor fault. For the first path, this result is consistent with the behaviour observed within simulation. The increase in distance travelled is due to the robots veering off the path and then moving along the wall to the end zone.

For both strategies in the presence of a middle sensor fault in path 3 where a larger total distance travelled was observed, the difference in distance was reasonably small, within 0.03m, this increase was likely due to the fact that without a middle sensor the robots are only performing large corrective movements when the Leader senses the edge of a path.

Partial Motor Faults in the Leader's Wheels

Very little fault tolerance was demonstrated for the metric of total distance travelled in the presence of partial motor faults in the Leader's wheels. Only one statistical test showed no significant difference for the explicit strategy in the third random environment in the presence of a fault in the leader's left wheel. All other tests across faults in either wheel and both communication strategies showed statistical difference.

Across the simple, line following and random environments the total distance travelled was recorded as higher for both strategies in the presence of either fault type. In some cases, such as for the implicit strategy in the second line following path and with a right wheel partial motor fault, this was up by almost double the distance. This often occurred for paths where low task completion was observed, which was consistent with previously observed behaviour.

Within the cluttered environments, a shorter total distance travelled was observed for the explicit strategy across all paths, and in the first two paths for the implicit strategy in the presence of a fault in the leader's left wheel. In the cluttered environments, the paths feature several left turns, the shorter distance can thus be attributed to the differential wheel speed making turns in the direction of the motor fault tighter.

Partial Motor Faults in the Follower's Wheels

The explicit strategy demonstrated the most robustness out of the two strategies for the total distance travelled metric, with 19 out of 30 statistical tests showing no significant difference. An increase in distance travelled for the strategy was observed in the first cluttered environment, which is consistent with behaviour observed for in paths with lower task completion.

The implicit strategy showed robustness in 15 out of 30 statistical tests. For almost all results that showed significant different, the total distance recorded was lower than the original data for faultless task completion. This was most visible for the third cluttered environment, in the presence of a partial motor fault in wheel 1 for the follower, where the difference in total distance was 0.22m. When observing the strategy in simulation it could be seen that in the presence of a fault in wheel 1, the robots performed less sweeping turns, as the reduced speed on that wheel reduced the velocity vector in the backwards direction of the follower robot. This enabled the robots to perform tighter turns throughout the environment. This behaviour can also account for the increased path fidelity observed in the implicit strategy for a wheel fault on the follower's first wheel.

6.3.3 Smoothness

Smoothness was measured by the maximum displacement of object during task execution and path fidelity.

Maximum Displacement of Object

The numerical results for the maximum displacement of the object in metres in the presence of vision sensor faults can be found in table E.3 in Appendix E.1, and in the presence of motor faults in Section E.2 in Appendix J.

Vision Sensor Faults

For both strategies, within all paths that achieved non zero task completion, no statistical difference was found when comparing the strategies' performance in the presence of a vision sensor fault to their performance in a faultless environment. This again indicates that the strategies' performance is not impacted by faults in the vision sensors unless they occur in the sensor linked to the predominate direction of the path.

Partial Motor Faults in the Leader's Wheels

The implicit strategy demonstrated some fault tolerance for the maximum displacement of object in the metric in the presence of partial motor faults. For a fault on the leader's left wheel two statistical tests showed no significant difference in the second and third line following paths. One statistical test showed no significant difference in the third line following path for a fault on the leader's right wheel.

The explicit strategy demonstrated significant difference across all environments and for faults in either wheel. The maximum displacement recorded was less in the presence of a partial motor fault than in a faultless environment, which met the expected behaviour of the strategy in the presence of a motor fault, as it was believed a greater wheel differential may cause tighter turns and smaller displacement between time steps. Similar behaviour was demonstrated in the implicit strategy in the presence of a fault in the leader's right wheel across all path planning environments.

Partial Motor Faults in the Follower's Wheels

The explicit strategy demonstrated the most fault tolerance out of the two strategies for the maximum displacement metric, with 25 out of 30 tests showing no significant difference. The most significant difference was observed in the explicit strategy in the first cluttered environment across faults in all of the follower's wheels. This behaviour is linked to the low task completion observed in this path and is consistent with other behaviour observed.

The implicit strategy showed robustness in 19 out of 30 statistical tests. Where significant difference was observed, the maximum displacement recorded in the presence of a fault was less than for the original faultless data. This was most visible in the second cluttered environment in the presence of a fault in wheel 1, where the maximum displacement was 0.009m lower in the presence of a fault. The trend of lower maximum displacement is consistent with the behaviour observed for faults in the Leader's wheels.

Path Fidelity

The numerical results for the percentage task completion of the two strategies in the presence of vision sensor faults can be found in table E.4 in Appendix E.1.

Vision Sensor Faults

For explicit communication, four out of six statistical tests showed no significant difference when comparing the performance of the strategy in the presence of a vision sensor fault, to its performance in a faultless environment. Statistical difference was only seen in paths one and three in the presence of a middle vision sensor fault.

The implicit strategy showed the least fault tolerance for the path fidelity metric, with only three statistical tests out of seven showing no statistical difference. For the left sensor fault in the first path this was consistent with previous behaviour observed. The mean path fidelity percentage of 21.63% related to the beginning of the path which was a straight segment that lay concurrent to the direction the robots were facing at the beginning of the run. The robots were able to follow the path for this segment and successfully pass through way points until the path began to curve left and the robots veered off the path.

Partial Motor Faults in the Leader's Wheels

Very little robustness was observed for the path fidelity metric. Very low path fidelity, less than 10%, was observed across all path planning environments for both strategies in the presence of a partial motor fault in either of the Leader's wheels. The path fidelity for the simple environment was notably low, approximating zero percent across both strategies. This met the expectations of the fault experiments in that a larger wheel differential would impact path fidelity during task execution.

When observing the strategies in the path planning environments, it could be seen that for both strategies the differential wheel speeds caused a veering movement in the direction of the motor fault. In the case of a motor fault in the leader's left wheel the caused the robots to consistently follow the path at an offset to the left of the trajectory, and for a fault in the right wheel, the robots would follow the path to the right of the trajectory. This resulted in low path fidelity as the robots did not pass through the way-points. This is viewable for a left wheel fault in Video 3d, and for a right wheel fault in Video 3e in Appendix B.

A 'rocking' behaviour could be observed in both strategies as the differential wheel speed caused the robots to veer in the direction of the fault away from the direction of the path, causing the robots to perform a corrective movement in line with their path following strategies. Whilst the fidelity values recorded across the line following paths were closer to the original values of the strategies operating without faults, only two statistical tests showed no significant difference. Both strategies demonstrated no significant difference in one statistical test in the first line following environment in the presence of a fault in the leader's left wheel.

Partial Motor Faults in the Follower's Wheels

The explicit strategy demonstrated the most fault tolerance to motor faults in follower's wheels for the path fidelity metric. No significant difference was found in 21 out of 30 statistical tests across faults in all wheels. Path fidelity was the most visibly affected for the explicit strategy in the first cluttered environment, where values were around 15% lower than those observed for task execution in the absence of faults. This is behaviour likely linked to the low task completion observed in this path.

The implicit strategy demonstrated less robustness, with only 14 statistical test showing no significant difference. Interestingly, for all environments except the simple environment, where significant difference was found, the recorded values for path fidelity were higher in the presence of a wheel fault in the follower's wheels than the original data recorded in the absence of faults. This trend was particularly visible for a fault in wheel 1 or a fault in wheel 3. This difference was typically only a few percent, but the largest difference was 10% observed in the second line following environment for a fault in wheel 1. As discussed previously for results for the total distance metric, the increase in path fidelity observed in wheel 1 can be attributed to the fact that such a wheel fault causes the robots to perform tighter turns.

6.3.4 Conclusion

This chapter investigated the fault tolerance of the two communication strategies when completing simple object manipulation tasks in the presence of two types of faults: complete vision sensor faults and partial motor faults. This was achieved by comparing the statistically significant difference between the performance of the two strategies demonstrated in Chapter 4 in the absence of any faults injected into the system, and the performance of the strategies in the presence of faults.

For the vision sensor fault, the implicit strategy demonstrated some statistical fault tolerance as 21 out of 28 statistical tests produced no significant difference across the four metrics used to measure performance. The explicit strategy demonstrated a higher fault tolerance, with 20 out of 24 tests showing no significant difference. However, it is crucial to remember, as seen in the task completion analysis, that performance was inhibited in the presence of a vision sensor fault if the fault appeared on the same side as the predominant direction of the path within that environment. It is therefore only possible to say that both strategies are only fault tolerant to vision sensor faults if they do not occur on the same side as the path direction, greatly impacting the flexibility of the strategies. The null hypothesis that vision sensor faults have no effect on performance must therefore be rejected.

The most fault tolerance was demonstrated for a fault in the middle sensor, as the fault occuring in this sensor did not impact either strategies when performing turns to follow the trajectory. For this fault, 19 out of 24 statistical tests demonstrated no significant difference, across both strategies. The implicit strategy demonstrated the most fault tolerance with 10 out of 12 tests showing no statistical difference, this was due to the smoother nature of the strategy previously observed in Chapter 4.

Table 6.2 provides a fault tolerance profile of the two strategies across the four metrics for vision sensor faults. The results indicated which strategy offers the most fault tolerance for a given fault and for a given metric. It is important to bear in mind when referencing this table that the strategies are not fault tolerant to vision sensor fault if it is on the same side as the path direction.

For the partial motor faults, different levels of fault tolerance were observed in the strategies, depending on whether the motor faults occurred in the leader's wheels or the follower's. This observed behaviour can be consolidated into our understanding of the strategies.

As observed in simulation, a fault in the Leader's wheels causes a continuous offset in the direction of the wheel fault, which the leader cannot correct or mitigate through a single instruction, as can be observed in the line following environments where oscillatory behaviour was observed. When considering both strategies as control loops, we can imagine a partial motor fault on the leader wheels results in an error signal being imposed on the input of either system, and read by the follower in both strategies as an error-less input. The two strategies function by trying to reduce the error between the follower's current position, and the positional information they are receiving from the Leader. This is done through either a deliberate movement, for the explicit strategy, or by reducing the error sensed on the input in a negative feedback look, for the implicit strategy. They are not able to differentiate between an instruction from the leader that is 'faulty' and erroneous or correct, so they make no attempt to reduce an error imposed on their input.

Conversely, a partial motor fault on a follower's wheel essentially induces an error after the input of the system, which either strategy reads like any other perturbation on the input and attempts to reduce it.

For a partial motor fault on one of the leader's wheels, the explicit strategy only demonstrated no significant difference in three out of 76 statistical tests. The implicit strategy only demonstrated no significant difference in four our of 80 tests. Thus the null hypothesis that a partial motor fault in one of the leader's wheels has no effect on the system must be rejected. This result is consistent with the expected behaviour of such a fault impacting the strategies' abilities to successfully perform object manipulation tasks in the presence of partial motor faults.

Table 6.3, shows the fault tolerance profiles of the two strategies across all four metrics and for all environment types. It highlights that the strategies are not robust to motor fault's on the leader's wheels, but provides insight for where the strategies demonstrated some robustness.

For a partial motor fault on one of the Follower's wheels, the explicit strategy demonstrates the most fault tolerance, with 87 out of 120 statistical tests showing no significant difference, compared to to 76 out of 120 for the implicit strategy. As discussed in previous chapters, the explicit strategy demonstrates noise immunity, which indicates how the strategy demonstrates stronger fault tolerance to a follower wheel fault than the implicit strategy, when attempting to reduce the error on its input caused by a partial motor fault in one of the follower's wheels.

Table 6.4, shows the fault tolerance profiles of the two strategies across all four metrics and for all environment types. It indicates which strategy demonstrates the most robustness for a given metric and environment type, and can be used as a reference when designing systems where robustness in certain design requirements is more desirable than in others.

This chapter expands on the evaluation of the performance of the two communication strategies in simple object manipulation tasks, by exploring the fault tolerance of the two strategies in the presence of two types of faults. The robustness profiles created in this chapter are used to inform the evaluation in Chapter 9 of a hybrid system that combines both types of communication, in the presence of the same faults.

Table 6.2: Fault Tolerance of Explicit and Implicit Strategies to Vision Sensor Faults in Simple Object Manipulation Tasks

Metric	Time Taken	Total Distance	Maximum Displacement	Path Fidelity
Left	Explicit/ Implicit	Implicit	Implicit	Explicit
Middle	Explicit/ Implicit	Explicit/ Implicit	Explicit/ Implicit	Implicit
Right	Explicit/ Implicit	Explicit/ Implicit	Explicit/ Implicit	Explicit

Table 6.3: Fault Tolerance of Explicit and Implicit Strategies to Partial Motor Faults in the Leader Wheels in Simple Object Manipulation Tasks

Metric	Time Taken			Total Distance			Maximum Displacement			Path Fidelity		
Environment	LF	SECE	RE	LF	SECE	RE	LF	SECE	RE	LF	SECE	RE
Left	Neither	Explicit	Neither	Neither	Neither	Explicit	Implicit	Neither	Neither	Explicit/ Implicit	Neither	Neither
Right	Neither	Neither	Neither	Neither	Neither	Neither	Implicit	Neither	Neither	Neither	Neither	Neither

Table 6.4: Fault Tolerance of Explicit and Implicit Strategies to Partial Motor Faults in the Follower Wheels in Simple Object Manipulation Tasks

Metric	Time Taken			Total Distance			Maximum Displacement			Path Fidelity		
Environ.	LF	SECE	RE	LF	SECE	RE	LF	SECE	RE	LF	SECE	RE
Wheel 1	Implicit	Implicit	Explicit / Implicit	Explicit	Explicit	Explicit	Explicit	Explicit	Explicit	Explicit / Implicit	Explicit	Explicit
Wheel 2	Explicit / Implicit	Implicit	Implicit	Explicit / Implicit	Explicit / Implicit	Implicit	Explicit / Implicit	Implicit	Explicit	Explicit / Implicit	Explicit	Explicit / Implicit
Wheel 3	Explicit / Implicit	Implicit	Explicit	Explicit / Implicit	Explicit / Implicit	Explicit / Implicit	Explicit	Implicit	Explicit	Implicit	Explicit	Explicit

Chapter 7

Combining Implicit and Explicit Communication into a Hybrid System

The previous work outlined in Chapters 4 and 5 form the foundation on which this chapter builds on: investigating a hybrid system that combines implicit and explicit communication in object manipulation tasks between two robots.

The analysis and construction of performance profiles for explicit and implicit communication working in isolation provide an understanding of their advantages and disadvantages and their performance with different object types. Understanding the strategies' performance in isolation is crucial to evaluating the performance of a combined system.

This chapter presents a novel hybrid system that combines implicit and explicit communication between two robots in an object manipulation task. To the author's knowledge no previous work has investigated the combination of implicit and explicit communication within this specific application and which mimics human joint action by using force information as the form of implicit communication. As discussed in Chapter 2, the majority of research investigating communication in object manipulation has mainly explored the validity of implicit communication as an alternative to explicit communication, through comparison (Aiyama et al., 1999; Pereira et al., 2002), or through proof of concept (Groß & Dorigo, 2004; Groß et al., 2006; Wang & Schwager, 2016).

Whilst the combination of explicit and implicit communication has been previously explored in multi-robot systems to improve coordination in search and rescue applications (Nasroullahi, 2012), and in transporting an object in a multi-robot environment(Wang et al., 2013a), the implicit communication employed in these works are both observational in nature. Nasroullahi (2012) employed stigmergy, where the continued observation of points of interest during the exploration task affected the agents' behaviour, and Wang et al. (2013a) used behaviour prediction, where the robots used a sensor network to observe the movement of other robots and make a prediction for their behaviour in order to avoid collisions. The work presented in this thesis differs in that the combined communication occurs between two robots manipulating an object together, rather than in a multi-robot system, and most importantly, that the combined system uses force information rather than observation as the form of implicit communication.

The simple object manipulation tasks described in this thesis were chosen as they are most similar to activities where humans employ joint action to cooperate together, as discussed in Chapter 2, and are the appropriate choice to test the proof of a concept of a robotic system that aims to mimic joint action in humans.

Whilst other tasks could have been chosen such as coordinated movement, object manipulation tasks still remain the most appropriate task choice as it is a testbed that demonstrates a practical, valuable action: being able to move an object from one place to another, and due to its tightly coupled nature of the robots moving an item jointly, involves the natural exertion of forces that can be used to imply information through the form of implicit communication described in this thesis. Object manipulation tasks between two robots also have a translatable real world application within manufacturing and shared autonomy spaces.

The number of robots used in manufacturing and shared autonomy spaces such as robotic warehouses is increasing rapidly, with organisations such as Amazon (Tam, 2014) and Ocado (Excell, 2017) investing in robotic solutions. Object manipulation is a fundamental task within these shared autonomy places in the commerce industry, where robots are often required to manipulate multiple objects across environments reliably, efficiently and carefully. These shared autonomy environments would offer an appropriate and attractive problem space to apply the Hybrid System presented in this chapter.

In this chapter, a new hybrid system, which combines the strategies outlined in Chapter 4 using a weighted sum, is described and evaluated when moving the original object also used in Chapter 4. In the following chapter, Chapter 8, it's consistency in performance was evaluated by testing the hybrid system with the different objects used in Chapter 5.

The four environments described in Chapter 4 and their paths were used to conduct the combination experiments. Consistent with previous analysis of the two strategies in isolation, the same design requirements detailed in Table 3.4 in Chapter 3were used to evaluate the performances of the hybrid system: task completion to measure reliability, time taken to complete the task and total distance travelled to measure efficiency, and maximum displacement of the object in a time step and path fidelity to evaluate smoothness. The same method as described in 3 was employed to calculate these metrics using the raw data from the experimental simulations.

7.1 The Hybrid System

The hybrid system was created by combining the two strategies derived in Chapter 4. The configuration of the system is identical to the original communication strategies: a two robot system comprised of a Leader and a Follower robot, who are rigidly attached to an object that they must manipulate from a start location to an end location. The Leader is the only robot with knowledge of its location in relation to the path and the end goal location and moves forward across the environment during task execution. The Follower must use information communicated to it by the Leader to calculate its speed and direction as it moves backwards across the environment.

The same morphological and technological restraints are imposed on the hybrid system as were imposed on the two isolated strategies, but are now adapted into one system:

- the Leader and Follower robots must have the ability to transmit and receive wireless messages
- the Leader must be equipped with the correct sensors and the computational ability to navigate across an environment from a start location to a desired end location, either using conventional path planning techniques, or sensors.
- the Follower must be equipped with a force sensor in order to measure and use force information
- the Follower must be equipped with omnidirectional wheels in order to transform force information measured in the x and y axis into lateral movement in any corresponding direction.

These morphological constraints are imposed in order for the hybrid system communication strategy to function as designed. For example, Force is a vector, it is therefore essential to be able to interpret force readings in both the x and y axis to use it as a form of implicit communication. Converting those force components in the x and y axes into velocity using Newton's Second Law results in velocity values in separate x and y components as well. Omniwheels, which allow the Follower to move in any direction in the x and y axes and effectively use force information to derive it's speed, are thus a morphological requirement. It is also required for the robot's to be rigidly attached to the object to reduce complexity in measuring the forces acting on the object to only be two dimensional and in the x and y axes. In this sense there are of course some dependencies of the hybrid system on the robot architecture used. However, as this thesis aims to provide a proof of concept of a hybrid system employing a combination of implicit and explicit communication in simple object manipulation tasks, these dependencies are not explored in detail within this thesis. The potential of exploring other robot architectures is discussed as Future Work in Chapter 10.

In the Hybrid System, Where previously the Follower either applied explicit or implicit communication to interpret information from the Leader and adjust its wheel velocities, it now receives information both explicitly and implicitly and combines that information to determine its movements. It calculates both its explicit wheel speeds and its implicit wheel speeds, performs a weighted sum of the two and applies these weighted wheel speeds to its velocity equations for its omnidirectional wheels, as depicted in Chapter 4

The controller for the Leader robot in the hybrid system is identical to that in the explicit strategy: at every time step, the Leader robot transmits its desired forward velocity, and depending on its position on its trajectory, it transmits the relevant instruction from the set "Left", "Right" and "Backwards", to inform the Follower which direction to move. When the Leader reaches the end of the path it transmits the message "Stop" and sets its desired forward speed to zero. The controller for the Follower combines the explicit and implicit strategies: it receives data explicitly from the Leader through wireless message transmission and it measures the force being exerted on its force sensor. When the Follower is receiving data from the Leader it determines its explicit wheel velocities, V_{exp_x}, V_{exp_y} and $V_{exp_{rot}}$ in an identical fashion to the explicit strategy described in Chapter 4.

The Follower also continuously, every time step and regardless of whether it has received explicit data from the Leader or not, measures the force and torque being exerted by the Leader onto the Follower's force sensor, and using the same assumptions of uniform mass density and the same equations derived in Chapter 4 it calculates its implicit wheel velocities, V_{imp_x}, V_{imp_y} and $V_{imp_{rot}}$.

These explicit and implicit wheel velocities are then combined together in a weighted sum to create the three wheel velocities V_x, V_y and V_{rot} that are applied to the wheel equations for the Follower's three omniwheels. The weighted sum equations are as follows:

$$V_x = w \times V_{imp_x} + (1 - w) \times V_{exp_x} \tag{7.1}$$

$$V_y = w \times V_{imp_y} + (1 - w) \times V_{exp_y} \tag{7.2}$$

$$V_{rot} = w \times V_{imp_{rot}} + (1 - w) \times V_{exp_{rot}} \tag{7.3}$$

Where w is a value between 0 and 1. For a value of $w = 0$ the implicit component is zeroed and the system becomes fully explicit. For a value of $w = 1$ the explicit component is zeroed and the system becomes fully implicit.

For values of w between 0 and 1, the end result is a system that enables the Follower to use a combination of implicit and explicit communication to cooperate with the Leader and jointly manipulate an object along a trajectory.

In the following chapters, in order to evaluate the hybrid system and investigate how a combination of implicit and explicit communication affects the performance of the system, three weightings were investigated: 0.25, 0.5 and 0.75, to from a linear scale of weightings from, $w = 0$, a fully explicit strategy, to $w = 1$, a fully implicit strategy.

The Hybrid System presented in this thesis aims to provide a proof of concept that combines the two communication strategies described in Chapter 4. As discussed in Chapter 1, the aim of this combination is to explore if the advantages of the individual strategies performing in isolation, as identified in Chapters C, 5 and 6, can be capitalised on when combined, resulting in a more efficient, reliable and smoother system than what can be offered by the strategies operating independently. An additional aim is to investigate what combination of the two strategies can produce the best performance.

The linear scale of weightings was chosen as a suitable foundation for this proof of concept as it can quickly demonstrate the performance of a system that combines implicit and explicit communication equally, and on a scale from fully explicit to fully implicit to indicate how the performance changes with the combination. More complex methods could have been used to choose the weightings, such as Reinforcement Learning or Multi Object Optimisation, such as Pareto optimality, however a linear scale was deemed sufficient for an initial proof of concept and exploration of the Hybrid System's performance profile. How these more complex methods could be implemented for future work in optimising the Hybrid System are discussed in more detail in Chapter 10.

The Hybrid System was tested in the same four environments and using the same experimental setup as described in Chapter 3.

Whilst the experimental setup and physical robots remained unchanged, the robot controllers were modified to employ the hybrid system described in Section 7.1.

7.2 Evaluating the Performance of the Hybrid System with the Original Object

The experiments described in this chapter evaluate the performance of the weighted hybrid system for three different weightings, when manipulating the original object from Chapter 4.

The null hypothesis used to analyse the hybrid system's performance across different weightings was as follows:

Null Hypothesis H_0: The change in weighting in the weighted sum hybrid system that combines explicit and implicit communication has no effect on performance. There is no statistical difference between the performance of the hybrid system at different weightings and the explicit strategy, and there is no statistical difference between the performance of the hybrid system at different weightings and the implicit strategy (rejected with a 95% tolerance).

7.3 Results

The performance of the system across the five metrics described in Table 3.4 in Chapter 3, were compared to the performance of the two strategies in isolation.

The graphical results for the hybrid system to complete the task with different combination weightings can be seen within this chapter in Figure 7.1 for the line following environment and Figure 7.2 for the random environment, to visually support the analysis of the results presented here.

The remaining graphs depicting the performance for the hybrid system can be found in the appendices, in Figure F.1 for the simple environment, and in Figure F.2 for the cluttered environment.

Mann-Whitney U tests were performed to compare the data set for the hybrid system manipulating the original object with each of the data sets for the two individual communication strategies manipulating the original object in Chapter 4 to reject or accept the null hypotheses formulated in this chapter.

7.3.1 Reliability

Reliability of the hybrid system when manipulating the original object was evaluated by measuring task completion.

Task Completion

The hybrid system achieved 100% task completion across all weightings in the simple, cluttered and random environments. This was consistent with or an improvement on the communication types working in isolation for the these environments.

In the line following environment, task completion varied with the weighting value, falling as low as 57% in the third path for the weighting of $w = 0.5$, as shown in Table 7.1. During observations in the graphical interface, it was visible that for higher values of noise injected into the system, when the system was weighted at 0.25 or 0.5 a corrective movement could cause an overshoot that rotated the leader's vision sensor's off the path, thus causing the robot's to veer off the trajectory and fail the task. This happened most frequently in the third path due to the sharp turn in this trajectory, and is viewable in Video 4a for the 0.25 weighting, and in Video 4b for the 0.5 weighting in Appendix B. This behaviour did not occur as often at the higher weighting of 0.75 for similar noise values, as the system performed smoother corrective movements, which did not cause the leader's vision sensors to be pulled off of the path, as demonstrated in Video 4c in Appendix B.

When first defining the communication strategies, the implicit strategy was defined as a negative feedback error loop that attempts to reduce error detected on its input, which is measured as a perturbation in the Leader's movements and thus the force it detects being exerted on it's sensor. When combining the systems, the implicit component aims to reduce the error of the hybrid system. However, since the explicit strategy acts like a feed-forward network by performing deliberative movements, it results in a large perturbation and thus a large error for the implicit component to try to reduce. As the weighting increases towards implicit communication, the implicit communication's ability to reduce error increases.

Table 7.1: Percentage Task Completion for the Hybrid System in Line Following Environments.

Weighting	Line Following Paths		
	1	2	3
w = 0.25	**91.00%**	**76.00%**	**62.00%**
Exp	100.00%	100.00%	100.00%
Imp	100.00%	100.00%	99.00%
w = 0.5	**98.00%**	**92.00%**	**57.00%**
Exp	100.00%	100.00%	100.00%
Imp	100.00%	100.00%	99.00%
w = 0.75	**100.00%**	**100.00%**	**79.00%**
Exp	100.00%	100.00%	100.00%
Imp	100.00%	100.00%	99.00%

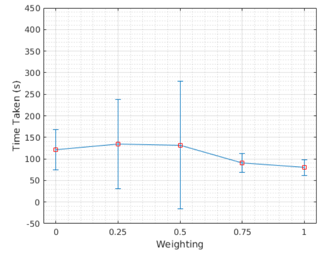
7.3.2 Efficiency

Efficiency of the strategies was measured by evaluating the time taken by the hybrid system to complete the task and the total distance travelled by the object during task execution.

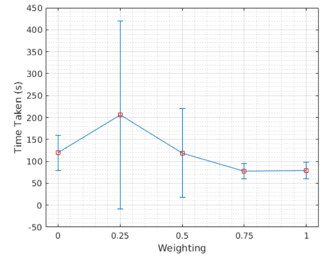
Time Taken

The full numerical results can be found in the appendices, in Tables F.1, F.2 and F.3 for the line following environment, the simple and cluttered environments and the random environment, respectively.

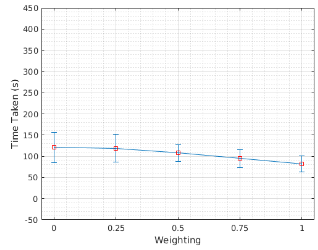
Across all environments a linear trend could be observed that time taken to complete the task decreased as weighting decreased towards the fully implicit system. This was less pronounced in the line following environment, particularly for weightings that had low task completion, which correlated to a higher time taken mean. This is particularly pronounced for the 0.25 weighting in path 2, which had a mean completion time taken of 206.05s compared to 119.22s



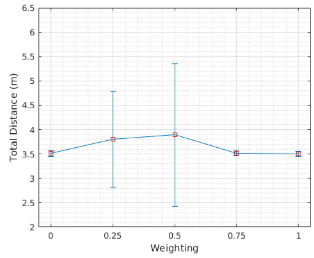
(a) Path 1: Mean Time Taken and Standard Deviation



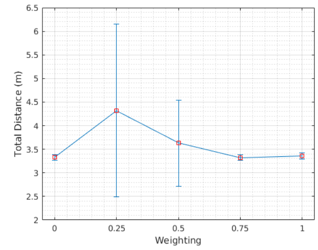
(b) Path 2: Mean Time Taken and Standard Deviation



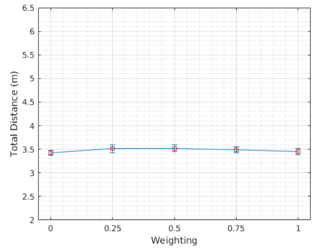
(c) Path 3: Mean Time Taken and Standard Deviation



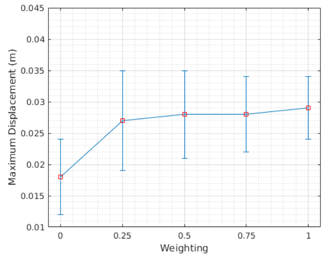
(d) Path 1: Mean Total Distance Travelled and Standard Deviation



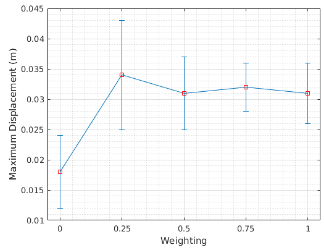
(e) Path 2: Mean Total Distance Travelled and Standard Deviation



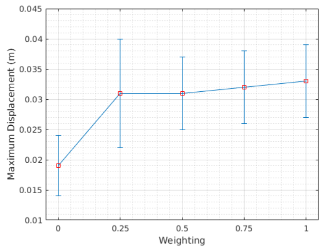
(f) Path 3: Mean Total Distance Travelled and Standard Deviation



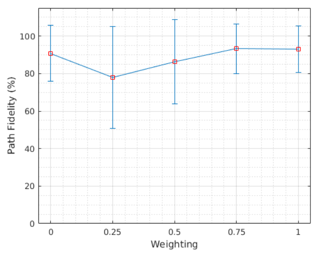
(g) Path 1: Mean Maximum Displacement and Standard Deviation



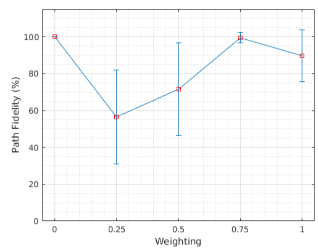
(h) Path 2: Mean Maximum Displacement and Standard Deviation



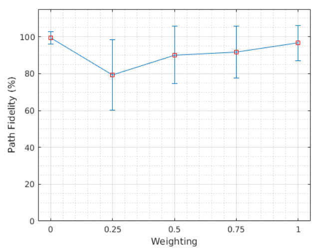
(i) Path 3: Mean Maximum Displacement and Standard Deviation



(j) Path 1: Mean Percentage Path Fidelity and Standard Deviation

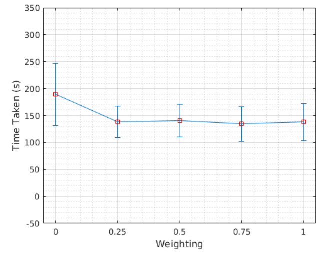


(k) Path 2: Mean Percentage Path Fidelity and Standard Deviation

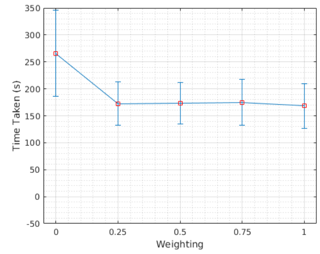


(l) Path 3: Mean Percentage Path Fidelity and Standard Deviation

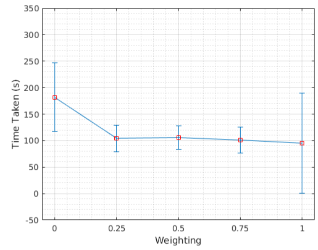
Figure 7.1: Performance for the Hybrid System across all design requirement metrics in the Line Following Environmental Setup



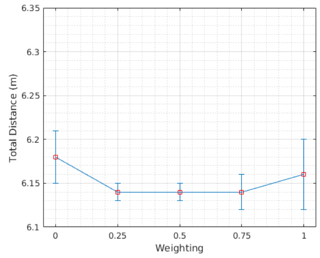
(a) Path 1: Mean Time Taken and Standard Deviation



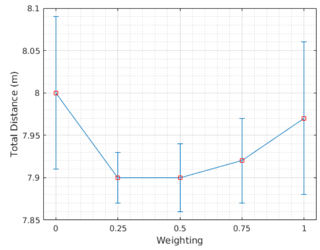
(b) Path 2: Mean Time Taken and Standard Deviation



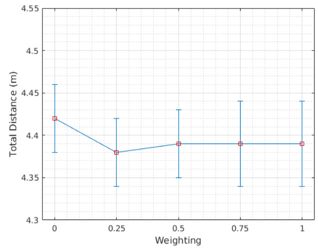
(c) Path 3: Mean Time Taken and Standard Deviation



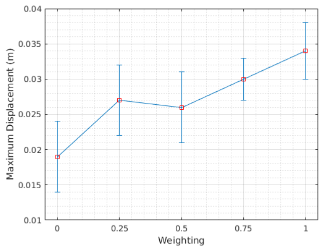
(d) Path 1: Mean Total Distance Travelled and Standard Deviation



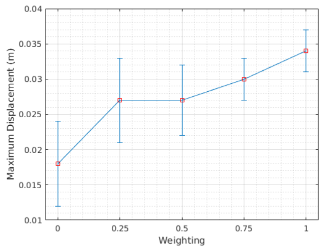
(e) Path 2: Mean Total Distance Travelled and Standard Deviation



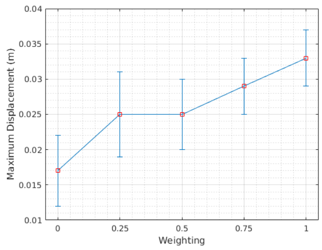
(f) Path 3: Mean Total Distance Travelled and Standard Deviation



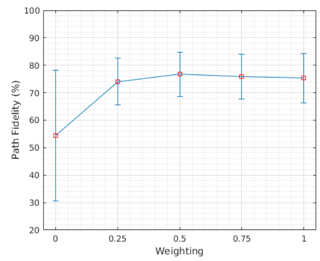
(g) Path 1: Mean Maximum Displacement and Standard Deviation



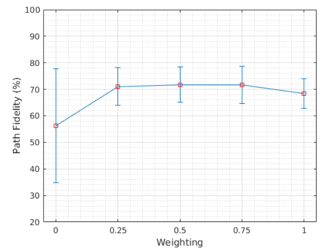
(h) Path 2: Mean Maximum Displacement and Standard Deviation



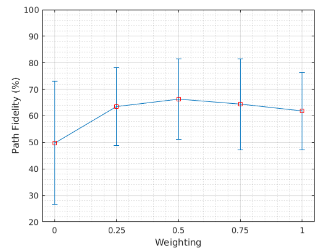
(i) Path 3: Mean Maximum Displacement and Standard Deviation



(j) Path 1: Mean Percentage Path Fidelity and Standard Deviation



(k) Path 2: Mean Percentage Path Fidelity and Standard Deviation



(l) Path 3: Mean Percentage Path Fidelity and Standard Deviation

Figure 7.2: Performance for the Hybrid System across all design requirement metrics in the Randomly Generated Environments

for the explicit strategy and 79.18s for the implicit strategy. The weighting also had a large standard deviation of 214.39s. As discussed previously in Chapter 5, in some cases it was observed that the robots veered off the trajectory and collided with the arena walls, but were able to move along the wall at such an angle that they could still reach the goal region, just at a time far longer than a standard run. This accounted for a large standard deviation in time taken for a weighting with a lower task completion percentage. The 0.25 weighting showed no significant difference to explicit communication across all paths. The majority of the remaining statistical tests showed significant difference to both strategies. This behaviour is viewable in Video 4d in Appendix B.

The path planning environments shared a similar trend to the line following environment with a more dramatic weighting towards the implicit communication: it can be observed that time taken decreases rapidly from the explicit communication value at the initial weighting of 0.25. This rapid increase can be accounted for by the functionality of the two communication strategies. As discussed in Chapter 4, in the isolated systems the follower in the explicit strategy does not continuously move in the x and y directions: only the V_y velocity has a non-zero value during a corrective movement, whereas the follower in the implicit strategy continuously calculates in both translational directions. In the hybrid system as soon as a weighted value of implicit communication is introduced the follower continuously calculates velocity values for both the x and y direction.

In the first random environment and the first and third cluttered environments the 0.25 weighting showed no significant difference to the implicit strategy. The 0.5 and 0.75 weightings showed no significant difference to the implicit strategy across all paths in the simple, cluttered and random environments. This is again consistent with the reasoning presented for task completion that the implicit component enabled the system to reduce error as weighting increases and improve performance.

Total Distance Travelled

The full numerical results are shown in the appendices, in Tables F.4, F.5 and F.6 for the line following environment, the simple and cluttered environments and the random environment, respectively.

In the simple environment the total distance travelled by the object varied very little across the weightings and all weightings showed no statistic difference to either explicit or implicit communication. In the line following environment a correlation was again seen between total distance travelled and task completion, with the 0.25 weighting that had low task completion percentages in paths 2 and 3 also achieving higher values of distance travelled, particularly in path two which saw an increase in a metre of the mean distance travelled. This again can be related to the robots veering off the path but managing to complete the task later on in the experimental run. Since the total distance is calculated as a summation of difference in x and y positions of the object over the course of the experimental run, all of the objects movements are included in the summation including erroneous movement caused by moving off the path, which generates a large total distance travelled mean.

The path planning environments shared the same pattern to each other, where total distance decreased from explicit communication for a weighting of 0.25, and then increased with weighting to implicit communication. With the exception of the 0.75 weighting in the second cluttered path, all total distance values across every weighting and path was less than the shortest distance travelled by either explicit or implicit strategy. Two out of 36 statistical tests showed no significant difference to the total distance travelled by the explicit strategy, the remaining 34 tests showed statistically significant difference to both strategies. As the time taken and path fidelity results both weighted heavily towards the implicit strategy, it could be called into question whether the implicit component is simply ‘overpowering’ the explicit component in the hybrid system and producing results similar to its performance. However, these results for total distance travelled indicate that this is not the case, as a linear decrease from explicit to implicit is not present: instead the hybrid system performs better in this metric than both strategies. This supports the idea that the implicit component is acting as a negative feedback loop and reducing error in the system.

7.3.3 Smoothness

Smoothness is a design requirement used to consider how smooth a strategy is to provide insight into whether or not the hybrid system could handle potentially fragile objects. Smoothness is measure through evaluating maximum displacement of the object and path fidelity.

Maximum Displacement of Object

The full numerical results are shown in the appendices, in Tables F.7, F.8 and F.9 for the line following environment, the simple and cluttered environments and the random environment, respectively.

Results showed that maximum displacement of the object increased linearly as weighting increased from fully explicit to fully implicit over all environmental configurations.

In the second path of the line following environment the 0.25 and 0.5 weightings showed no significant difference to the implicit strategy as well as the 0.75 weighting in the third path of the same environment. All other statistical tests across the four environments showed significant difference with the performance of the explicit strategy and the implicit strategy.

As discussed previously, the implicit strategy is faster, which can often lead to large maximum displacement values between time steps, since the higher weighting values of the implicit component increased the speed of the hybrid system, the displacement of the object between time steps also increased.

Path Fidelity

The full numerical results can be found in the appendices, in Tables F.10, F.11 and F.12 for the line following environment, the simple and cluttered environments and the random environment, respectively.

In the line following environment path fidelity dropped at the 0.25 weighting and then increased with weighting value up to the fully implicit system. The low path fidelity was correlated to task completion: weightings that had lower task completion also showed lower path fidelity than the independent systems. They also showed a higher standard deviation, as their performance fluctuated in paths they struggled with. This low path fidelity is due to the overshooting behaviour discussed previously, which would cause the robots to miss way points along the trajectory. In path 1 the path fidelity for the 0.5 and 0.75 weighting showed no statistical difference to the path fidelity of explicit communication or implicit communication, and the path fidelity for the 0.75 weighting in the third path showed no statistical difference to the explicit communication. All other Mann-Whitney U tests indicated a significant difference between the weighted hybrid system and the explicit and implicit strategies.

In the simple environment the path fidelity did not vary greatly across the different weighting values, and all weightings showed no significant difference to either explicit communication or implicit communication. In the remaining path planning environments the same trajectory was observed across all paths where path fidelity increased from explicit communication as weighting increased, and then decreased down to implicit communication. The path fidelity peaked at the 0.5 weighting in all three random environments and the first cluttered environment, and at the 0.25 weighting in the two remaining cluttered environments. In the first and third paths of the random environment all three weightings performed statistically similarly to implicit communication, with the Mann-Whitney U tests showing no significant difference, indicating the implicit component reduced the error present in the hybrid system's performance and improved path fidelity.

7.4 Conclusions

This chapter presents a hybrid system that combines the explicit and implicit strategies described in Chapter 4 into one system using a weighted sum, enabling two robots to continuously communicate with a combination of explicit and implicit communication whilst manipulating objects through the four experimental environments employed throughout this thesis.

This chapter then investigated the performance of the weighted sum hybrid system that combined explicit and implicit communication between two robots in an object manipulation task, and compared this performance to the performance of the two forms of communication when applied in isolation. The hybrid system was tested in four different environmental settings by measuring the metrics task completion, time taken, total distance travelled by the object, maximum displacement of the object and path fidelity.

The null hypothesis stated at the beginning of this chapter that: "The change in weighting in the weighted sum hybrid system that combines explicit and implicit communication has no effect on performance". Mann-Whitney U tests were conducted throughout the analysis of the hybrid system to determine statistical similarity. Out of 120 statistical tests comparing the hybrid system to the explicit communication strategy, only 19 tests showed no significant difference between data sets. For the implicit strategy, only 38 out of 120 tests showed no significant difference. As the majority of the statistical tests show a significant difference, the null hypothesis must be rejected.

No weighting in the hybrid system consistently outperformed either strategy in any metric, so it cannot be said that the combined system is inherently better than either strategy working in isolation. However, what can be observed is that the hybrid system offers a trade-off between metrics and capitalises on advantages of both systems.

It is therefore possible to identify particular weightings that offer the best compromise of performance. This differs between environments due to the nature of the respective path following algorithms.

For the line following environments, it can be identified that a weighting of 0.75 offers the best compromise of performance when compared to the explicit and implicit strategies working in isolation. The highest task completion percentages were observed for this weighting across all paths compared to the other two weightings.

Regarding time taken to complete the task, the 0.75 weighting offered the fastest completion time out of the three weightings. It had no significant difference to the implicit strategy in the second path, which has been identified as the fastest strategy out of explicit and implicit. The hybrid system with a weighting of 0.75 was within 15 seconds of the implicit strategy for the other two paths.

The 0.75 weighting also provided the shortest total distance that the object travelled out of all the weightings. It had no significant difference to the explicit or implicit strategies for the first path, and was within 0.04m of the implicit strategy for the other two paths, where the implicit strategy was shown to be the most efficient strategy in isolation for this metric in Chapter 4.

For maximum displacement, whilst the 0.75 weighting was not the best performing weighting across all three paths in this environment, the increase in displacement for this weighting was marginal (0.001m) when compared to the better performing weightings. Since the difference was marginal a trade-off can be justified for this metric in order to capitalise on the high performance of the 0.75 weighting in other metrics.

Finally, in terms of path fidelity, the 0.75 weighting offered the best path fidelity out of the other weightings. There was no significant difference to the explicit communication performance in two out of three paths, wherein explicit communication had the highest path fidelity out of the full explicit and implicit strategies. Thus similar performance to explicit communication for this metric can be statistically guaranteed.

For the path planning environments, a weighting of 0.25 was identified to offer the best compromise. This strategy achieved 100% task completion across all path planning environments, which was the same as the other two weightings.

In terms of time taken for the hybrid system to complete the task, a weighting of 0.25 had a statistically similar performance to the fastest strategy, the implicit strategy, in three out of seven statistical tests. Whilst the 0.5 and 0.75 weightings show no significant difference to implicit communication across all seven path planning paths, the 0.25 weighting proves to be a better compromise for path fidelity, total distance travelled and maximum displacement for a trade-off of a maximum of 8 seconds time difference.

The 0.25 weighting offers the shortest total distance travelled across all weightings in the hybrid system and both strategies used in isolation. Up to a 0.2m decrease was observed compared to the explicit strategy, and up to a 0.15m decrease was observed compared to the implicit strategy.

For the maximum displacement of the object during task execution, the 0.25 weighting offered the smallest value out of all three weightings in the hybrid system. Whilst the value was still higher than that of the explicit strategy used in isolation, it still offered the best compromise out of the three weightings.

Finally, for path fidelity, the 0.25 weighting offered the highest path fidelity out of all three weightings, and the two communication strategies used in isolation. Up to a 20% increase in path fidelity was observed in the randomly generated environments and up to a 10% increase was observed in the cluttered environments.

To conclude, the hybrid system's performance lies, on average, on a scale between the explicit strategy and implicit strategy as weighting increases. Out-performance of the two original strategies is observed in the path planning environments in both path fidelity and total distance travelled by the object. A weighting of 0.75 in the line following environment, and a weighting of 0.25 in the path planning environments have been identified as the weightings that capitalise on the most metrics and provide the best compromise of performance in their respective environments. Table 7.2 summarises the conclusions drawn here in a matrix, showing which weighting has the best performance for each design requirement across all environments.

The evaluation of the hybrid system provided here is built on in the next chapter, Chapter 8, where the hybrid system's performance is tested with different sized and shaped objects.

Table 7.2: Performance Profiles of the Hybrid System in Simple Object Manipulation Tasks

	Reliability	Efficiency		Smoothness	
	Reliable task completion	Shortest completion time	Shortest distance travelled by object	Minimum object displacement	Strongest path fidelity
Line Following	0.75	0.75	0.75	0.5	0.75
Simple Environment	any	0.75	0.25 / 0.75	0.5	0.5
Cluttered Environment	any	0.75	0.25	0.25	0.25
Randomly Generated Environment	any	0.75	0.25	0.5	0.5

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Chapter 8

Hybrid System with Objects of Different Size and Shape

In real life applications in environments such as automated warehouses, robots need to be able to manipulate a wide range of objects that differ in size and morphology. In order to fully evaluate the performance of the hybrid system for such use cases, and to conduct a thorough comparison between the hybrid system and explicit and implicit communication when operating in isolation, it is essential to test the performance of the hybrid system with different object types.

An analysis of the hybrid system's consistency in performance with different object types will provide further evidence of whether the system capitalises on the advantages of the two individual communication strategies, and whether any consistency in performance shown by the two strategies in Chapter 5 is preserved in the hybrid system, or even outperformed.

This chapter describes a series of experiments that investigate how the hybrid system handled objects of different size and shape within the experimental set ups employed throughout this thesis.

The objects used in these experiments are the same objects described in Section 3.4 of Chapter 3, and the same as those used in Chapter 5.

The only modifications made to the robot configuration were the size and shape of the object, and the values for object mass and moments of inertia for each object. The mass and inertia values for each object type were identical to those used for the corresponding objects in Chapter 5.

The performance of each weighting of the hybrid system with different sized and shaped objects was compared to its performance with the original object.

8.1 Size

When investigating the performance of the hybrid system in relation to object size, the same object sizes were used as described in Subsection 3.4.1 in Chapter 3.

The null hypothesis used to analyse the hybrid system's performance with different object sizes was as follows:

Null Hypothesis H_0: The change in size of object has no effect on the system completing the task. There is no statistical difference between the performance of the hybrid system with the new object size and the performance of the system with the original object size (rejected with a 95% tolerance).

This was formulated under the same expectation from Chapter 5 that the object size should have no effect on performance as the object is attached to the robots in such a way that movement of the robots is unimpeded by object morphology.

In addition, as the hybrid system is provided with the mass of the object and the moments of inertia prior to the task commencing it has the object dependent information to calculate necessary wheels speeds to manipulate the new object size.

8.2 Shape

When investigating the performance of the hybrid system in relation with different object shapes, the same object shapes were used as described in Subsection 3.4.2 in Chapter 3.

The null hypothesis used to analyse the strategies' performance with different object shapes was as follows:

Null Hypothesis H_0: The change in shape of object has no effect on the hybrid system completing the task. There is no statistical difference between the performance of the hybrid system with the new object shape and the performance of the system with the original object size (rejected with a 95% tolerance).

This was formulated under the expectation that the object shape should have no effect on performance, as the hybrid system does not require the dimensions of the object in order to calculate desired wheel speeds and direction, and the Follower is again provided with the mass of the object and the moments of inertia prior to the task commencing to calculate the necessary wheels speeds to manipulate the new object shape. Additionally, as was the case with object size, the object is attached to the robots in a way independent of the shape of the object.

8.3 Results

The same metrics were used to evaluate the performance of the hybrid system with different object sizes and shapes as were used in Chapter 7.2. The results for the fully weighted hybrid system from Chapter 5 are also included for comparison.

Some graphical results have been included within this chapter, to visually support the analysis of the results presented here. The results for the hybrid system to complete the task with different combination weightings for the medium object can be seen within this chapter in Figure 8.1 for the line following environment and Figure 8.2 for the random environment. The results for the cuboid can be found in Figure 8.3 for the line following environment and Figure 8.4 for the random environment

The remaining graphs depicting the performance for the hybrid system can be found in the appendices, in Section G.1 for different object sizes and in Section G.2 for different object shapes.

8.3.1 Reliability

Task completion was measured to explore the reliability of the hybrid system.

Task Completion

The hybrid system achieved 100% task completion across all three randomly generated environments for all weightings when manipulating the medium and large objects, for all object shapes in the first and second paths of the line following environment and randomly generated environments and for third path in the cluttered environment. It also achieved 100% task completion for all weightings and object types in the simple environment. The hybrid system proved less reliable in the line following and cluttered environments for different sized objects, and in the third paths for the line following, randomly generated and cluttered environments and the first path of the cluttered environment for different shaped objects. The worst performance was observed with the Cylinder in the second cluttered environment, which had 0% task completion across all weightings.

The task completion percentages for the hybrid system manipulating different sized objects in the line following and cluttered environments can be found in the appendices, in Tables H.1 and H.2, respectively.

The task completion percentages for different shaped objects, can be found in the appendices, in Table H.3 for the line following environment, Table H.4 for the cluttered environment and Table H.5 for the randomly generated environment.

In all tables, the results for the hybrid system's performance with the original object for a given weighting, and the results for the fully weighted systems with different object sizes from Chapter 5 are provided for comparison.

Similar to the performance of explicit and implicit communication manipulating different objects in isolation, percentage task completion in the hybrid system was affected by object size. In environments with sharp turns, such as the third path in the line following environment and the second path in the cluttered environment, as object size increased, task completion across the weightings was less than that for the original object. Additionally, similar behaviour observed in Chapter 7.2, wherein certain weightings in the line following environment would have lower task completion percentages due to large corrective movements pulling the Leader's sensors off the path, combined with the behaviour seen with larger objects to create substantially lower task completion percentages. A particularly large overshoot was observed for the Medium object in particular, where the 0.5 weighting only achieved a task completion percentage of 27% compared to a percentage of 57%. This is viewable in Video 5a in Appendix B.

With the exception of the paths that have previously known to affect task completion with different object types, the hybrid system proved consistent for at least seven out of ten paths for the different sized objects, and for at least four of ten paths for different shaped objects. Where it achieved the same task completion as the hybrid system with the original object.

8.3.2 Efficiency

The two metrics used to gain an understanding of the efficiency of the hybrid system when manipulating different object shapes and sizes were time taken to complete the task and total distance travelled by the object. Time taken was determined as the simulation time recorded when the Leader logged the task as complete.

Total distance travelled by the object was calculated by performing a summation on the distances between consecutive x and y coordinates in the Follower's logged position data.

Time Taken

The results for time taken to complete the task for different sized objects can be seen in Figures G.1 and G.3 for the simple environment, Figures 8.1 and G.4 for the line following environment, Figures G.2 and G.5 for the cluttered environment and Figures 8.2 and G.6 for the random environment.

The results for time taken to complete the task for different shaped objects can be seen in Figures G.7, G.9 and G.13 for the simple environment, Figures 8.3, G.10 and G.14 for the line following environment, Figures G.8, G.11 and G.15 for the cluttered environment and 8.4, G.12 and G.16 for the random environment.

The numerical results for time taken for the different sized and shaped objects in the four different environments can be seen in Sections H.2.1 and H.2.2, respectively.

Time taken to complete the task was the metric that the hybrid system proved to be the most consistent for different object types. For object sizes, the hybrid system showed no significant difference across all weightings in the first and second path of the random environment and the first path of the cluttered environment, and showed no significant difference for the 0.5 and 0.75 weightings in the remaining random path. In the simple environment, the weightings 0.25 and 0.75 showed no statistical difference to the hybrid system with the original object. For different object shapes, the hybrid system showed no significant difference across all weightings in the second random environment when manipulating the cuboid and cylinder, and no significant difference across the majority of the weightings in the random, cluttered and simple environments.

In cases where results differed, the difference could be attributed to the correlation observed between time taken and task completion. For example in the first and second paths in the line following environments, the time taken to complete the task when manipulating different object sizes and shapes was found to be less than for the original object across all weightings of the hybrid system. It can also be observed that the task completion for different objects was higher across all weightings than for the original system, thus as the robots were not getting stuck or veering off the path and completing the task with a completion percentage of 100%, the mean time taken was higher. Conversely in the second path of the cluttered environment, the hybrid system had completion times of over 100 seconds more than for the original system across all weightings. This is related to the poor task completion observed in this path, as the increased offset error in the system caused by the length of the cuboid caused the robots to struggle with the corner in the top right hand corner of the arena, consistent with the behaviour observed in the explicit and implicit strategies.

Overall, 61.67% of statistical tests across all paths and weightings indicated consistency in performance with different object sizes for the metric of time taken to complete the task. This was more consistent than the explicit communication strategy working in isolation, which only showed significant difference in 25% of all statistical tests. The hybrid system was less consistent than the implicit system working in isolation, which showed significant difference in 80% of all statistical tests.

For different object shapes, 50.57% of statistical tests showed no significant difference across all weights between the hybrid system manipulating different objects and the hybrid system manipulating the original object. The hybrid system again outperformed the explicit strategy working in isolation, where only 30% of tests showed no significant difference, but again the implicit strategy in isolation proved to be the most consistent, with 62.07% of all statistical tests showing consistency in performance with different object shapes for the completion time metric. Similar to the results found for path fidelity, the hybrid system is more consistent with different object types than explicit communication operating alone.

In terms of individual weightings, the 0.75 weighting showed the most consistency in performance in time taken across all object types. For object sizes, 13 out of 20 tests for the 0.75 weighting showed no significant difference across the two object sizes. This weighting was more consistent than the explicit communication working in isolation, and close to the implicit communication's consistency. The other two weightings were close behind each with 12 out of 20 tests showing no significant difference.

For different object shapes, the 0.75 weighting showed consistency in performance in 20 out of 29 tests, which was more consistent than either communication type operating in isolation. The second most consistent weighting to object type for the time taken metric was 0.25, which showed no significant difference for 17 out of 29 tests and was more consistent than explicit communication in isolation, and similar in consistency to implicit communication.

Total Distance Travelled

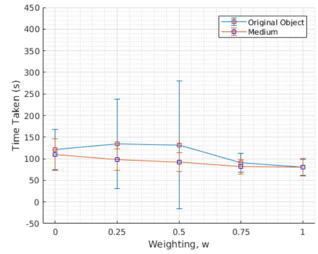
The results for total distance travelled by the object during task execution for different sized objects can be seen in Figures G.1 and G.3 for the simple environment, Figures 8.1 and G.4 for the line following environment, Figures G.2 and G.5 for the cluttered environment and Figures 8.2 and G.6 for the random environment.

The results for total distance travelled by the object during task execution for different shaped objects can be seen in in Figures G.7, G.9 and G.13 for the simple environment, Figures 8.3, G.10 and G.14 for the line following environment, Figures G.8, G.11 and G.15 for the cluttered environment and 8.4, G.12 and G.16 for the random environment.

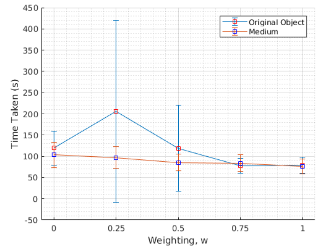
The numerical results for total distance travelled for the different sized and shaped objects in the four different environments can be seen in Sections H.3.1 and H.3.2, respectively.

When analysing consistency in performance with different object sizes, the hybrid system was observed to not have consistent performance. Statistical tests for all three weightings in the medium object showed significant difference when compared to their respective performance with the original object, and only seven tests out of of 30 showed no significant difference for the large object. For object shapes, whilst the hybrid system showed consistency in performance with different object types in the simple environment, only 12 out of the remaining 78 tests showed significant difference across all weightings for the three object types in the line following, random and cluttered environments.

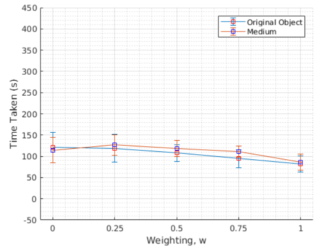
In the line following environment, the statistical difference was due to a large decrease in total distance travelled between the hybrid system manipulating the different object sizes and the original object, which at it's highest was a difference of 0.99m for the 0.25 weighting with the medium object in the second path. This again can be correlated to task completion. The hybrid system manipulating the original object had lower task completion percentages



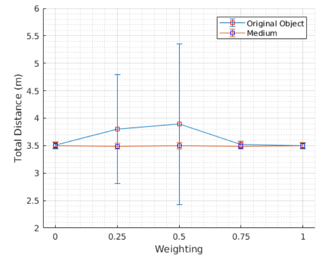
(a) Path 1: Mean Time Taken and Standard Deviation



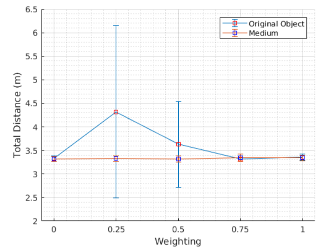
(b) Path 2: Mean Time Taken and Standard Deviation



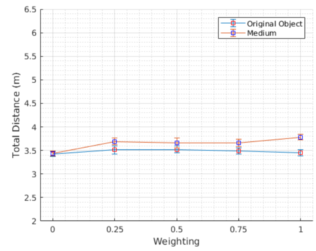
(c) Path 3: Mean Time Taken and Standard Deviation



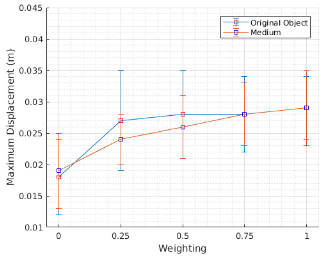
(d) Path 1: Mean Total Distance Travelled and Standard Deviation



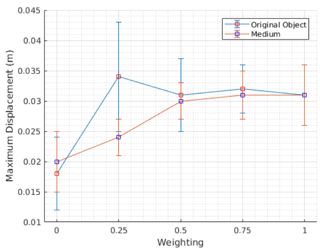
(e) Path 2: Mean Total Distance Travelled and Standard Deviation



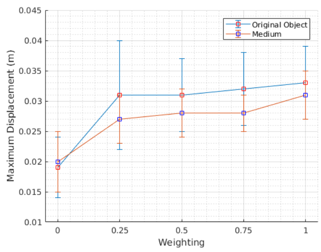
(f) Path 3: Mean Total Distance Travelled and Standard Deviation



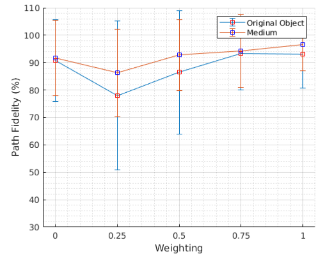
(g) Path 1: Mean Maximum Displacement and Standard Deviation



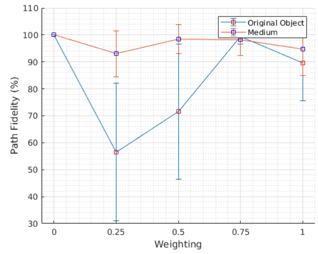
(h) Path 2: Mean Maximum Displacement and Standard Deviation



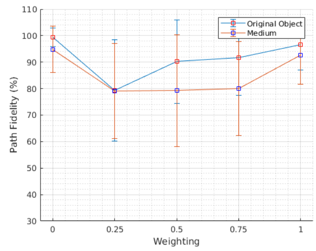
(i) Path 3: Mean Maximum Displacement and Standard Deviation



(j) Path 1: Mean Percentage Path Fidelity and Standard Deviation

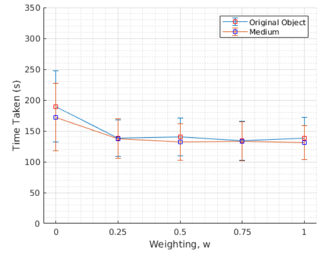


(k) Path 2: Mean Percentage Path Fidelity and Standard Deviation

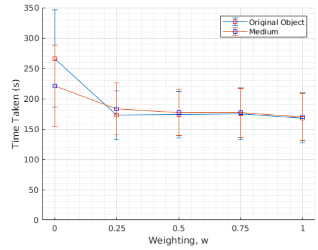


(l) Path 3: Mean Percentage Path Fidelity and Standard Deviation

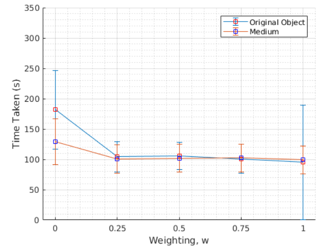
Figure 8.1: Performance for the Hybrid System across all design requirement metrics in the Line Following Environmental Setup for the Medium Object



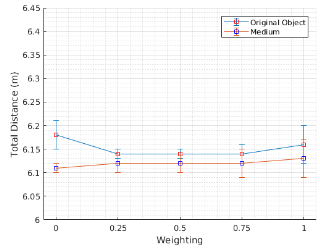
(a) Path 1: Mean Time Taken and Standard Deviation



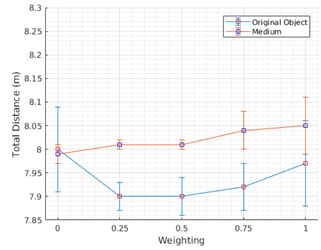
(b) Path 2: Mean Time Taken and Standard Deviation



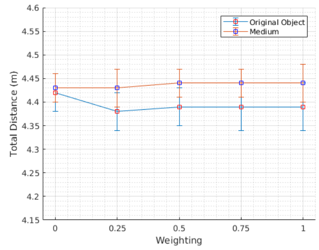
(c) Path 3: Mean Time Taken and Standard Deviation



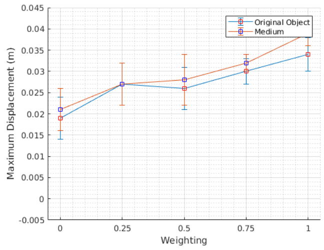
(d) Path 1: Mean Total Distance Travelled and Standard Deviation



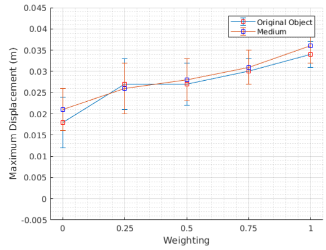
(e) Path 2: Mean Total Distance Travelled and Standard Deviation



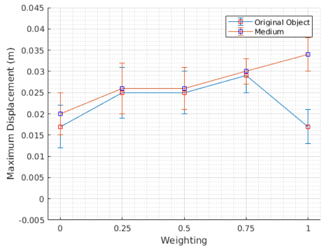
(f) Path 3: Mean Total Distance Travelled and Standard Deviation



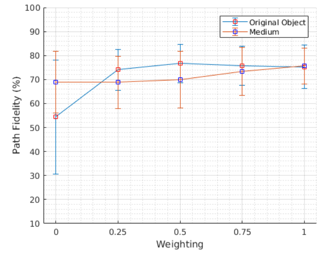
(g) Path 1: Mean Maximum Displacement and Standard Deviation



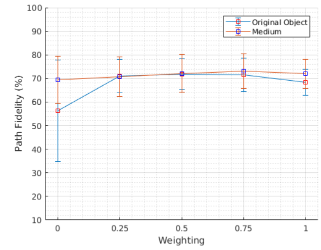
(h) Path 2: Mean Maximum Displacement and Standard Deviation



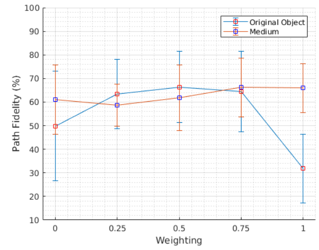
(i) Path 3: Mean Maximum Displacement and Standard Deviation



(j) Path 1: Mean Percentage Path Fidelity and Standard Deviation

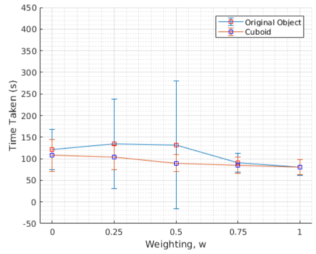


(k) Path 2: Mean Percentage Path Fidelity and Standard Deviation

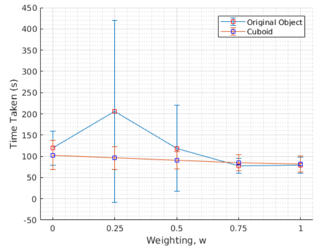


(l) Path 3: Mean Percentage Path Fidelity and Standard Deviation

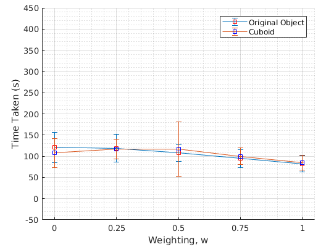
Figure 8.2: Performance for the Hybrid System across all design requirement metrics in the Randomly Generated Environments for the Medium Object



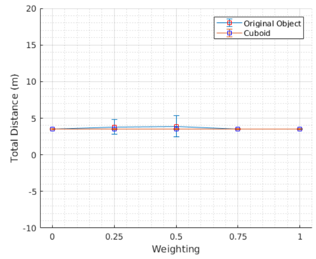
(a) Path 1: Mean Time Taken and Standard Deviation



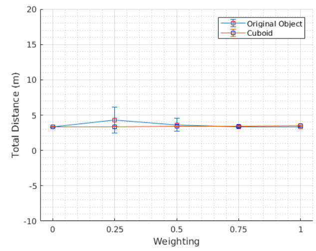
(b) Path 2: Mean Time Taken and Standard Deviation



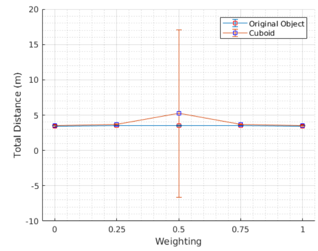
(c) Path 3: Mean Time Taken and Standard Deviation



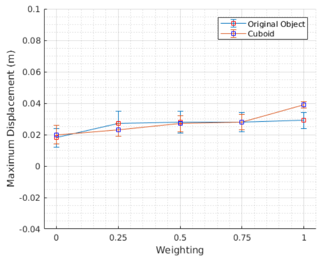
(d) Path 1: Mean Total Distance Travelled and Standard Deviation



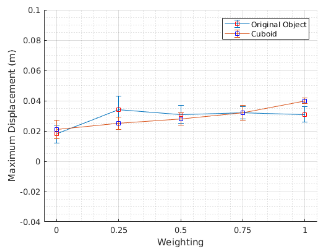
(e) Path 2: Mean Total Distance Travelled and Standard Deviation



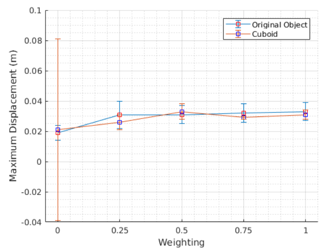
(f) Path 3: Mean Total Distance Travelled and Standard Deviation



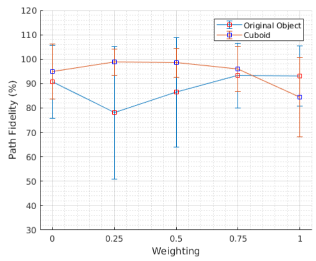
(g) Path 1: Mean Maximum Displacement and Standard Deviation



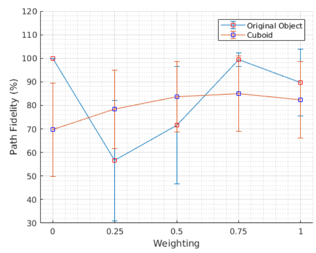
(h) Path 2: Mean Maximum Displacement and Standard Deviation



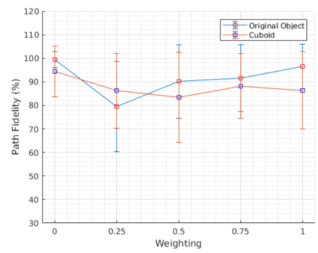
(i) Path 3: Mean Maximum Displacement and Standard Deviation



(j) Path 1: Mean Percentage Path Fidelity and Standard Deviation

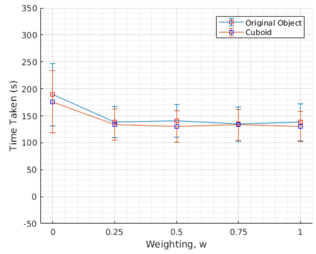


(k) Path 2: Mean Percentage Path Fidelity and Standard Deviation

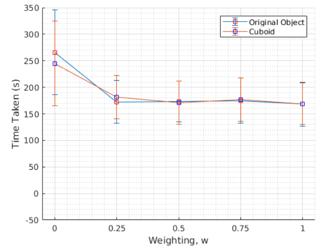


(l) Path 3: Mean Percentage Path Fidelity and Standard Deviation

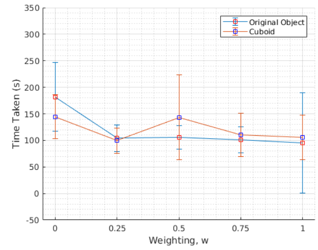
Figure 8.3: Performance for the Hybrid System across all design requirement metrics in the Line Following Environmental Setup for the Cuboid



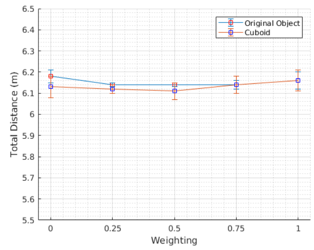
(a) Path 1: Mean Time Taken and Standard Deviation



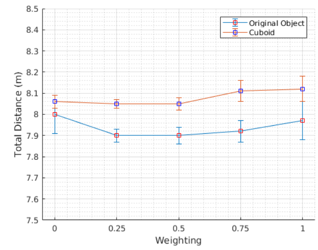
(b) Path 2: Mean Time Taken and Standard Deviation



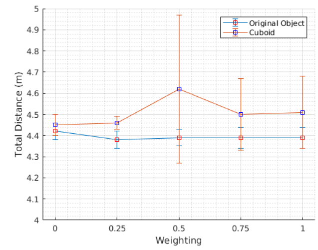
(c) Path 3: Mean Time Taken and Standard Deviation



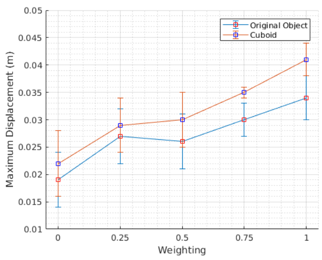
(d) Path 1: Mean Total Distance Travelled and Standard Deviation



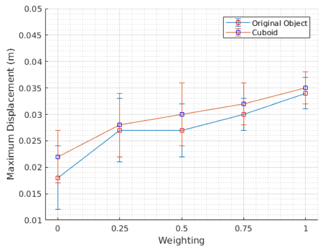
(e) Path 2: Mean Total Distance Travelled and Standard Deviation



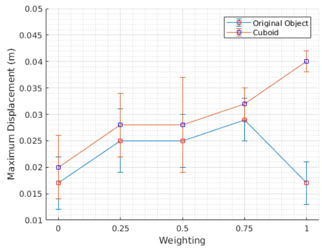
(f) Path 3: Mean Total Distance Travelled and Standard Deviation



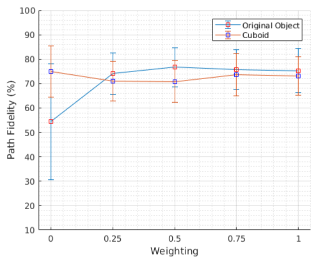
(g) Path 1: Mean Maximum Displacement and Standard Deviation



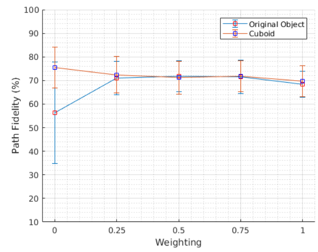
(h) Path 2: Mean Maximum Displacement and Standard Deviation



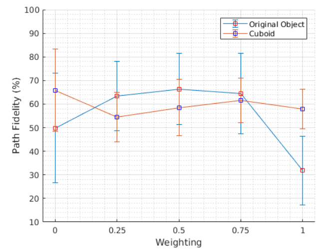
(i) Path 3: Mean Maximum Displacement and Standard Deviation



(j) Path 1: Mean Percentage Path Fidelity and Standard Deviation



(k) Path 2: Mean Percentage Path Fidelity and Standard Deviation



(l) Path 3: Mean Percentage Path Fidelity and Standard Deviation

Figure 8.4: Performance for the Hybrid System across all design requirement metrics in the Randomly Generated Environments for the Cuboid

across the weightings for the three line following paths, which as discussed in Chapter 7.2, can contribute to larger total distance travelled means. For different object sizes the hybrid system had higher task completion percentages and did not struggle with those paths, thus contributing to a lower total distance travelled across the weightings.

In the cluttered environment, an increase in total distance travelled was observed in environments where the hybrid system struggled with task completion, particularly in the second path. This result is consistent with previously identified behaviour.

Overall, regarding consistency in performance in the total distance travelled for object sizes, 16.67% of statistical tests with the hybrid system showed no significant difference, which proved to be less consistent than both communication strategies working in isolation, where explicit communication showed consistency in 45% of the tests, and implicit communication showed consistency in 20%.

For object shapes, 21.84% of statistical tests showed no significant different when comparing the total distance travelled by the hybrid system manipulating different shaped objects compared to the same system manipulating the original object. This was more consistent than the implicit strategy working in isolation, which showed no significant difference in 17.24% of statistical tests. However, the explicit strategy in isolation was more consistent, with 37.93% of tests showing no significant difference.

For individual weightings, although the consistency in performance shown was minimal, the 0.75 weighting showed the most consistency in total distance travelled, with 12 out of 49 tests showing no significant difference across all object sizes and shapes, which was more consistent than the implicit communication operating in isolation.

8.3.3 Smoothness

To test the hybrid system for its performance with different object types, the design requirement 'Smoothness' was measured by the maximum displacement of object during task execution and path fidelity of the robots to the pre-determined paths.

Maximum Displacement of Object

The results for the maximum displacement of object during task execution for different sized objects can be seen in Figures G.1 and G.3 for the simple environment, Figures 8.1 and G.4 for the line following environment, Figures G.2 and G.5 for the cluttered environment and Figures 8.2 and G.6 for the random environment.

The results for the maximum displacement of object during task execution for different shaped objects can be seen in in Figures G.7, G.9 and G.13 for the simple environment, Figures 8.3, G.10 and G.14 for the line following environment, Figures G.8, G.11 and G.15 for the cluttered environment and 8.4, G.12 and G.16 for the random environment.

The numerical results for maximum displacement for the different sized and shaped objects in the four different environments can be seen in Sections H.4.1 and H.4.2, respectively.

When considering object sizes, the hybrid system showed consistency in performance with the medium object size for maximum displacement of the object during task execution. The hybrid system also showed no significant difference when compared to its performance with the original object for the first path of the line following environment and the second path of the randomly generated environment. The 0.75 weighting showed no significant difference in the simple and cluttered environments, and for the majority of the paths in the line following and random environments. The 0.75 weighting showed similar consistency in performance for the large object, with 6 out of ten tests showing no significant difference for the weighting's performance in the different paths. This resulted in the hybrid system showing more consistency than either strategy working in isolation. Overall, the hybrid strategy showed no significant difference in 50% of statistical tests comparing its performance with different object sizes to the original object. The explicit and implicit strategies when working in isolation only showed significant difference in 20% and 40% of tests, respectively. This again shows that a system that combines explicit and implicit communication has more consistent performance than a system that only employs one form in isolation.

For object shapes, a consistency in performance result was achieved that was consistent with the performance of both strategies working in isolation: 25.29% of Mann-Whitney U tests showed no significant difference across all weightings in the hybrid system. Explicit communication and implicit communication both showed no significant difference in 24.14% of all statistical tests comparing their performance with different objects to their performance with the original object.

The 0.75 weighting was the most consistent weighting for different object types, with 14 out of 20 tests showing no significant difference, which considerably outperformed the explicit and implicit strategies. For object shapes, the 0.25 weighting showed the most consistency in performance, with 10 out of 29 tests showing no significant difference, the 0.75 weighting was close behind with 9 out of 29 tests showing no significant difference, and both weightings were more consistent than either communication strategy operating in isolation.

Path Fidelity

The results for path fidelity for different sized objects can be seen in Figures G.1 and G.3 for the simple environment, Figures 8.1 and G.4 for the line following environment, Figures G.2 and G.5 for the cluttered environment and Figures 8.2 and G.6 for the random environment.

The results for path fidelity for different shaped objects can be seen in Figures G.7, G.9 and G.13 for the simple environment, Figures 8.3, G.10 and G.14 for the line following environment, Figures G.8, G.11 and G.15 for the cluttered environment and 8.4, G.12 and G.16 for the random environment.

The numerical results for path fidelity for the different sized and shaped objects in the four different environments can be seen in Sections H.5.1 and H.5.2, respectively.

In the line following environment, the hybrid system showed consistency in performance with different object sizes for the medium object in the first path. It consistency in performance with different to object shapes for the cuboid in the third path with all three statistical tests for the 0.25, 0.5 and 0.75 weightings showing no significant difference in performance between the two objects and the original object. The hybrid system showed significant difference compared to the original object and the large object, the cylinder and the sphere. In the second path this was due to the path fidelity for the hybrid system with the different sized and shaped objects being higher than that for the original object. This higher path fidelity is correlated to the fact that the hybrid system had a higher task completion with the different objects across the weightings in this path.

The hybrid system showed consistency in performance in the simple environment for the medium object and the sphere, and for the cuboid in two paths in the cluttered environment and one path in the random environment. For the majority of the other paths in the random and cluttered environments and objects of different size, whilst the results were significantly different it can be observed in Figures G.2, G.5, 8.2 and G.6 that the path fidelity results are close together for the original object and the different sized object. For object shapes in the cluttered and random environments, it can be observed the path fidelity is lower for different object shapes than for the original object, which is consistent with the behaviour of the implicit communication with different object shapes, indicating that the implicit component of the hybrid system affects the system's performance with different object shapes.

When considering performance with different object in path fidelity overall, 36.67% of statistical tests for all three weightings over the ten paths showed no statistical difference for objects of different sizes. In comparison, the explicit and implicit strategies only showed consistency in performance for 20% of statistical tests for different sized objects when employed in isolation. For object shape, 25.29% of statistical tests across all weightings showed no significant difference, compared to 10.34% for the explicit strategy and 31.03% for the implicit strategy. This shows that the hybrid system employing a combination of explicit and implicit communication is more consistent with different objects for path fidelity than explicit communication operating alone, and is more consistent than either communication type operating alone for different object sizes.

In terms of individual weightings, the 0.25 weighting showed the most consistency in performance in path fidelity for different object shapes with 11 out of 29 statistical tests showing no significant difference across the three different shaped objects when compared to the performance of the hybrid system at the same weighting with the original object. This weighting was more consistent than either communication operating in isolation. The 0.75 weighting showed the second most consistency with 9 out of 29 statistical tests showing no significant difference, offering similar performance to implicit communication operating in isolation. For object sizes, the 0.5 weighting showed the most consistency in performance with 8 out of 20 Mann-Whitney U tests showing no significant difference, the 0.25 and 0.75 weightings showed similar performance with seven out of 20 tests showing no significant difference each. All three of these weightings showed more consistency in performance with different object sizes than either explicit or implicit communication operating alone.

8.4 Conclusions

This chapter investigated the performance of the hybrid system that combines explicit and implicit communication between two robots in a simple object manipulation task, when manipulating different object sizes and shapes. It evaluated the consistency in performance by analysing the statistically significant difference between metrics measured in Chapter 7.2 and the same metrics in experiments using different sized and shaped objects. The consistency in performance demonstrated by the hybrid system was also compared to the consistency in performance demonstrated by explicit and implicit communication when used in isolation, detailed in Chapter 5.

Results showed that the weighted hybrid system's performance remained consistent with different object types in the time taken metric, and remained consistent with object sizes for the maximum displacement of the the object during task execution metric, with the majority of statistical tests conducted for these metrics showing no significant difference. The hybrid system showed more consistency in performance with different object sizes than both communication strategies for the metrics of path fidelity and maximum displacement, and showed more consistency in performance than the explicit strategy in isolation for the time taken metric. These findings are consistent with the conclusions made in Chapter 7.2, where the combination of communication strategies in the hybrid system was found to reduce error in the individual strategies and improve performance in metrics like path fidelity.

Across all four metrics, the hybrid system showed consistent performance with different object sizes in 99 out of 240 statistical tests. For object shape, the hybrid system showed consistent performance in 107 out of 324. Since the majority of Mann-Whitney U tests showed significant difference, the null hypotheses must thus be rejected.

For metrics where less consistent performance was observed, the behaviour affecting consistency matched the hybrid system's performance with the original object, and was consistent with the implicit and explicit strategies' performance when manipulating different objects. The task completion, time taken and total distance metrics were linked together, where poor performance in task completion lead to longer time taken and total distance travelled metrics as the robots struggled to complete the task in some environments, particularly the third path in the line following environment, and the second path in the cluttered environment. The increased offset error for larger object sizes that affected performance in Chapter 5, also affected performance in the hybrid system. The offset error must therefore also be taken into account when employing the hybrid system in environments that have tight corners or trajectories that lay close to obstacles or arena walls.

As previously mentioned in Chapter 4, when discussing the offset error, it is important to state that this error is linked to the configuration of the robots. As the Leader is situated at the back of the configuration it translates information that are related to it's position earlier on the path than the Follower, resulting in a delay of relevant positional information. This means the results presented in this chapter, particularly for task completion and path fidelity, are affected by the robot architecture. Chapter 10 discusses how different robot architectures can be explored to explore this dependence.

Whilst the hybrid system did not have consistent performance across all weightings, the most consistent weightings can be identified that provide the best performance across the measured metrics. The 0.75 weighting showed to have the best performance for manipulating different object types. The weighting had consistent performance with different object types in time taken to complete the task, and with different object sizes in the maximum displacement of objects. Out of all statistical tests comparing the performance of the 0.75 weighting with different object types to its performance with the original object, 84 out of 188 tests showed no significant difference. This can be easily consolidated into our understanding of the hybrid system. As discussed in Chapter 7.2, the 0.75 weighting is known to perform similarly to implicit communication, due to the implicit component being close to the fully weighted value towards implicit communication. And as discussed in Chapter 5, the implicit strategy proved to be the most consistent in the time taken and maximum displacement metric. When comparing the performance of the 0.75 weighting to the implicit communication in operating different object types, 54 out of 116 tests showed no significant difference for different object shapes, and 37 out of 80 tests showed no significant difference for different object sizes, indicating the higher weighting has a similar performance profile to implicit communication operating in isolation.

The second most consistent weighting was the 0.25 weighting, which showed no significant difference in 71 out of 188 statistical tests across all four metrics for different object types. The 0.25 weighting was shown to be consistent in performance for the time taken metric for all object types, as equally consistent as the 0.75 weighting for path fidelity for all object types, and more consistent than the 0.75 weighting for maximum displacement of the object when manipulating different object shapes.

In Chapter 7.2 it was concluded that the 0.75 weighting offered the best performance in the line following environments and a 0.25 weighting offered the best performance in the path planning environments. Incorporating the results found in this chapter, the 0.75 weighting still proves to be the most attractive weighting for a high performing hybrid system in the line following environments, as it has been shown to be the most consistent with different object types. For the path planning environments it can still be argued that the 0.25 weighting offers the best compromise for a high performing hybrid system. Whilst the 0.75 weighting proved to be more consistent in performance in the path planning environments, the 0.25 weighting was the second most consistent, and its increased performance as described in Chapter 7.2 means it offers the best overall compromise on performance out of all three weightings in the path planning environments.

This chapter expands on the evaluation of a hybrid system that combines explicit and implicit communication in a hybrid system for object manipulation tasks between two robots. It can be concluded that whilst the general performance of the hybrid system lies, on average, on a scale between the performance of explicit and implicit strategy operating in isolation, the hybrid system offers better performance with different object shapes than a system that only employs one form of communication in isolation. This chapter also verifies that the 0.75 weighting has the best performance in the line following environment as it is also the weighting withthe most consistent performance when manipulating different object types. The 0.25 weighting offers the best compromise in performance out of the three weightings for all three path planning environments investigated in this work. Tables 8.1 and 8.2 summarise the conclusions drawn here in two matrices, showing which weighting has the best performance when manipulating different object types for each design requirement across all environments.

Table 8.1: Performance Profiles of the Hybrid System when Manipulating Different Sized Objects in Simple Object Manipulation Tasks

	Time Taken			Total Distance			Maximum Displacement			Path Fidelity		
	LF	SECE	RE	LF	SECE	RE	LF	SECE	RE	LF	SECE	RE
Medium	0.75	0.75	none	0.75	0.25	0.25	0.25	0.25	0.25	0.75	0.25/0.5	0.75
Large	0.75	0.75	0.75	0.5	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25

Table 8.2: Performance Profiles of the Hybrid System when Manipulating Different Shaped Objects in Simple Object Manipulation Tasks

	Time Taken			Total Distance			Maximum Displacement			Path Fidelity		
	LF	SECE	RE	LF	SECE	RE	LF	SECE	RE	LF	SECE	RE
Cuboid	0.75	0.75	0.5	0.25/0.75	0.25	0.25	0.25	0.25	0.25	0.75	0.25	0.75
Cylinder	0.75	none	0.5	0.25	0.25	0.25	0.25	0.25	0.25	0.75	0.25	0.25
Sphere	0.75	0.75	0.75	0.25/0.5	0.25	0.25	0.25	0.25	0.25	0.75	0.5	0.5

Chapter 9

Fault Tolerance of Hybrid System in Object Manipulation Tasks

The hypothesis of this thesis postulated that a hybrid system, which combined explicit and implicit communication, could capitalise on the advantages found in both communication strategies when operating alone. A valuable design requirement for the performance of the hybrid system is to be fault tolerant.

To provide greater understanding of the fault tolerance and robustness of the system, this chapter investigates how the system performs in the presence of simple faults that mimic realistic faults that could occur whilst operating in real life. It aims to demonstrate further that the hybrid system capitalises on the advantages of the individual strategies and to determine if the fault tolerance observed in Chapter 6 is conserved or outperformed.

The faults injected into the hybrid system are the same as those described in Section 3.5 of Chapter 3. As discussed in the experimental setup chapter, the robot controllers were only modified to inject the fault, no other modifications were made, and the physical robotic architecture remained the same.

The hybrid system was tested in all four environment types with the original object in the presence of one simple fault at the time, the results were statistically compared to the results of the hybrid system's performance in the presence of no faults.

9.1 Vision Sensor Fault

The null hypothesis used to analyse the hybrid system's fault tolerance and robustness to a vision sensor fault is as follows:

Null Hypothesis H_0: The presence of a vision sensor fault in one of the Leader's vision sensors has no effect on the hybrid system completing the task. There is no statistical difference between the performance of the hybrid system with a vision sensor fault and the performance of the strategy operating faultlessly (rejected with a 95% tolerance).

Similarly to in Chapter 6, the purpose of this null hypothesis is to use statistical tests to measure the fault tolerance and robustness of the strategies whilst manipulating an object across different environments. The robot controllers employed in the hybrid strategy do not attempt to determine and mitigate erroneous inputs, and thus assume faultless behaviour. It is therefore expected the hybrid system will behave similarly to the communication strategies when operating in isolation, and some negative impact on performance will be observed in the presence of a vision sensor fault.

Faults in the left or right sensors will impact performance the most as they will inhibit the hybrid system when attempting to make corrective movements to follow the path. This have the greatest impact on metrics such as task completion and path fidelity.

9.1.1 Expected Results

It is expected that the hybrid system will yield similar results to those discussed in Chapter 6, where faults were injected into the two independent strategies. As neither strategy demonstrated fault tolerance to vision sensor faults on the same side of the path direction, it is expected that the hybrid strategy will struggle in similar scenarios but show consistent behaviour on the other paths to the hybrid system when operating faultlessly.

9.2 Partial Motor Fault

The null hypothesis used to analyse the hybrid system's fault tolerance and robustness to a partial motor fault is as follows:

Null Hypothesis H_0: The presence of a partial motor fault in one of the Leader's wheels or one of the Follower's wheels has no effect on the hybrid system completing the task. There is no statistical difference between the performance of the hybrid system with a partial motor fault and the performance of the system operating faultlessly (rejected with a 95% tolerance).

Once again, this null hypothesis was formulated in order to use statistical tests to measure the fault tolerance and robustness of the hybrid system in simple object manipulation tasks. There is no fault-tolerance purposefully implemented in the system to identify or mitigate partial motor faults. It is expected the hybrid system's performance will be negatively impacted by a partial motor fault, in a similar manner to how the individual strategies' performance was impacted in Chapter 6, due to the increase in differential wheel speeds in the presence of a motor fault.

It is expected the metrics task completion, path fidelity and maximum displacement of object will be most impacted by partial motor faults.

9.2.1 Expected Results

9.3 Results

The metrics as shown in Table 3.4 in Chapter 4 were used to investigate the performance of the system in the presence of faults, in order to evaluate how fault tolerant and robust the communication strategies were in the four environments.

Mann-Whitney U tests were performed on the data set for the hybrid system performing with the original object in the presence of a fault and the data set for the original object in fault-less conditions used in Chapter 4 to reject or accept the null hypotheses formulated in this chapter.

Graphs showing the mean and standard deviation across all design requirement metrics for both communication strategies in the presence of faults can be found in Appendix I.

In all graphs of the results for vision sensor faults the labels 'O', 'VSL', 'VSM', and 'VSR' stand for Original, Vision Sensor Left, Vision Sensor Middle and Vision Sensor Right, respectively, and the numbers correspond to the path number. For partial motor faults the labels 'LL' and 'LR' stand for Leader Left and Leader Right, respectively, and the labels 'F1', 'F2' and 'F3' stand for 'Follower 1', 'Follower 2' and 'Follower 3', and reference which wheel has the partial motor fault.

9.3.1 Reliability

Reliability of the two communication strategies when performing in the presence of faults was evaluated by measuring task completion.

Task Completion

The percentage task completion for both strategies in the presence of vision sensor faults can be seen in Section J.1 in Appendix J. For partial motor faults, task completion results can be found in the same appendix, in Section J.2.1 and in Section J.2.2, for faults in leader's wheels and faults in follower's wheels, respectively.

Vision Sensor Faults

For a fault in the middle sensor, the hybrid system performed similarly to task completion in a faultless environment, which was consistent to the behaviour observed when comparing the two strategies performance in the presence of a middle sensor fault in Chapter 6. Zero task completion was observed in the third path in the presence of a left sensor fault across all weightings, which was consistent with the behaviour observed in both independent strategies as the left sensor was on the same side of the curve within the third path.

Interestingly, where zero percent task completion was also observed previously for the independent strategies, in the first path for the left sensor fault and in the second path for the right sensor fault, the hybrid system was able to complete the task across the three weightings, albeit with lower task completion percentages than observed in a faultless environment. When observing the simulations, it was evident that similar behaviour was occurring as observed when comparing fault tolerance in the independent strategies, in that task completion was being achieved by the robots coincidentally moving through the end zone, despite having veered off the path. For the 0.5 and 0.75 weightings, as viewable in videos 6a and 6b in Appendix B, this behaviour was very consistent with that observed in the implicit strategy operating in isolation, which is consistent with the findings in Chapters 7.2 and 8, that indicated that the performance of the hybrid system is essentially a linear scale between a fully explicit weighting and a fully implicit weighting.

For the 0.25 weighting in the first path and for a left vision sensor fault, viewable in video 6c in Appendix B, behaviour was observed where the robots veered off the path to the right and performed a circle in the lower left corner of the arena, for certain noise values the robots then crossed the path again, perform a corrective right turn and finish the task in the vicinity of the end zone, resulting in a small percentage of successful task completion. The same behaviour but in the opposite direction was observed for the second path in the presence of a right vision sensor.

This behaviour, whilst erroneous is consistent with our understanding of the hybrid system, in the for a weighting of 0.25, larger perturbations are difficult for the implicit strategy to mitigate as an error reduction negative feedback loop. As can be observed here, as weighting increases so to does the implicit component's ability to reduce error, changing the behaviour from a circle to veering off the path and colliding with the wall. It can be concluded that whilst task completion is technically non zero for weightings in the hybrid system for a left sensor fault on the first path, the behaviour observed during task execution is not desirable for an efficient, reliable task performance. These results thus support the observations made in Chapter 6 that the hybrid system is not fault tolerant to vision sensor faults that lie on the same side as the direction of the path's curve.

Significantly lower task completion was observed for the 0.25 and 0.5 weightings in the second path in the presence of a left vision sensor fault, and in the first path in the presence of a right sensor fault, which were inconsistent with both the performance of the hybrid system at those weightings in a faultless environment, and with the strategies operating independently in the presence of the same faults. Lower task completion was also observed across all weightings within the third path in the presence of a right sensor fault. This can be attributed to the fact that in the presence of no vision sensor faults the hybrid system is able to compensate for a perturbation by a corrective moment in the other direction, but in the presence of a vision sensor fault a corrective movement cannot be made, and for lower weightings the implicit component struggles to reduce this error.

Partial Motor Fault in the Leader's Wheels

For partial motor fault in the Leader's wheels, task completion was 100% across all weightings for the simple environment and the third random environment. Task completion was also 100% across all weightings in the third paths in the random and cluttered environment for a fault in the leader's right wheel. For all other environments, task completion was affected for the hybrid system when performing an object manipulation task in the presence partial motor faults in the either of the leader's wheels.

In the presence of a partial motor fault in the left wheel, the 0.75 percent weighting had the best performance out of all the weightings in the line following environment, which was consistent with behaviour observed in Chapter 7.2 for the hybrid system performing in the absence of any faults. However, in the second and third paths, task completion was still lower for the 0.75 weighting than either strategy performing in isolation.

When observing the strategies in the second line following path, the fully explicit strategy would demonstrate an oscillatory behaviour where the left wheel fault would cause the robots to drift to the left, which would then cause the leader to perform an over corrective movement to correct the drift, which would swing the robots to the right, causing the leader to perform an over corrective movement to the left to counteract it, where the left wheel fault would then cause a drift in the left direction and so on. Whilst this behaviour appeared erratic, as can be seen in Video 6d in Appendix B, the robots were still able to complete the task. For the hybrid system, this corrective movement would cause a large perturbation on the input for the negative feedback control loop of the follower, which at low weightings the system struggled to reduce. Furthermore, in the hybrid case the follower robot is applying wheel velocities so that it can continuously in both the x and y directions, when the leader performs a corrective movement in this instance, this perturbation can move the leader's sensors off of the path and cause the robots to veer off, as shown in Video 6e in Appendix B.

As weighting increases to 0.75, the hybrid systems ability to reduce error increases, as seen in Chapters 7.2 and 8, but as there is still an explicit component perturbations still occur, causing a lower task completion than implicit communication acting independently.

In the path planning environments, for a left wheel fault on the Leader robot, the 0.25 weighting demonstrated the best task completion in the second and third cluttered environments, outperforming either strategy operating in isolation. The 0.25 weighting also offered the best task completion in the third random environment, outperforming the explicit strategy and performing similarly to the implicit strategy.

In the third random environment and the first cluttered environment, low task completion was observed across all weightings for a left wheel fault in the leader robot, which was consistent with the low task completion observed in both strategies operating in isolation for these environments in the presence of the same fault.

In the presence of a partial motor fault in the right wheel, performance varied across weightings in the line following environment. The 0.25 weighting demonstrated higher task completion for the first and third paths. In the second path, the 0.75 weighting demonstrated higher task completion. In both the first and second path the best performing weightings were still outperformed by either strategy operating in isolation. When observing the simulations the same behaviour that affected task completion for a left wheel fault was observed but in the opposite direction, as the robots would veer off the path in the direction of the wheel differential caused by the wheel fault.

In the path planning environments, the 0.5 weighting achieved the best task completion out of all the weightings and either strategy operating in isolation, with the exception of the third random environment, where the 0.75 weighting achieved the best task completion.

Partial Motor Fault in the Follower's Wheels

Consistent with the behaviour observed in Chapter 6 when comparing the two strategies in isolation in the presence of the same faults, the hybrid system demonstrated considerable robustness for faults in the follower wheels.

Across all wheel types and across all weightings task completion was unaffected in the simple environment, in the random environments and in the second and third cluttered environments.

For a partial motor fault in wheel 1 of the follower, task completion was most affected out of all the follower wheel faults. The task completion increased as weighting increased with the 0.25 weighting recording the lowest completion percentage. Whilst this was a consistent trend to the one seen in Chapter 7.2, the presence of a fault in wheel 1 resulted in an even lower task completion across all weightings than it's faultless counterpart. Whilst the 0.75 weighting had the best task completion out of any weighting it was outperformed by both strategies operating in isolation. Out of the three line following environments the worst task completion was observed in the third path.

When observing the system within simulation at lower weightings like $w = 0.25$, the robots would exhibit large perturbations that would cause the robots to veer off the path, consistent with behaviour observed in Chapter 7.2. The introduction of a fault in wheel 1 however, reduced the speed the of velocity of that wheel, making the system behave more similarly to the explicit strategy, where only corrective movements in the left or right direction are made, this essentially emulated an increase in the explicit component, and increase in error for the implicit strategy to try to reduce. As the weighting towards implicit communication increased, the system's ability to reduce the error increased.

For the same wheel fault task completion was also affected in the first cluttered environment compared to the hybrid system's performance in the same environment in the absence of faults. However the hybrid system outperformed the explicit strategy's performance in the presence of the fault across all weightings, and the 0.5 and 0.75 weightings outperformed the implicit strategy.

For a partial motor fault in wheel 2 of the follower, task completion was observed to differ from the hybrid system's faultless performance in the line following environments again. However in this instance task completion was observed to be higher, in some cases only by 5%, such as in the first path for the 0.25 weighting, and in one case as much as 21%, for the 0.25 weighting in the second path.

As discussed in Chapter 7.2, it was found for high noise values in the line following environment a large perturbation would cause the robots to veer off the path and fail the task. In the presence of wheel faults in wheels 2 and 3, similar behaviour was observed for high values of noise. However whereas for some values of noise where the faultless system would veer off the path and fail the task, as seen in video 4b in Appendix B, the hybrid system would not have such a large perturbation and would complete the task successfully, as seen in video 6f. This behaviour can be attributed to the fact that a partial motor fault reduces the speed of the wheel and consequently the whole system, and thus reduces the size of the corrective movements that typically pull the robots off of the path, resulting in a smoother performance. This can be supported by the higher path fidelity observed in these instances as well.

Task completion was negatively impacted for the same fault in the first cluttered environment across all weightings, compared to the hybrid system's performance in the absence of faults. When observing the strategy it was evident the same behaviour was occurring as that observed in Chapter 6, where for low noise values injected into the system the robots would not reach the end zone before the leader set it's wheel velocities to zero, thus effectively completing the task but failing to signal it as complete and stop the simulation. This is viewable in Video 6h in Appendix B. However when comparing the performance of the faulty hybrid system and the fault strategies working in isolation, all weightings out performed the explicit strategy operating with the same fault. The 0.5 also outperformed the implicit strategy operating in isolation in the presence of the same fault.

In the case of a fault in wheel 3 of the follower similar behaviour was observed as for the wheel 2 fault. Higher task completion was again observed in the line following environments ranging from an increase of 3%, for the 0.25 weighting in the second line following path, to 25%, for the 0.5 weighting in the third line following path. This was consistent with the behaviour observed in the wheel 2 fault, and similar behaviour was observed in simulation, as can be seen in video 6g.

Task completion was also negatively impacted for the same fault in the first cluttered environment. However, all weightings outperformed either strategy when operating in isolation under the same fault. The 0.5 weighting demonstrated the highest task completion. This was again due to the behaviour previously observed where the robots would stop before they reached the end zone.

9.3.2 Efficiency

Efficiency of the strategies was measured by evaluating the time taken by the strategies to complete the task and the total distance travelled by the object during task execution.

Time Taken

The numerical results for the time taken to complete the task in seconds in the presence of vision sensor faults can be found in Section J.1 in Appendix J. For partial motor faults, task completion results can be found in the same appendix, in Section J.2.1 and in Section J.2.2, for faults in leader's wheels and faults in follower's wheels, respectively.

Vision Sensor Faults

Across all vision sensor faults, the 0.75 weighting showed the most robustness, with 3 out of 8 statistical tests showing no significant difference. However no single weighting demonstrated significant fault tolerance to vision sensor faults for the time taken metric.

Typically significant difference was attributed to the time taken for the hybrid system in the presence of fault being higher than that for the hybrid system in a faultless environment. This was also observed for weightings that showed lower task completion in the presence of a fault. For example, in the presence of a fault in the left sensor, time taken was higher across all weightings in the first path, as well as for the 0.25 and 0.5 weightings in the second path, which was consistent with behaviour observed in the strategies acting independently in the presence of the same fault.

Interestingly, a shorter time taken was observed across all weightings for a fault in the middle sensor, causing significant statistical difference. For the 0.75 weighting, although there was a significant difference the results were similar and within a few seconds of each other, for the 0.25 and 0.5 weightings however differences of up to 115 seconds could be observed. However, it is important to note that these results for the hybrid system performing in a faultless environment were noted atypical in Chapter 7.2. The results in this chapter, whilst producing a significant difference, remain consistent with the other weightings and the independent strategies.

Partial Motor Fault in the Leader's Wheels

Consistent with the results for the strategies operating in isolation in the presence of motor faults in the leader's wheels, very little robustness was demonstrated by the hybrid system in the presence of the same faults.

For a partial motor fault in the left wheel, significant difference was found across all thirty statistical tests conducted for the three weightings used in the hybrid system. In all cases, the statistical difference could be attributed to the time taken being higher for the hybrid system operating in the presence of a left motor fault, than the results record for the hybrid system performing in the absence of faults. This is consistent with our understanding of how the partial motor faults in the leader's wheels impact task execution discussed in Chapter 6. The partial motor fault decreases the velocity of the wheel, and thus slows the system down throughout task execution.

The largest disparity in time taken was observed in cases where low task completion was observed. This is again a consistent relationship that has been observed. The most prominent disparity occurred in the line following environment, where completion time was double or triple the time taken for the hybrid system to complete the task in the absence of faults.

In these cases, task failure was observed wherein the robots would veer off the path and collide with the wall. In some cases, consistent with that observed for the vision sensor fault, the robots would perform a circle and then when the leader's vision sensors were back on the path were able to perform a corrective movement and continue along the trajectory, this likely accounts for the higher time taken recorded for the line following paths with low task completion.

In the cluttered environments, whilst the time taken was consistent higher in the presence of faults than without, the hybrid system presented lower time taken results than either strategy operating in isolation for the first and second paths, demonstrating the hybrid system shows more robustness than either strategy acting independently. This can also be linked to the task completion results observed for these environments, where the hybrid system achieved higher task completion than either strategy operating in isolation.

Similar behaviour was observed for a partial motor fault in the right wheel. The time taken for the hybrid system to complete the task in the presence of a fault was consistently higher, and more so in environments where low task completion was observed. Only one statistical test showed no significant difference for the time taken metric. This occurred in the third line following environment for the 0.5 weighting. This result should be critiqued, however, as there is actually a 223.5 second difference between the means of the data sets. The 0.5 weighting only achieved 1% task completion and the Mann-Whitney U tests are known to be less reliable when comparing small data sets, so this may have impacted the result of the statistical test.

Similar to the behaviour observed for the left wheel fault, in the cluttered environment the time taken for the hybrid system to complete the tasks across all weightings was lower than either strategy operating in isolation, again suggesting the hybrid system has more fault tolerance.

Partial Motor Fault in the Follower's Wheels

The hybrid system demonstrated the most fault tolerance in the time taken metric across all weightings and wheel faults in the follower's wheels. In total, 65 out of 90 tests showed no significant difference when compared to the hybrid system's performance in the absence of faults.

For a partial motor fault in wheel 1 for the follower the 0.75 weighting was determined as the best weighting across all environment types, with eight out of ten tests showing no significant difference. Consistent with previous trends observed for the hybrid system, the time taken decreased as weighting increased from a fully explicit system to a fully implicit system.

Significant difference was observed in the line following environments where the time taken recorded for the hybrid system in the presence of a wheel 1 fault was higher than its faultless counterpart. This is linked to the low task completion percentages observed for these environments, where the robots were observed to veer off the path, perform a circle and then rejoin the path to complete the task, resulting in a longer time taken for completion.

Interestingly, where significant difference was also observed in the first cluttered environment, the time taken recorded was lower in the presence of a wheel 1 fault than without. This can be attributed to the behaviour observed in this environment for low noise values injected in the system, where the robots would reach the end of the path and the leader would set its wheel velocities to zero before the robots were in the end zone to trigger the task as successfully completed. This scenario did not occur for higher noise values, which caused the robots to move faster, resulting in a faster mean time taken recorded for successful task completions. Similar behaviour was observed for faults in wheels 2 and 3, causing statistical difference in the presence of those faults too.

For a partial motor fault in wheel 2, the 0.25 weighting was observed to be the most fault tolerant out of the three weightings, with nine out of ten tests showing no significant difference.

Similarly to wheel 1, statistical difference was observed in the first cluttered environment for the 0.5 and 0.75 weightings, where the time taken was again observed to be less than for the hybrid system operating in the absence of faults.

The most fault tolerance was shown for a partial motor fault in wheel 3, where the 0.25 weighting showed no significant difference in every statistical test, outperforming the implicit strategy operating in isolation.

Total Distance Travelled By Object

The numerical results for the total distance travelled by the object in metres in the presence of vision sensor faults can be found in Section J.1 in Appendix J. For partial motor faults, task completion results can be found in the same appendix, in Section J.2.1 and in Section J.2.2, for faults in leader's wheels and faults in follower's wheels, respectively.

Vision Sensor Faults

The 0.75 weighting demonstrated the most robustness to vision sensor faults again for the metric total distance travelled, with 5 statistical tests showing no significant difference out of 8, compared to two tests for the 0.25 weighting and just one test for the 0.5 weighting. This supports the conclusions discussed in Chapters 7.2 and 8 that suggest that the 0.75 weighting was the best weighting for the hybrid system in line following environments.

For tests that did show significant difference the results were consistent with those for the independent strategies operating in the presence of a fault. That is to say, a link could be observed between higher total distance travelled and lower task completion, for example in the second and first path in the presence of a fault in the left sensor, and in the second path in the presence of a fault in the right sensor across all weightings. This relationship was most visible in the first path in the presence of the left sensor fault and in the second path in the presence of the right sensor fault where the fault lay on the same side as the predominant direction of the path, and the independent strategies achieved either zero or very low task completion.

When observing the hybrid system in the presence of a fault in the left sensor in the first path, and in the presence of a fault in the right sensor in the second path, the higher total distance values recorded were consistent with the behaviour observed. As discussed previously, in this instance across weightings the hybrid system would veer of the path and only complete the task by chance if the robots coincidentally moved past the end zone in the environment, this often lead to the robots running for a longer duration and thus travelling a greater distance.

Partial Motor Fault in the Leader's Wheels

The hybrid system demonstrated little robustness to motor faults in the leader's wheels for the total distance metric. For a partial motor fault in the left wheel only weightings showed no significant difference in one statistical test each. The 0.25 weighting showed no significant difference in the first cluttered environment and the 0.5 weighting showed no significant difference in the second cluttered environment. In all other environments and across all weightings, no statistically significant robustness was demonstrated.

For a fault in the right wheel, the 0.75 weighting showed no significant difference was found in the second cluttered environment. No significant difference was also found for the 0.5 weighting in the third line following environment. It must be stressed again that this result is likely erroneous due to the small data set used in the statistical test.

Typically the total distance recorded for the hybrid system in the presence of a fault was higher than the hybrid system operating in the absence of faults, and was most visible in environments where lower task completion was observed. This is consistent with previously observed behaviour, where the robots would veer off the path but in some instances would later rejoin the trajectory to finish the task. As the total distance metric is calculated through a summation of differences between x and y coordinates every time step, such behvaviour dramatically increases the total distance recorded during task execution.

Partial Motor Fault in the Follower's Wheels

The hybrid system demonstrated the least fault tolerance to partial motor faults in the follower's wheels with only 28 out of 90 tests showing no significant difference. The 0.75 weighting demonstrated the most robustness with 12 out of 30 tests showing no significant difference.

For a partial motor fault in wheel 1, the 0.75 weighting was observed to be the most fault tolerant weighting with five out of ten statistical tests showing no significant difference. However the hybrid system did not outperform the explicit strategy performing in isolation in the presence of the same fault.

In the third line following environment, total distance was observed to be greater across all weightings of the hybrid system. This could be attributed to the lower task completion observed in these environments, and is consistent with previously identified relationships between metrics.

In the path planning environments, total distance travelled by the object was observed to be less in the presence of a wheel 1 fault than without. As discussed in Chapter 6, this is linked with the higher path fidelity observed in the systems in the presence of follower wheel faults.

For a partial motor fault in wheel 2, the 0.75 weighting was also determined to be the best weighting, with seven out of ten tests showing no statistically significant difference.

In the second cluttered environment, significant difference was found for the 0.25 weighting where total distance travelled by the object was observed to be higher in the presence of a fault in wheel 2. This could be linked to the lower task completion observed in that strategy.

Similar behaviour as that observed in a wheel 1 fault was observed in the other path planning environments, where total distance travelled was less in the presence of fault. This can be linked to how the faults in wheels 2 and 3 affect the behaviour of the system. The differential wheel velocity caused by the wheel fault caused the hybrid system to perform smoother turns in the presence of these wheel faults, and less distance travelled when performing turns around corners.

The same behaviour was also observed in the line following environments. These environments also saw higher task completion percentages and higher path fidelity, supporting the conclusion that these attributes are linked together.

For a partial motor fault in wheel 3, the 0.5 weighting showed the most robustness with four out of ten statistical tests showing no significant difference, although the weighting was outperformed by both the explicit and implicit strategies operating in isolation in the presence of the same faults.

Consistent behaviour was observed for this fault, significant difference was observed in the first cluttered environment for the 0.25 weighting, where the total distance recorded was higher than its faultless counterpart. This again can be linked to low task completion observed in this environment. A similar trend is observed in the random environment, where total distance travelled is higher in the presence of a wheel 3 fault.

In the cluttered environments, with the exception of the first path, and in the line following environments, total distance was once again recorded to be less in the presence of a fault than when the hybrid system performed without any faults.

9.3.3 Smoothness

Smoothness was measured by the maximum displacement of object during task execution and path fidelity.

Maximum Displacement of Object

The numerical results for the maximum displacement of the object in metres in the presence of vision sensor faults can be found in Section J.1 in Appendix J. For partial motor faults, task completion results can be found in the same appendix, in Section J.2.1 and in Section J.2.2, for faults in leader's wheels and faults in follower's wheels, respectively.

Vision Sensor Faults

Both the 0.5 and 0.75 weightings demonstrated similar robustness to vision sensor faults, with both demonstrating no significant difference in four out of eight statistical tests. The 0.25 weighting showed no statistical difference in 3 out of 8 tests.

In the presence of a fault in the left sensor it was observed that the mean maximum displacement was lower for the 0.5 weighting by up to 0.08m in the first and second path, and up to 0.07m for the 0.25 weighting in the second path than the results found for the hybrid system operating faultlessly. A lower mean maximum displacement value was also observed for the o.25 weighting in the second path in the presence of the middle sensor fault, again by 0.08m. This was consistent with the behaviour observed for these faults in these weightings, where large perturbations could occur resulting in large displacements between time steps.

All other values, whilst showing statistically significant difference, were close in values and consistent with other results.

Partial Motor Fault in the Leader's Wheels

The most robustness was demonstrated by the hybrid system for the maximum displacement metric.

In the left motor fault, the 0.75 weighting was the most robust weighting, with six out of ten statistical tests showing no significant difference. The 0.25 and 0.5 weightings also showed no significant difference in two tests each.

In the right motor fault, the 0.75 weighting and the 0.25 demonstrated the most robustness, with two out of ten tests showing no significant difference. The 0.5 weighting also demonstrated no significant difference, but this was again in the third line following environment, indicating another erroneous result.

In the path planning environment consistent behaviour was observed where the maximum displacement of the hybrid system in the presence of faults followed a linear trend between a fully explicit and fully implicit system.

In the line following environments, maximum displacement values higher than those recorded for either strategy operating in isolation were recorded. This can be attributed to the behaviour observed in this environment, where the hybrid system for some noise values would veer off the path to later rejoin the trajectory and complete the task. In these instances the robots would perform a tight circle, which caused large displacements between time steps.

Partial Motor Fault in the Follower's Wheels

Statistical difference was found in 60 out of 90 statistical tests for the maximum displacement metric in the presence of partial motor faults in the follower's wheels.

In wheel 1 faults, the 0.25 and 0.5 weighting both demonstrated fault tolerance in five out ten statistical tests, but were outperformed by both the explicit and implicit strategies operating independently in the presence of the same fault.

In the line following environments, the maximum displacement was observed to be lower, another characteristic that is linked to the higher path fidelity observed across the environment and weightings.

For a partial motor fault in wheel 2, the 0.75 weighting demonstrated the most robustness with nine out of ten statistical tests showing no significant difference. This offered the same performance as explicit or implicit communication operating in isolation in the presence of the same fault.

In the line following environments, the maximum displacement was observed to be lower than the hybrid system's in the absence of faults, but the results recorded for the different weights remained higher than the explicit and implicit strategies operating alone. This was consistent with observed faultless behaviour.

In the wheel 3 fault, the 0.5 weighting offered the most fault tolerance, with nine out of ten tests showing no significant difference. This performance was consistent with that of the explicit strategy operating in isolation in the presence of the same fault.

In the first cluttered environment, maximum displacement values were close between the hybrid system's performance in the presence of a wheel 3 fault and its' performance without. However there was significant different in the 0.5 and 0.75 weightings. Consistent in behaviour being observed for the other wheel faults, maximum displacement was often observed to be lower in the presence of a fault.

Path Fidelity

The numerical results for the percentage task completion of the two strategies in the presence of vision sensor faults can be found in Section J.1 in Appendix J. For partial motor faults, task completion results can be found in the same appendix, in Section J.2.1 and in Section J.2.2, for faults in leader's wheels and faults in follower's wheels, respectively.

Vision Sensor Faults

For path fidelity the 0.25 weighting demonstrated the most fault tolerance to vision sensor faults, which was supports with the results in Chapters 7.2 and 8 that also indicate 0.25 is the best performing weighting for the path fidelity metric.

Where statistical difference was observed, this was typically linked to where low task completion was also observed, and consistent with the behaviour discussed in Chapter 6.

Interestingly, in the presence of a middle sensor fault the path fidelity was observed to be higher for all paths and weightings, causing significant difference. This is again linked to the fact that the results being compared to for the hybrid system were noted as atypical in Chapter 7.2, due to the robots veering off the path in some instances during task execution. The results in this chapter, whilst producing a significant difference, remain consistent with the other weightings and the independent strategies.

Partial Motor Fault in the Leader's Wheels

In the presence of a partial motor fault in the left wheel, all weightings in the hybrid system showed significant difference across all environments.

Across both wheel faults, in the line following environments, the path fidelity was lower than that of the hybrid system operating in the absence of faults. This ranged from nine to thirty percent. Interestingly however, in the second line following environment and in the presence of a left wheel fault, path fidelity increased for the 0.25 and 0.5 weighting, despite having considerably lower task completion percentages. When observing the simulation, in a faultless scenario the oscillatory behaviour of the robots performing a corrective movement and then having to perform a counter corrective movement was observed, which caused the object to move off the trajectory and miss way-points. When observing the hybrid system in the presence of a left wheel fault, the differential wheel velocity caused by the fault slows the system down, and limits the size of the corrective movement that can be performed, this means the robots follow the paths more closely.

In path planning environments, the path fidelity recorded in the presence of a fault were incredibly low, under 10% in almost all cases, this was similar to the behaviour observed in the strategies operating in isolation under the presence of the same faults. The differential wheel velocity caused by a partial motor fault would cause the robots to veer to the side of the path in the direction of the wheel fault, this resulted in the robots not passing through way points during task execution.

For a partial motor fault in the right wheel, two statistical tests showed no significant difference for the 0.25 and 0.5 weighting, both in the third line following path. Again it should be noted that the 0.5 result is likely erroneous due to the small data set size for that weighting.

Partial Motor Fault in the Follower's Wheels

In the path fidelity metric, 59 out of 90 statistical tests showed no significant difference, again indicating the hybrid system is robust to partial motor faults in the follower's wheels. Overall, the 0.75 weighting demonstrated the most robustness with 24 out of 30 tests showing no significant difference.

For a partial motor fault in wheel 1, the 0.25 weighting demonstrated the most robustness with six out of ten tests showing no significant difference. However, it did not outperform the explicit strategy operating in isolation in the presence of the same fault.

Significant difference was observed in the line following environments and in the first cluttered path. The lower path fidelity observed was linked to the low task completion percentages recorded in these environments in the presence of a partial motor fault in a follower's wheels.

For faults in wheel 2 and wheel 3, the 0.75 weighting showed the most robustness with all statistical tests showing no significant tests for a wheel 2 fault, and nine out of ten tests showing no significant difference for a wheel 3 fault. In both cases, the 0.75 weighting outperformed the explicit strategy and the implicit strategy when operating in isolation in the presence of the same fault. For both wheel 2 and wheel 3 faults, the path fidelity in the line following environments was observed to be higher. This was consistent with behaviour observed in that the faults in wheels 2 and 3 allowed for a smoother task completion by the robots, resulting in higher path fidelity.

Similar to what was observed in a fault in wheel 1, a lower path fidelity was observed across weightings for partial motor faults in wheel 2 or wheel 3 in the first cluttered environment, which can be attributed to the lower task completion observed in this environment.

9.3.4 Conclusion

This chapter investigated the fault tolerance of the hybrid system presented in Chapter 7.2 in the presence of two different fault types. The performance of the hybrid system in the presence of faults was statistically compared to the performance of the hybrid system presenting in the absence of faults. These findings were also compared to the fault tolerance results for the two communication strategies operating in isolation, in order to determine where the hybrid system outperformed either strategy.

For the vision sensor fault, the hybrid system showed very little robustness to this type of fault, which was consistent with what was observed in the two strategies operating in isolation. The 0.75 weighting demonstrated the most robustness with 13 out of 32 statistical tests showing no statistical difference, which was consistent with the conclusions drawn in Chapters 7.2 and 8 that showed the 0.75 weighting exhibited the strongest performance in line following environments. However no weighting was observed to outperform either strategy in isolation. It is important to note the hybrid system was still negatively impacted by vision sensor faults that lay on the same side as the predominant direction of the path, and thus the system only showed fault tolerance to faults where that was not the case. The null hypothesis that vision sensor faults have no effect on the performance of the hybrid system must thus be rejected.

Table 9.1 summarises the fault tolerance of the hybrid system to vision sensor faults discussed throughout this chapter and indicates which weighting offers the most robustness for a given metric.

For the partial motor faults, similar to the results in Chapter 6 when comparing the strategies in isolation, the hybrid system demonstrated different amounts of fault tolerance depending on what wheel's exhibited a fault.

Consistent with the observed behaviour for a fault in the leader's wheel, the hybrid system demonstrated minimal robustness to these fault types. Across all metrics and across all weightings only 22 out of 240 tests showed no significant difference. The weighting that demonstrated the most fault tolerance was the 0.75 weighting, where nine out of 80 statistical tests showed no significant difference across all metrics. This weighting outperformed either strategy in isolation, particularly in the maximum displacement metric. However, due to the low number of statistical tests showing no significant difference, the null hypothesis must be rejected. The hybrid system struggled to reduce the error caused by partial motor faults in the leader's wheel for the same reasons discussed for the independent strategies in Chapter 6, in that it was unable to differentiate the error in the leader's movement caused by a partial motor fault, and a valid movement performed by the Leader. These results met the expectations laid out at the beginning of the chapter that the hybrid system would not be fault tolerant to these types of faults.

Whilst the null hypothesis must be rejected, it is still possible to identify which weightings offer the most robustness for the different environment types. In the line following environment five statistical tests showed no significant difference, however four of those occurred in the third line following environment and were identified as potentially erroneous due to the data set size for that weighting. Excluding those erroneous results, the 0.25 weighting and the 0.75 weighting both offer the same robustness with three out of twelve tests indicating no significant difference each. In the path planning environments, the 0.75 weighting demonstrated the most robustness with 6 out of 12 statistical tests showing no significant difference. This is consistent with results found for the hybrid system operating without faults.

Table 9.2 provides a summary of the robustness profile for the hybrid system to partial motor faults in the leader's wheels. It indicates which weighting offers the most robustness for a given metric and environment type.

For partial motor faults, considerable fault tolerance was exhibited, similar to that shown by the strategies operating in isolation. Across all metrics and across all weightings 212 out of 360 statistical tests demonstrated no significant difference, strongly indicating the hybrid system is fault tolerant to follower wheel partial motor faults. The most fault tolerant weighting was deemed to be the 0.75 weighting, which achieved no significant difference in 77 out of 120 statistical tests across all metrics. This weighting outperformed the implicit strategy when operating in isolation, but did not outperform the explicit strategy. Where the explicit strategy demonstrated statistical similarity in more tests was for the total distance metric, however, and it can be seen that for this metric the 0.75 weighting produced lower values for total distance travelled than its faultless counterpart and lower values than the explicit strategy operating in isolation. This indicates the hybrid system is not only able to mitigate the effects of a fault but achieve better task performance despite the fault. The 0.25 weighting was the second strongest in demonstrating fault tolerance, with 70 out of 120 tests showing no significant difference. It was not able to outperform either strategy operating in isolation.

Table 9.3 provides a summary of the robustness profile of the hybrid system to partial motor faults in the follower's wheels, and summarises the analysis presented in the chapter for this fault type. It indicates which weighting offers the most robustness for a given metric and environment type.

This chapter concludes the evaluation and analysis of a hybrid system that combines explicit and implicit communication in simple object manipulation tasks between two robots. It provides an evaluation of the hybrid system's fault tolerance to two different simple fault types, to give a better understanding of how the system might perform in imperfect environments where faults can occur. Whilst it can be concluded the hybrid system is not inherently more fault tolerant than either strategy operating in isolation across all fault types discussed in this thesis, the system does demonstrate fault tolerance to partial motor faults in the follower's wheels, as the system is able to identify the fault as an error on the input and attempt to reduce it.

The 0.75 weighting demonstrated the most robustness weighting across all metrics and for all fault types. In the line following environments, the 0.75 weighting was the most robust, with 38 statistical tests out of 92 showing no significant difference, this is consistent with findings discussed in Chapters 7.2 and 8, which also identified the 0.75 weighting as the best weighting for those environments. In the path planning environments, the 0.25 weighting demonstrated the most robustness, with 62 out of 200 statistical tests showing no significant difference. Again this is consistent with other findings presented in this thesis, and supports the claim that the 0.25 weighting offers the best compromise in performance within the path planning environments. Faulty incompletion behaviour near end zone.

Table 9.1: Fault Tolerance of the Hybrid System to Vision Sensor Faults in Simple Object Manipulation Tasks

Metric	Time Taken	Total Distance	Maximum Displacement	Path Fidelity
Left	none	0.75	0.25/ 0.75	0.25/ 0.75
Middle	0.75	0.75	0.5	none
Right	0.5	0.25	0.5/ 0.75	0.25/ 0.75

Table 9.2: Fault Tolerance of the Hybrid System to Partial Motor Faults in the Leader's Wheels in Simple Object Manipulation Tasks

Metric	Time Taken			Total Distance			Maximum Displacement			Path Fidelity		
Environment	LF	SECE	RE	LF	SECE	RE	LF	SECE	RE	LF	SECE	RE
Left	none	none	0.25	none	0.25	none	0.75	0.75	0.25/ 0.75	none	none	none
Right	none	none	none	none	0.5	none	0.25	none	0.75	0.25	none	none

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Table 9.3: Fault Tolerance of the Hybrid System to Partial Motor Faults in the Follower's Wheels in Simple Object Manipulation Tasks

Metric	Time Taken			Total Distance			Maximum Displacement			Path Fidelity		
Environment	LF	SECE	RE	LF	SECE	RE	LF	SECE	RE	LF	SECE	RE
Wheel 1	0.75	all	0.75	0.75	0.25/ 0.75	0.25/ 0.75	all	0.25	0.5	0.5	0.25	0.75
Wheel 2	0.25/ 0.75	all	0.5	0.75	0.5/ 0.75	all	all	0.75	0.25/ 0.75	0.75	0.75	0.25/ 0.5
Wheel 3	0.25/ 0.5	0.25	all	0.5/ 0.75	0.5	0.25/ 0.5	0.5	0.25	all	0.75	0.25	0.25/ 0.75

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Chapter 10

Conclusions and Future Work

This chapter provides a summary of the work presented in this thesis and outlines its key contributions. This chapter also discusses limitations of the system and areas of future work to that could be explored to further develop the system/

10.1 Discussion

The hypothesis stated at the start of this thesis was as follows:

Hypothesis: Humans' innate ability to coordinate when moving objects together can be mimicked in object manipulation tasks between two robots by creating a system that employs a combination of explicit communication, in the form of wireless message transfer, and implicit communication, in the form of force sensing. The hybrid system will capitalise on the advantages that are found in both forms of communication when employed in isolation.

In Chapter 1, when first stating this thesis' hypothesis, several research goals were defined to support the hypothesis and the list of contributions made within this thesis was provided, including both contributions to knowledge and understanding and novel contributions. Whether these research goals have been met can now be critically reflected on.

The first research goal was "To implement communication strategies employing explicit communication and implicit communication in isolation in an object manipulation task between two robots, as a foundation for comparison." It is believed this research goal was successfully met within Chapter 4, which described the implementation of the communication strategies and demonstrated their ability to successfully complete simple object manipulation tasks across a range of environments.

The two strategies were devised to employ explicit and implicit communication separately in object manipulation tasks between two robots. They mimicked joint action in humans by employing wireless messaging transfer for explicit communication, which mimicked human speech, and force sensing for implicit communication, which mimicked human's use of force cues in joint action.

The robots were configured in a Leader-Follower configuration. The Leader had knowledge of its position on a pre-determined path and the goal location, the Follower relied on information communicated to it by the Leader to coordinate its movements with the Leader's.

The explicit strategy employed wireless messaging to transfer information from one robot to the other, where the Leader transmitted a message to the Leader along with a desired forward velocity. The implicit strategy employed Newtonian mechanics to use force information as a form of implicit communication, where the Follower measured force exerted on its force sensor and calculated the required velocity it had to move at for the two robots to jointly move the object.

By achieving this research goal the following contribution to knowledge and understanding was made: "Two communication strategies for a two robot Leader-Follower configuration. One strategy employs wireless messaging to allow explicit communication to occur between robots, the other strategy employs Newtonian physics to use force as a form of implicit communication."

The second and third research goals were closely linked, and were as follows:

- To deepen understanding of how the two strategies perform in isolation within different environments and with different objects, and how they perform in comparison with each other.
- To develop performance profiles and robustness profiles on the strategy to a greater level of detail than currently present in existing literature.

These research goals were addressed within Chapters 4, D and 6, where the performance of the two communication strategies was evaluated across different environments, with different object types, and in the presence of simple faults.

This work provides further understanding of the advantages and disadvantages of the two forms than previously found in existing literature.

In Chapter 4, it was expected that the two strategies would perform similarly, consistent with the results found by Pereira et al. (2002) that said implicit communication performed similarly to explicit communication for simple data transfer. However, the results in this chapter were not as expected and the strategies were proven to perform differently to one another. The implicit strategy was reasonably efficient, in that it was the fastest strategy across all environmental paths. It also proved to be more reliable: outperforming explicit communication with a higher task completion and path fidelity. Explicit communication demonstrated some efficiency and reliability, and smoothness by showing the minimum displacement of the object during task execution.

Chapter 5 explored how the strategies performed with different object types. It was expected that object type would have no effect on the performance of either strategy, as the implicit strategy used updated mass and inertia information relevant to the new object, and the explicit strategy did not require any knowledge of the object to communicate instructions. The results within this chapter demonstrated that implicit communication showed the most consistent performance with different object types, but neither strategy proved to have statistically consistent performance regardless of object type, due to an offset error in the system that was caused by the Leader being at the back of the configuration, which increased with object size.

In Chapter 6, it was expected that the introduction of faults into the two strategies would negatively impact performance. The results confirmed this for the introduction of a vision sensor fault and for the introduction of a partial motor fault on the leader's wheels. However, the two strategies demonstrated fault tolerance to partial motor faults on the follower's wheels due to the fact they are employ control algorithms that aim to reduce error sensed on their input and thus were able to mitigate the error caused by the follower wheel fault. The explicit strategy demonstrated the most robustness across fault types with 110 out of 220 tests showing no significant difference when compared to the strategy's performance in the absence of faults.

It is believed that the second and third research goals were sufficiently met within these chapters. As first discussed in Chapter 2, previous research comparing explicit communication and implicit communication was limited to one object type, one environment and where only one metric was compared for performance. Within this thesis six different object types were considered across ten different environmental configurations, as well as for eight different fault configurations. Across these experimental configurations five performance metrics were analysed. This resulted in 595 data points for comparison for each strategy, providing a performance profile supported by a wealth of data that far outweighs previous comparisons. It is important to note that this comparison is limited in that it only exists within simulation, and thus the reality gap could impact the validity of these results when operating in the real world. How this reality gap can be closed in future work is discussed in Section 10.3

By achieving these research goals the following contributions to knowledge and understanding were made:

- Performance profiles for the two communication strategies operating in isolation that is more detailed than existing analysis. These profiles describe the strategies' advantages and disadvantages when manipulating different object types across four different environments.
- Fault tolerance profiles for the two communication strategies operating in isolation that is more detailed than existing analysis. These profiles describe the robustness of the strategies when manipulating objects in the presence of two simple faults across four different environments.

The fourth research goal was "To combine the two strategies into a hybrid system that employs a combination of explicit and implicit communication", this was addressed within Chapter 7.2, where the new hybrid system was described that combined implicit and explicit communication using a weighted sum algorithm. The new system calculated explicit and implicit wheel velocities using the techniques employed in the original strategies, and created new wheel speeds by combining the implicit and explicit strategies in a weighted sum. Where the weighting, w, corresponded to a value between 0 and 1, and where a weighting value of 0 resulted in a fully explicit system, and a value of 1 resulted in a fully implicit system. Three weightings were chosen between this range, of the values 0.25, 0.5 and 0.75. The linear distribution of weightings were deemed sufficient to explore a proof of concept for the novel hybrid system. Methods for exploring different weightings for the system are discussed in Section 10.3.

It is believed this research goal was met within this thesis, as demonstrated by the successful implementation of the hybrid system as shown by the experimental results in Chapters 7.2, 8 and 9.

The final research goal was "to examine how the hybrid system performs in comparison to the two strategies operating in isolation in the same experimental test beds." This was addressed in Chapter 7.2, whether the hybrid system was evaluated when manipulating the original object, in Chapter 8, where the hybrid system was tested using different object types and in Chapter 9, where the hybrid system's performance was examined in the presence of simple faults.

In Chapter 7.2, it was expected for the hybrid system to outperform either strategy operating in isolation, and capitalise on the advantages of both, consistent with the biological inspiration for the system, in that combining both in human behaviour is more advantageous. The results indicated that the hybrid system's performance lay, on average, on a scale between the explicit strategy and implicit strategy as weighting increased. Out-performance of the two original strategies was observed in the path planning environments in both path fidelity and total distance travelled by the object. Whilst no singular weighting outperformed either strategy in isolation, a weighting of 0.75 in the line following environment, and a weighting of 0.25 in the path planning environments were identified as the weightings that capitalised on the most high performing metrics and provided the best compromise of performance in their respective environments.

In Chapter 8, it was expected that object type would likely affect results in a similar manner to how it affected results for the two communication strategies operating in isolation. However, experimental results indicated that the hybrid system offered more consistent performance to different object shapes than a system that only employs one form of communication in isolation. This chapter also verified that the 0.75 weighting had the best performance in the line following environment as it was also the most consistent weighting to different object types. The 0.25 weighting offered the best compromise in performance out of the three weightings for all three path planning environments investigated in this work.

Chapter 9 presented a series of fault tolerance experiments to evaluate the robustness of the hybrid system. It was expected that the presence of simple faults would negatively impact the performance of the hybrid system. This again was true for the vision sensor faults and the partial motor faults on the leader's wheels. However, the hybrid system did show more robustness than the strategies operating in isolation, and provided a compromise between the two strategies' performance. The hybrid system also demonstrated similar fault tolerance to the explicit strategy in the presence of partial motor faults in the follower's wheels. This chapter once again verified that the 0.75 weighting had the best performance in the line following environment and the 0.25 weighting offered the best compromise for the path planning environments.

It was believed this research goal was sufficiently met as the hybrid system was examined across all of the experimental test beds described in this thesis. The understanding of the explicit and implicit components provided by the experimental results of earlier comparative chapters informed the analysis of the hybrid system within these experimental chapters. The performance profile of the hybrid system was substantial due to the variety of experimental configurations investigated. Across the different environments, object types, fault types and metrics measured, 1,785 data points were determined in total across the three weightings used in the hybrid system.

Similar to the comparative analysis of the two strategies performing in isolation, the performance profile of the hybrid system is limited in that it relies on results from within simulation only. Section 10.3 discusses how the reality gap could be closed and how the systems described in this thesis could be ported to real world platforms.

The results of these experimental chapters formed the following novel contributions within this thesis:

- A performance profile of the hybrid system, which demonstrates: that the hybrid system capitalises on the advantages identified in both strategies operating in isolation, that different weightings offer a compromise between the performances of the two strategies, and that the hybrid system shows better performance with different object shapes than either communication strategy working in isolation.

- A fault tolerance profile of the hybrid system, which demonstrates that different weightings offer a compromise between the performances of the two strategies and for certain fault types work to reduce the error more effectively than either strategy working in isolation.

Thus, taking these results into account, the initial aims of this thesis have been met and a case has been made for the combination of implicit and explicit communication to improve object manipulation tasks between two robots. The research presented in this thesis presents a valuable contribution within the field of object manipulation and cooperation, which, when refined, could prove an attractive and effective mechanism for robot-robot cooperation in a range of automated environments.

The most obvious application for the hybrid system described in this thesis is within automated warehouses, such as those being developed by Amazon and Ocado, who employ robots to move stock and perform automated tasks within their logistical operations and supply chain. Robots that can efficiently and effectively communicate with one another and manipulate objects across environments that will likely feature obstacles such as other robots, shelves, conveyor belts and other machinery, will be essential for these automated environments to function successfully. More traditional manufacturing spaces such as assembly lines could also benefit from this type of communication during object manipulation.

Other applications include search and rescue operations, where robots must communicate successfully with each other and manipulate objects such as debris or even human survivors. In these scenarios a system that can be weighted to prioritise smoothness or efficiency would be beneficial for task execution. Furthermore, a combined system that can demonstrate fault tolerance to faults such as sensor faults or motor faults, within a dynamic or hostile environment is an attractive approach for such applications.

The fault tolerance demonstrated in this hybrid system, coupled with the fact that the combined communication strategy enables the robots to cooperate independently of humans, means the system could be used in other applications that exist in hostile environments. The use of robotics systems in space exploration is a rapidly expanding research area, particularly with the increased interest and privatisation of space research, such as Elon Musk's and NASA's plans to colonise Mars. Robots provide an attractive solution for performing tasks to prepare planets for humans or gather resources, in deep space mining, on planets completely independently of humans. It is important to note, that due to the nature of the hybrid system using force information as a form of implicit communication, the system is primarily suited for applications where two robots are physically connected either through an object they are manipulating or to each other to coordinate movements.

The aims of this thesis were to provide in-depth comparative analysis and performance profiles of implicit and explicit communication performing in simple object manipulation tasks, and to present the implementation and evaluation of a proof of concept for a hybrid system that combines both forms with a weighted sum. Whilst it is believed the research goals set out at the beginning of this thesis to achieve these aims have been met, it can not bed said the systems described within this thesis are perfect with no room for development. The next section discusses the primary weaknesses and limitations of these systems.

10.2 Limitations of the System

As discussed throughout the analysis presented within this thesis, there have been limitations in the systems' implementation and performance. The systems described in this thesis are also imperfect, with weakness that affect their adaptability and flexibility.

The first weakness of the system is the Leader-Follower configuration employed where the Leader is at the back of the configuration. As discussed throughout the analysis presented in this thesis, this configuration causes an offset error, where the Leader transmits positional data the is in essence delayed for the Follower's own position on the path trajectory. In Chapters 5 and 8 this offset error was shown to increase with object length. This reduces the flexibility of the system as it is limited to only performing manoeuvres with the Leader at the back of the configuration. However, this limitation is enforced by the design of the implicit strategy when calculating wheel velocities, as the Follower needs to measure the force being exerted by the Leader onto the object in a pushing motion within the direction of the path trajectory.

The implicit strategy is limited in that it is dependent on knowing the mass of the object and the Leader, and the moments of inertia for the object offline before task execution. This means the system can only be adaptable to different object types if the controllers are given updated information for the object. Additionally it means that the system is not flexible to the object changing in these characteristic mid task-execution, for example if it changed size or mass.

An additional limitation of the system is the constraints on the robot platform required for the strategies to operate. As stated in Chapters 4 and 7.2, the main constraints on the robot platforms are that the Follower robot must have omnidirectional wheels to be able to move simultaneously in the x and y directions and it must have a force sensor so that it can measure force and torque being exerted on the object. Additionally, it is required that robots are rigidly attached to each other and the object to simplify the force calculations when determining wheel speeds using implicit communication. These constraints affect the adaptability of the system as it means the strategies are not inherently platform agnostic, and will only function on platforms that meet the constraints. The potential for porting the systems on to real world platforms, and suggestions for those platforms are discussed in section 10.3.

For the systems described in this thesis that operate within path planning environments, pre-planned paths are loaded within the controllers before task execution. This means the systems are inflexible to changes in the environment such as new obstacles appearing in the pre-determined trajectory. However, whilst this is a limitation of the systems in this thesis, online path planning is a rich research field with multiple successful implementations, and the systems' controllers could be easily adapted to employ a different path planning technique.

One large limitation of the systems described in this thesis is that they are not immediately adaptable to real world robotic platforms. All experiments described in this thesis occurred within simulation using the commercial simulator CoppeliaSim. It was decided to only investigate the system within simulation for several reasons. Firstly, the ability to quickly prototype systems within simulation and quickly make changes to the environment, object or controllers, making it possible to perform the multitude of experiments within this thesis across four different environments, six different objects and eight different faults and gather extensive results on the performance of the system. Linked to this, the ability to run simulations headlessly made it possible to run several experimental configurations in parallel and faster than if the experiments were running in real time. Ten configurations were often run in parallel, for the ten different environments, each for 100 experimental runs. This typically took 3-4 hours to run headlessly. In comparison, if the same ten experimental configurations were run consecutively in the real word this could have taken a total of 222.22 hours.

Finally, the fundamental purpose of this thesis was to provide a proof of concept for a novel hybrid system that could combine explicit communication, in the form of wireless messaging, and implicit communication, in the form of force sensing, in a two robot system for object manipulation tasks. Creating this system and evaluating its performance with different objects, across different environments and within the presence of simple faults within simulation was deemed enough to satisfy a proof of concept. Whilst there was an expectation the system would be developed further, real world experiments were out of scope for the purpose of this initial investigation and exploration.

As previously discussed in Chapter 3, only using simulation presented the question of a reality gap occurring between the performance of the controllers being developed withing this thesis within simulation and within real life, where perfect, noiseless and faultless performance cannot be guaranteed.

Some measures were taken to attempt to close the reality gap within these simulations, including injecting noise on the Leader's wheels to mimic motor noise and exploring the system's fault tolerance to vision sensor and motor faults. Expanding on these measures to close the reality gap further, and test the system within the real world is discussed in more detail as future work in the next section of this chapter.

It could be criticised that the system presented in this thesis is not compared to other existing research. It is, however, important to note that the hypothesis of this thesis was to investigate whether it was possible to mimic joint action within two robots manipulating an object in a novel way that had not yet been explored, and whether the system could capitalise on the advantages that are found in both forms of communication when employed in isolation. The scope of the thesis was to create a proof of concept of the novel system to test that hypothesis, but the scope did not extend to whether this system was the optimum mechanism for communication between two robots in object manipulation tasks or to test the system outperformed other mechanisms.

However, now the proof of concept has been made within this thesis, there is potential to explore comparisons between the hybrid system presented in this thesis with other object manipulation mechanisms. This could include mechanisms that employ different forms of implicit communication, such as observation, or within different object manipulation tasks. For example, this thesis investigates object manipulation where the robots are rigidly connected to the object and tightly coupled, with the object suspended between them, comparisons could thus be made with other systems where the robots are not attached to the object, or where the object is on the floor rather than suspended and is pushed.

10.3 Future Work

There are several areas that can be explored to further develop the work presented in this thesis.

The two communication strategies and the hybrid system were only investigated when executing object manipulation tasks at one velocity, which was purposefully done to narrow down the performance profile analysis. However, as discussed in Chapters 4 and 7.2, the noise that was injected into the wheel speeds to produce some variability affected the performance of the strategies and hybrid system, particularly for high noise values. A velocity profile would be the next logical step in developing this system to provide greater insight into the system's stability when operating at different velocities. This would be achieved by taking the hybrid system described in Chapter 7.2 and running the same experiments across the different environments for a range of velocity values. The system currently uses a rotational velocity value of 0.03 within the simulations, which is a linear velocity value of 0.75 metres per second when accounting for the wheel radius of 0.04m. A noise value between 0 and 1 was injected on the wheel speeds creating a noise envelope between 0.75 and 1.75 metres per second. A starting point for velocity profile analysis would be to investigate a range of linear velocities from 0.5 to 2.5 metres per second in intervals of 0.05 metres per second, which would translate to a rotation velocity range between 0.02 and 0.1 radians per second.

The method of combination employed in the hybrid system is a weighted sum algorithm, and three discrete weighting values were used in Chapters 7.2 and 8 to evaluate the performance of the hybrid system. Further work should explore a larger parameter sweep for weighting values to provide a clearer image of how performance of the hybrid system changes with weighting. Results in Chapter 7.2 showed that there was a sharp decrease in time, and a sharp increase in path fidelity from the fully explicit system (weighting value of 0) to the 0.25 weighting. A smaller interval parameter search between 0 and 0.25 should be explored, as a starting point to understand how behaviour changes within that window, and begin a wider analysis of weighting values in the hybrid system.

Rather than an exhaustive search across possible weighting values, machine learning techniques could be implemented to optimise the hybrid system in two ways. Firstly, work could be conducted to determine the weighting values required for the hybrid system to individually optimise each of the five metrics during task execution. For example, reinforcement learning algorithms, where the system is rewarded for performing well in a specific metric, could be explored. This would provide more understanding of the performance profile of the hybrid system and enable implementations of the system where only one metric needs to be optimised. This analysis would be performed by developing a reinforcement learning neural network for the hybrid system described in Chapter 7.2 and training it to optimise a single metric at a time.

Secondly, the search space could be explored for the weighting that optimises the system across all metrics. Multi object optimisation should be investigated in order to do this. As found in Chapters 7.2 and 8, the test metrics of task completion, completion time, path fidelity, total distance travelled and maximum displacement do not complement each other: in some cases the performance of one contradicts the performance of the other. For example the fastest completion time at a weighting of 0.75 results in the highest value of maximum displacement of the object. An optimisation strategy needs to be able to maximise and minimise different metrics simultaneously. Multi object optimisation, such as Pareto optimality, would allow for the parameter space to be searched and to converge on the weighting value that provided the most optimal compromise across the five metrics (known as the Pareto front). The Non-dominated Sorting Genetic Algorithm II, which has been shown to be a fast and elitist algorithm that converges close to the Pareto-optimal front (Deb et al., 2002), could be used to achieve this. The starting point for this analysis would be to apply the non-dominated sorting genetic algorithm II to the hybrid system described in Chapter 7.2 across the four different environments used throughout this thesis. This would determine a weighting which optimises performance across all metrics for the different environments. It would then be possible to expand the analysis to explore the Pareto front for the system manipulating different object types.

Thirdly, as discussed earlier in this chapter, a limitation of the existing analysis presented in this thesis is that the hybrid's system is only evaluated within simulation. Valuable future work would involved working towards closing the reality gap and performing experiments within the real world. Jakobi et al. (1995) stated demonstrated that a way to close the reality gap was to introduce noise within a simulation, as it makes the simulation more realistic. The first step to closing the reality gap in this system would thus be to create an appropriate noise envelope for the hybrid system described in Chapter 7.2 and by injecting noise into the vision sensors on the Leader, the force sensor on the Follower and on the motor's of both robot's wheels. This analysis would provide insight as to whether the controllers could perform similarly within the real world. The next step would be to port the controllers onto real world platforms, which would be an extensive undertaking. The BubbleRob platform used throughout this thesis only exists in simulation, so real world alternatives would have to be used to implement this system in real life. There exist multiple commercially available omnidirectional robots with three wheels similar to the morphology of the Follower robot described in this thesis such as one created by Nexus Robots [1], and one by Active Robots [2]. These robots would need to be modified to include a force sensor for the Follower robot to measure force exerted by the Follower. The popular educational robot platform the e-puck, (Mondada et al., 2009) could be used as a two wheel platform for the Leader robot. These robot platforms can all be programmed within the programming language C++, one of the main programming language of CoppeliaSim, which will aid in porting the controllers from one platform to another.

Finally, the inspiration for the hybrid system in this thesis is the human ability to combine explicit and implicit communication within object manipulation tasks. When cooperating in this manner, humans actually vary the combination of the two forms throughout task execution, depending on the situation. For example, if two humans are carrying a box together during a house move, sensing the forces being exerted on the box can suffice with the occasional verbal instruction (a combination of explicit and implicit communication). However, if the two humans suddenly approach a staircase that one human in the pair cannot see, a quick verbal instruction to 'Stop!' (fully explicit communication) is the most effective form of communication in that moment. Introducing additional complexity to the hybrid system, either through an evolutionary or reinforcement learning technique, which allows the system to adjust the combination value throughout a task, would make the system more adaptive to dynamic environments than a fully explicit or implicit strategy working in isolation.

[1]`https://www.robotshop.com/uk/3wd-compact-omni-directional-arduino-compatible-mobile-robot.html` (Accessed: 21/04/2022)

[2]`https://www.active-robots.com/3wd-100mm-omni-directional-triangle-mobile-robot-kit.html` (Accessed: 21/04/2022)

Appendix A

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Appendix B

Video Library of Simulations

Video recordings of some of the simulations conducted throughout this thesis were recorded and uploaded to YouTube, where they are viewable for reference [1]

This Appendix provides a list of the videos included in the YouTube playlist that are referenced throughout the Thesis.

1. Chapter: 4: Comparing Communication Strategies in Simple Object Manipulation Tasks
   (a) The explicit strategy overshooting corners in the second cluttered environment
   (b) The implicit strategy demonstrating a tremor in the third cluttered environment
2. Chapter: 5: Communication Strategies Manipulating Objects of Different Size and Shape
   (a) The implicit strategy exhibiting task failure in the third random environment with the cylinder
   (b) The implicit strategy exhibiting task failure in the third line following environment with the cylinder
   (c) The implicit strategy performing a corrective movement with the medium object at the beginning of the task to align with the path trajectory in the first random environment
3. Chapter: 6: Fault Tolerance of Implicit and Explicit Communication in Object Manipulation Tasks
   (a) The implicit strategy demonstrating task completion after veering off the path in the first line following environment and in the presence of a vision sensor fault in the left sensor
   (b) The implicit strategy demonstrating task failure in the third line following path in the presence of a partial motor fault in the leader's right wheel

[1] `https://youtube.com/playlist?list=PL3VOqIjlEAJdDfrwCjuX5f2Jof4j0San3` (Accessed: 21/04/2022)

   (c) The explicit strategy demonstrating incorrect incompletion behaviour by not reaching the end zone in the third random environment in the presence of a partial motor fault in the leader's left wheel
   (d) The explicit strategy demonstrating an offset in path fidelity in the simple environment in the presence of a partial motor fault in the leader's left wheel
   (e) The explicit strategy demonstrating an offset in path fidelity in the simple environment in the presence of a partial motor fault in the leader's right wheel
   (f) The explicit strategy demonstrating incorrect incompletion behaviour by not reaching the end zone in the first cluttered environment in the presence of a partial motor fault in wheel 1 of the follower

4. Chapter: 7.2: Combining Implicit and Explicit Communication into a Hybrid System
   (a) The hybrid system at a 0.25 weighting exhibiting task failure in the third line following path
   (b) The hybrid system at a 0.5 weighting exhibiting task failure in the third line following path
   (c) The hybrid system at a 0.75 weighting exhibiting task completion in the third line following path
   (d) The hybrid system at a 0.25 weighting exhibiting task completion after veering off the path in the second line following environment

5. Chapter: 8: Hybrid System with Objects of Different Size and Shape
   (a) The hybrid system at a 0.5 weighting with the medium object demonstrating task failure in the third line following environment due to a large overshoot

6. Chapter: 9: Fault Tolerance of Hybrid System in Object Manipulation Tasks
   (a) The hybrid system with a weighting of 0.5 exhibiting task completion after veering off the path in the first line following environment in the presence of a left vision sensor fault
   (b) The hybrid system with a weighting of 0.75 exhibiting task completion after veering off the path in the first line following environment in the presence of a right vision sensor fault
   (c) The hybrid system with a weighting of 0.25 exhibiting task completion after veering off the path and performing a circle in the first line following environment in the presence of a left vision sensor fault
   (d) The explicit strategy demonstrating erratic oscillatory behaviour during task completion in the second line following environment in the presence of a partial motor fault in the leader's left wheel

(e) The hybrid system with a weighting of 0.25 demonstrating task failure in the second line following environment in the presence of a partial motor fault in the leader's left wheel

(f) The hybrid system with a weighting of 0.5 exhibiting task completion in the third line following environment in the presence of a partial motor fault in wheel 2 of the follower

(g) The hybrid system with a weighting of 0.5 exhibiting task completion in the third line following environment in the presence of a partial motor fault in wheel 3 of the follower

(h) The hybrid system with a weighting of 0.25 exhibiting incompletion behaviour by not reaching the end zone in the first cluttered environment in the presence of a partial motor fault in wheel 1 of the follower

Appendix C

Experimental Data Results from Chapter 4: Comparing Strategies in Simple Object Manipulation Tasks

Table C.1: Mean Time Taken and Standard Deviation for Communication Strategies to Complete Task in Seconds

Type		Path		
		1	2	3
LF	Exp	121.81 (46.49)	119.22 (40.55)	121.15 (35.70)
	Imp	80.25 (18.25)	79.18 (18.89)	81.45 (19.03)
	Sig. Diff.	p <0.001	p <0.001	p <0.001
SE	Exp	170.98 (62.64)		
	Imp	118.84 (26.18)		
	Sig. Diff.	p <0.001		
CE	Exp	414.36 (127.10)	445.31 (113.61)	431.18 (120.53)
	Imp	271.44 (67.54)	257.93 (58.21)	263.55 (65.87)
	Sig. Diff.	p <0.001	p <0.001	p <0.001
RE	Exp	189.45 (57.78)	266.01 (80.07)	181.78 (94.63)
	Imp	137.92 (34.28)	168.28 (41.27)	95.06 (20.45)
	Sig. Diff.	p <0.001	p <0.001	p <0.001

Table C.2: Mean and Standard Deviation Total Distance Travelled By Object in Metres

Type		Path		
		1	2	3
LF	Exp	3.51 (0.06)	3.33 (0.06)	3.42 (0.05)
	Imp	3.50 (0.05)	3.36 (0.07)	3.45 (0.06)
	Sig. Diff.	0.974	0.019	0.004
SE	Exp	5.27 (0.05)		
	Imp	5.28 (0.06)		
	Sig. Diff.	0.506		
CE	Exp	12.82 (0.20)	12.51 (0.06)	12.40 (0.14)
	Imp	12.85 (0.25)	12.63 (0.21)	12.52 (0.24)
	Sig. Diff.	0.971	p <0.001	0.002
RE	Exp	6.18 (0.03)	8.00 (0.09)	4.42 (0.04)
	Imp	6.16 (0.04)	7.97 (0.09)	4.39 (0.05)
	Sig. Diff.	p <0.001	p <0.001	p <0.001

Table C.3: Mean Maximum Displacement and Standard Deviation of Object During Task Execution in Metres

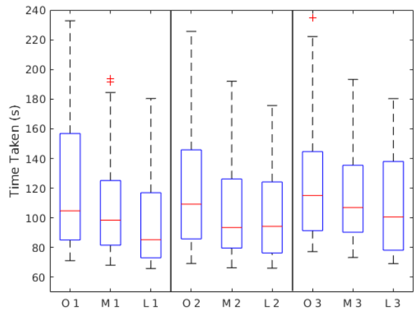
Type		Path		
		1	2	3
LF	Exp	0.018 (0.006)	0.018 (0.006)	0.019 (0.005)
	Imp	0.029 (0.005)	0.031 (0.005)	0.033 (0.006)
	Sig. Diff.	p <0.001	p <0.001	p <0.001
SE	Exp	0.018 (0.006)		
	Imp	0.031 (0.004)		
	Sig. Diff.	p <0.001		
CE	Exp	0.019 (0.005)	0.016 (0.004)	0.017 (0.005)
	Imp	0.037 (0.003)	0.038 (0.002)	0.038 (0.003)
	Sig. Diff.	p <0.001	p <0.001	p <0.001
RE	Exp	0.019 (0.005)	0.018 (0.006)	0.017 (0.005)
	Imp	0.034 (0.004)	0.034 (0.003)	0.033 (0.004)
	Sig. Diff.	p <0.001	p <0.001	p <0.001

Table C.4: Percentage Mean and Standard Deviation Path Fidelity for Both Communication Strategies

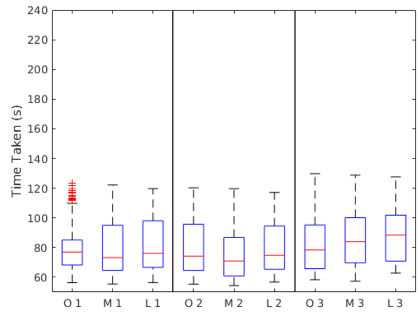
Type		Path		
		1	2	3
LF	Exp	90.75% (14.93%)	100% (∼0%)	99.40% (3.43%)
	Imp	93.00% (12.35%)	89.67% (14.17%)	96.57% (9.49%)
	Sig. Diff.	0.357	p <0.001	0.005
SE	Exp	91.00% (2.12%)		
	Imp	91.79% (1.60%)		
	Sig. Diff.	0.002		
CE	Exp	64.09% (15.65%)	72.96% (8.33%)	69.04% (15.25%)
	Imp	70.78% (3.55%)	69.44% (2.80%)	70.56% (3.35%)
	Sig. Diff.	p <0.001	0.013	0.216
RE	Exp	54.36% (23.85%)	56.36% (21.46%)	49.84% (23.26%)
	Imp	75.31% (9.04%)	68.40% (5.61%)	61.80% (14.57%)
	Sig. Diff.	p <0.001	p <0.001	p <0.001

Appendix D

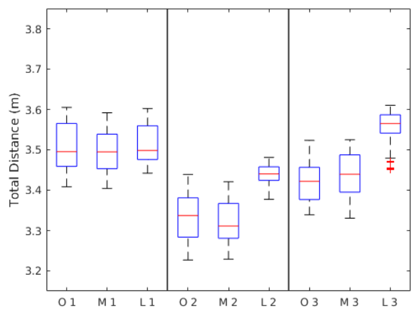
Experimental Data from Chapter 5: Communication Strategies Manipulating Objects of Different Size and Shape



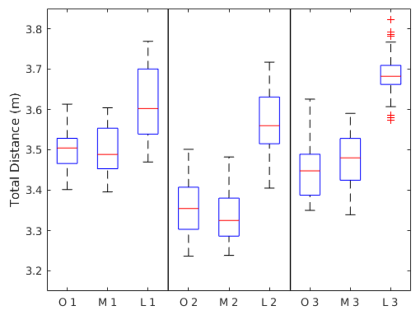
(a) Explicit: Mean Time Taken and Standard Deviation



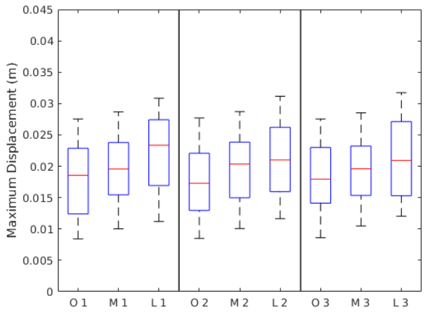
(b) Implicit: Mean Time Taken and Standard Deviation



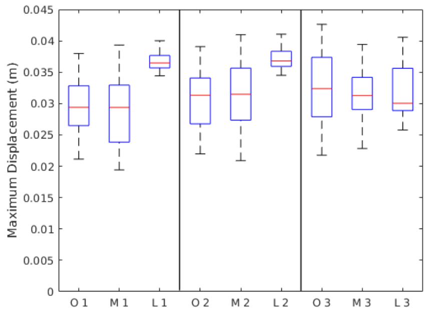
(c) Explicit: Mean Total Distance Travelled and Standard Deviation



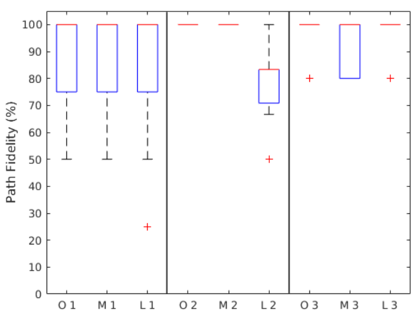
(d) Implicit: Mean Total Distance Travelled and Standard Deviation



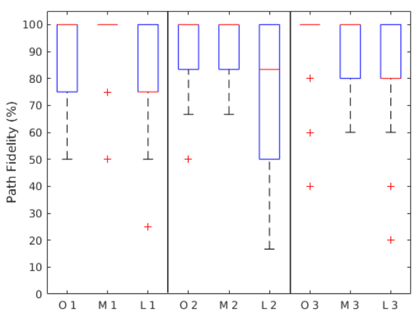
(e) Explicit: Mean Maximum Displacement and Standard Deviation



(f) Implicit: Mean Maximum Displacement and Standard Deviation

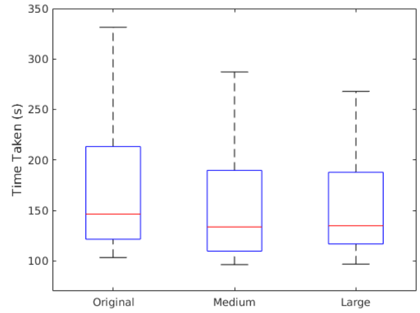


(g) Explicit: Mean Percentage Path Fidelity and Standard Deviation

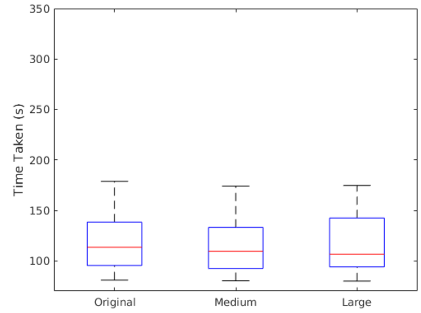


(h) Implicit: Mean Percentage Path Fidelity and Standard Deviation

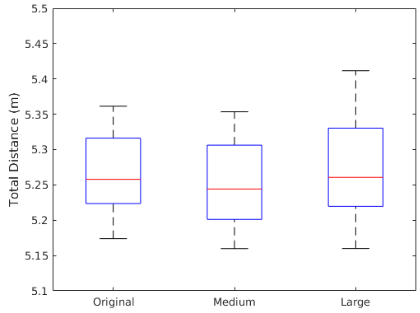
Figure D.1: Performance of both communication strategies across all design requirement metrics in the Line Following Environment for different sized objects



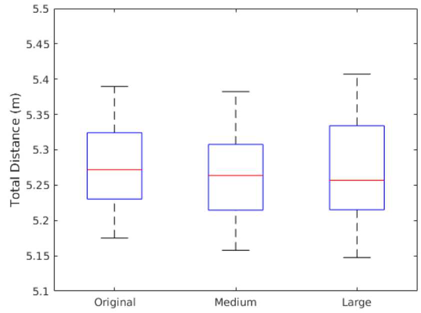
(a) Explicit: Mean Time Taken and Standard Deviation



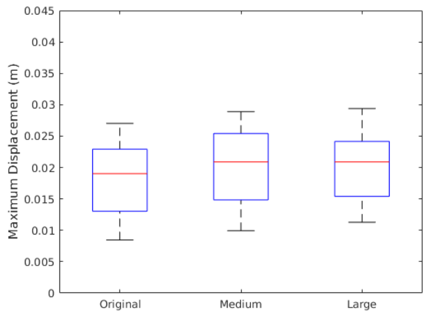
(b) Implicit: Mean Time Taken and Standard Deviation



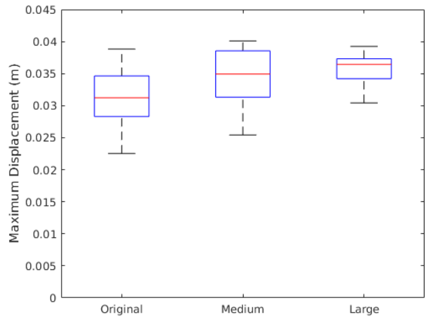
(c) Explicit: Mean Total Distance Travelled and Standard Deviation



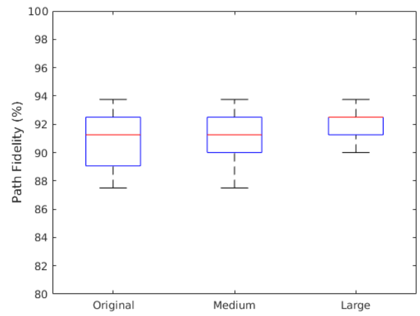
(d) Implicit: Mean Total Distance Travelled and Standard Deviation



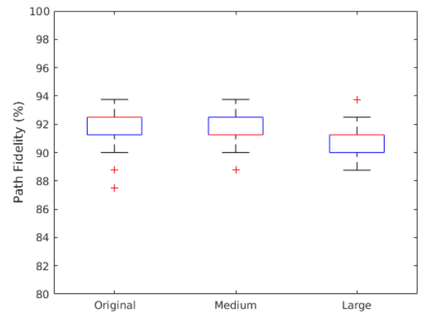
(e) Explicit: Mean Maximum Displacement and Standard Deviation



(f) Implicit: Mean Maximum Displacement and Standard Deviation

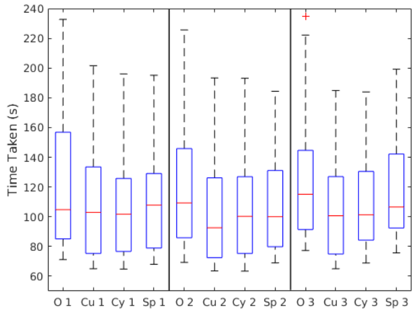


(g) Explicit: Mean Percentage Path Fidelity and Standard Deviation

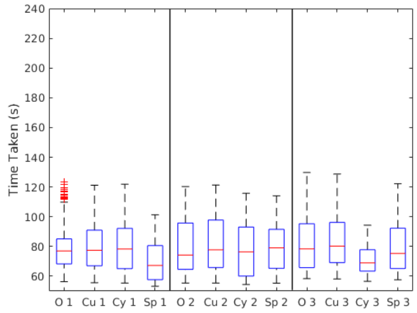


(h) Implicit: Mean Percentage Path Fidelity and Standard Deviation

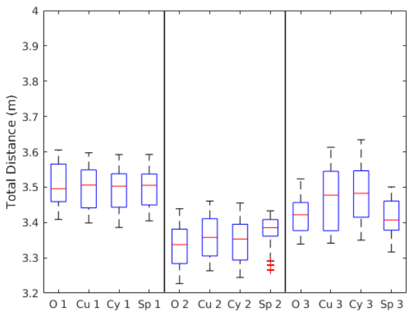
Figure D.2: Performance of both communication strategies across all design requirement metrics in the Simple Environment for different sized objects



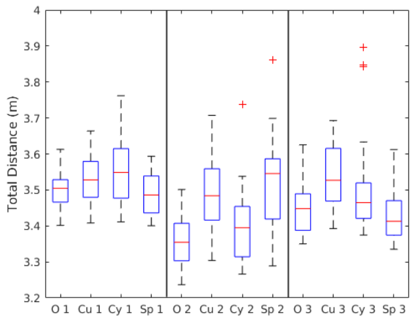
(a) Explicit: Mean Time Taken and Standard Deviation



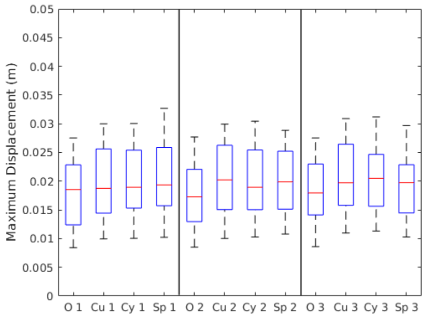
(b) Implicit: Mean Time Taken and Standard Deviation



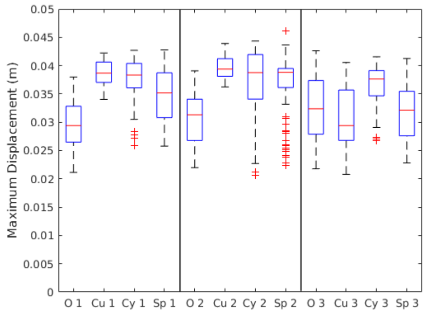
(c) Explicit: Mean Total Distance Travelled and Standard Deviation



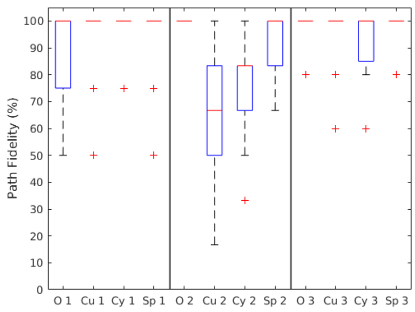
(d) Implicit: Mean Total Distance Travelled and Standard Deviation



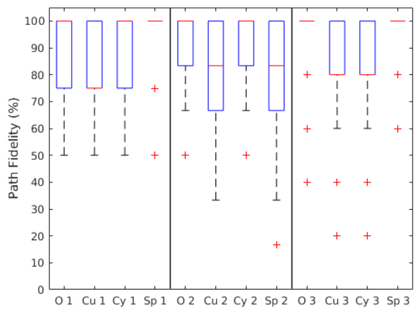
(e) Explicit: Mean Maximum Displacement and Standard Deviation



(f) Implicit: Mean Maximum Displacement and Standard Deviation

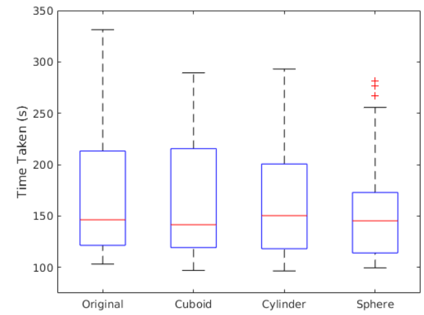


(g) Explicit: Mean Percentage Path Fidelity and Standard Deviation

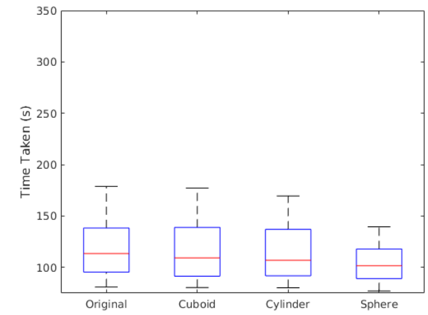


(h) Implicit: Mean Percentage Path Fidelity and Standard Deviation

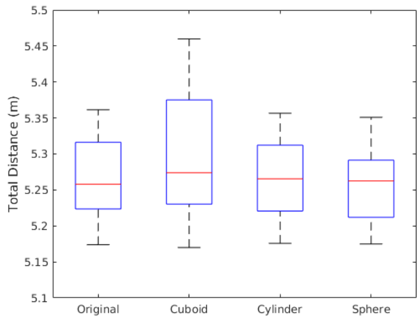
Figure D.3: Performance of both communication strategies across all design requirement metrics in the Line Following Environment for different shaped objects



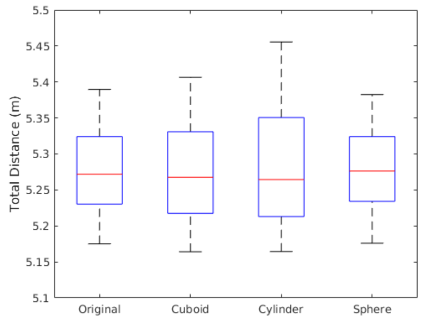
(a) Explicit: Mean Time Taken and Standard Deviation



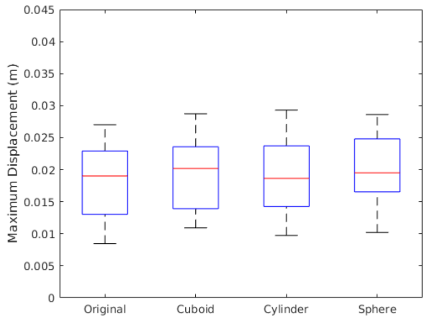
(b) Implicit: Mean Time Taken and Standard Deviation



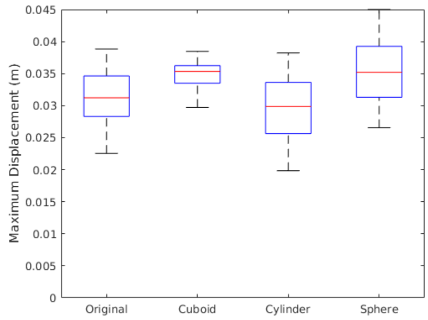
(c) Explicit: Mean Total Distance Travelled and Standard Deviation



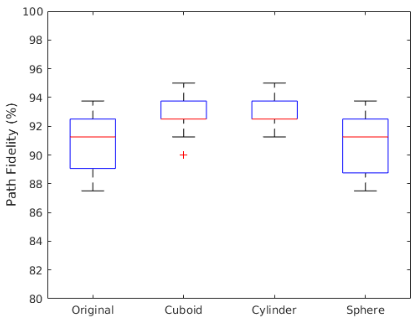
(d) Implicit: Mean Total Distance Travelled and Standard Deviation



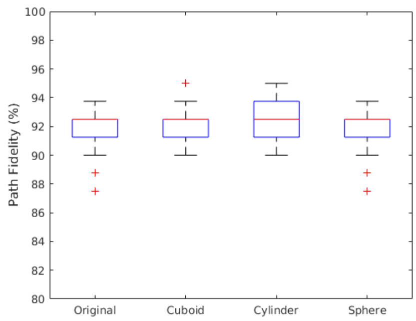
(e) Explicit: Mean Maximum Displacement and Standard Deviation



(f) Implicit: Mean Maximum Displacement and Standard Deviation



(g) Explicit: Mean Percentage Path Fidelity and Standard Deviation



(h) Implicit: Mean Percentage Path Fidelity and Standard Deviation

Figure D.4: Performance of both communication strategies across all design requirement metrics in the Simple Environment for different shaped objects

Table D.1: Mean Time Taken in Seconds and Standard Deviation to Complete Task for Both Communication Strategies Manipulating Different Sized Objects in Line Following Environment

Object Size	Type	Line Following Paths		
		1	2	3
Medium	Exp	110.15 (36.34)	103.20 (29.99)	114.58 (29.99)
	Exp Original	121.81 (46.49)	119.22 (40.55)	121.15 (35.70)
	Sig. Diff	0.138	0.006	0.301
	Imp	80.51 (20.25)	76.32 (17.90)	86.05 (19.00)
	Imp Original	80.25 (18.25)	79.18 (18.89)	81.45 (19.03)
	Sig. Diff	0.561	0.142	0.060
Large	Exp	98.95 (31.63)	102.55 (30.90)	109.30 (33.62)
	Exp Original	121.81 (46.49)	119.22 (40.55)	121.15 (35.70)
	Sig. Diff	$p < 0.001$	0.003	0.007
	Imp	81.49 (18.46)	80.91 (17.85)	87.94 (17.17)
	Imp Original	80.25 (18.25)	79.18 (18.89)	81.45 (19.03)
	Sig. Diff	0.803	0.614	0.002

Table D.2: Mean Time Taken in Seconds and Standard Deviation to Complete Task for Both Communication Strategies Manipulating Different Sized Objects in the Simple and Cluttered Environmental Setups

Object Size	Type	Path			
		1		2	3
		SE	CE	CE	CE
Medium	Exp	153.61 (53.24)	367.45 (117.37)	411.77 (96.83)	357.12 (104.05)
	Exp Original	170.98 (62.64)	414.36 (127.10)	445.31 (113.61)	431.18 (120.53)
	Sig. Diff.	0.028	p <0.001	p <0.001	p <0.001
	Imp	114.57 (26.20)	264.56 (57.86)	269.61 (49.02)	254.58 (52.23)
	Imp Original	118.84 (26.18)	271.44 (67.54)	257.93 (58.21)	263.55 (65.87)
	Sig. Diff	0.709	0.201	0.051	0.424
Large	Exp	154.24 (48.96)	397.76 (86.10)	453.23 (64.87)	374.15 (84.30)
	Exp Original	170.98 (62.64)	414.36 (127.10)	445.31 (113.61)	431.18 (120.53)
	Sig. Diff.	0.088	0.167	0.341	0.001
	Imp	117.74 (28.22)	259.35 (58.22)	396.06 (24.93)	250.73 (49.66)
	Imp Original	118.84 (26.18)	271.44 (67.54)	257.93 (58.21)	263.55 (65.87)
	Sig. Diff	0.891	0.035	p <0.001	0.232

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Table D.3: Mean Time Taken to Complete Task in Seconds and Standard Deviation for Both Communication Strategies Different Sized Objects in Randomly Generated Environments

Object Size	Type	Randomly Generated Environment		
		1	2	3
Medium	Exp	172.27 (54.74)	221.42 (66.42)	128.70 (37.67)
	Exp Original	189.45 (57.78)	266.01 (80.07)	181.78 (94.63)
	Sig. Diff	p <0.001	p <0.001	p <0.001
	Imp	130.83 (27.55)	169.64 (39.01)	99.31 (22.88)
	Imp Original	137.92 (34.28)	168.28 (41.27)	95.06 (20.45)
	Sig. Diff	0.234	0.875	0.397
Large	Exp	187.93 (45.48)	320.92 (26.08)	143.73 (36.33)
	Exp Original	189.45 (57.78)	266.01 (80.07)	181.78 (94.63)
	Sig. Diff	0.014	p <0.001	p <0.001
	Imp	127.13 (27.15)	169.84 (38.40)	98.00 (22.14)
	Imp Original	137.92 (34.28)	168.28 (41.27)	95.06 (20.45)
	Sig. Diff	0.034	0.888	0.167

Table D.4: Mean Time Taken in Seconds and Standard Deviation to Complete Task for Both Communication Strategies Manipulating Different Shaped Objects in the Line Following Environmental Setup

Object Shape	Type	Line Following Environment Path		
		1	2	3
Cuboid	Exp	107.70 (37.31)	102.67 (34.21)	107.54 (34.70)
	Exp Original	121.81 (46.49)	119.22 (40.55)	121.15 (35.70)
	Sig. Diff.	0.025	p <0.001	0.005
	Imp	80.49 (17.28)	82.24 (18.80)	84.59 (17.91)
	Imp Original	80.25 (18.25)	79.18 (18.89)	81.45 (19.03)
	Sig. Diff	0.822	0.340	0.135
Cylinder	Exp	109.33 (37.13)	106.12 (34.81)	108.91 (33.18)
	Exp Original	121.81 (46.49)	119.22 (40.55)	121.15 (35.70)
	Sig. Diff.	0.097	0.013	0.007
	Imp	81.16 (19.30)	77.71 (17.77)	71.24 (10.43)
	Imp Original	80.25 (18.25)	79.18 (18.89)	81.45 (19.03)
	Sig. Diff	0.774	0.301	0.003
Sphere	Exp	110.92 (35.90)	109.25 (34.70)	119.43 (34.93)
	Exp Original	121.81 (46.49)	119.22 (40.55)	121.15 (35.70)
	Sig. Diff.	0.199	0.098	0.700
	Imp	69.73 (12.71)	80.68 (16.70)	81.12 (18.45)
	Imp Original	80.25 (18.25)	79.18 (18.89)	81.45 (19.03)
	Sig. Diff	p <0.001	0.582	0.997

Table D.5: Mean Time Taken in Seconds and Standard Deviation to Complete Task for Both Communication Strategies Manipulating Different Shaped Objects in the Simple and Cluttered Environmental Setups

Object Shape	Type	Path			
		1		2	3
		SE	CE	CE	CE
Cuboid	Exp	165.22 (56.84)	368.87 (97.27)	556.18 (26.47)	348.40 (106.28)
	Exp Original	170.98 (62.64)	414.36 (127.10)	445.31 (113.61)	431.18 (120.53)
	Sig. Diff.	0.551	0.005	0.006	p <0.001
	Imp	117.49 (29.44)	255.63 (54.45)	449.97 (11.20)	263.37 (56.13)
	Imp Original	118.84 (26.18)	271.44 (67.54)	257.93 (58.21)	263.55 (65.87)
	Sig. Diff	0.497	0.158	p <0.001	0.703
Cylinder	Exp	165.36 (57.02)	408.31 (95.60)	579.09 (14.09)	371.34 (98.62)
	Exp Original	170.98 (62.64)	414.36 (127.10)	445.31 (113.61)	431.18 (120.53)
	Sig. Diff.	0.577	0.648	0.019	p <0.001
	Imp	114.47 (25.48)	267.02 (56.41)	N/A	245.92 (57.82)
	Imp Original	118.84 (26.18)	271.44 (67.54)	257.93 (58.21)	263.55 (65.87)
	Sig. Diff	0.239	0.948	N/A	0.054
Sphere	Exp	154.38 (47.36)	348.72 (92.62)	401.87 (92.39)	351.91 (102.14)
	Exp Original	170.98 (62.64)	414.36 (127.10)	445.31 (113.61)	431.18 (120.53)
	Sig. Diff.	0.115	p <0.001	0.022	p <0.001
	Imp	103.99 (16.98)	221.68 (40.92)	246.10 (35.61)	217.40 (34.26)
	Imp Original	118.84 (26.18)	271.44 (67.54)	257.93 (58.21)	263.55 (65.87)
	Sig. Diff	p <0.001	p <0.001	0.643	p <0.001

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Table D.6: Mean Time Taken to Complete Task in Seconds for Both Communication Strategies Manipulating Different Shaped Objects in Randomly Generated Environments

Object Shape	Type	Randomly Generated Environment		
		1	2	3
Cuboid	Exp	176.15 (58.07)	244.54 (79.93)	144.61 (41.27)
	Exp Original	189.45 (57.78)	266.01 (80.07)	181.78 (94.63)
	Sig. Diff	0.021	0.019	0.010
	Imp	130.21 (27.91)	169.01 (39.19)	105.31 (42.19)
	Imp Original	137.92 (34.28)	168.28 (41.27)	95.06 (20.45)
	Sig. Diff	0.170	0.781	0.046
Cylinder	Exp	179.52 (60.75)	237.12 (73.45)	141.67 (38.09)
	Exp Original	189.45 (57.78)	266.01 (80.07)	181.78 (94.63)
	Sig. Diff	0.028	0.002	0.002
	Imp	126.94 (31.18)	160.42 (37.01)	101.55 (19.64)
	Imp Original	137.92 (34.28)	168.28 (41.27)	95.06 (20.45)
	Sig. Diff	0.013	0.172	0.023
Sphere	Exp	183.60 (57.17)	236.66 (65.54)	139.24 (44.57)
	Exp Original	189.45 (57.78)	266.01 (80.07)	181.78 (94.63)
	Sig. Diff	0.262	0.007	p <0.001
	Imp	118.54 (20.87)	144.78 (27.25)	86.70 (17.23)
	Imp Original	137.92 (34.28)	168.28 (41.27)	95.06 (20.45)
	Sig. Diff	p <0.001	p <0.001	0.002

Table D.7: Mean and Standard Deviation Total Distance Travelled by Object in Metres for Both Communication Strategies Manipulating a Medium Sized Object and a Large Sized Object in the Line Following Environmental Setups

Object Size	Type	Line Following Environments		
		1	2	3
Medium	Exp	3.50 (0.06)	3.32 (0.05)	3.44 (0.05)
	Exp Original	3.51 (0.06)	3.33 (0.06)	3.42 (0.05)
	Sig. Diff	0.364	0.053	0.009
	Imp	3.50 (0.06)	3.34 (0.06)	3.48 (0.06)
	Imp Original	3.50 (0.05)	3.36 (0.07)	3.45 (0.06)
	Sig. Diff	0.371	0.030	0.001
Large	Exp	3.52 (0.05)	3.44 (0.02)	3.55 (0.04)
	Exp Original	3.51 (0.06)	3.33 (0.06)	3.42 (0.05)
	Sig. Diff	0.253	p <0.001	p <0.001
	Imp	3.62 (0.09)	3.57 (0.07)	3.69 (0.05)
	Imp Original	3.50 (0.05)	3.36 (0.07)	3.45 (0.06)
	Sig. Diff	p <0.001	p <0.001	p <0.001

Table D.8: Mean and Standard Deviation Total Distance Travelled by Object in Metres for Both Communication Strategies Manipulating a Medium Sized Object and a Large Sized Object in the Simple and Cluttered Environmental Setups

Object Size	Type	Path			
		1		2	3
		SE	CE	CE	CE
Medium	Exp	5.25 (0.06)	12.81 (0.07)	12.50 (0.02)	12.38 (0.05)
	Exp Original	5.27 (0.05)	12.82 (0.20)	12.51 (0.06)	12.40 (0.14)
	Sig. Diff.	0.092	0.010	0.973	0.816
	Imp	5.26 (0.06)	12.92 (0.11)	12.09 (1.50)	12.53 (0.12)
	Imp Original	5.28 (0.06)	12.85 (0.25)	12.63 (0.21)	12.52 (0.24)
	Sig. Diff	0.257	p <0.001	0.041	p <0.001
Large	Exp	5.27 (0.07)	12.92 (0.06)	12.62 (0.06)	12.54 (0.06)
	Exp Original	5.27 (0.05)	12.82 (0.20)	12.51 (0.06)	12.40 (0.14)
	Sig. Diff.	0.508	0.833	p <0.001	p <0.001
	Imp	5.27 (0.07)	13.06 (0.19)	13.05 (0.13)	12.61 (0.15)
	Imp Original	5.28 (0.06)	12.85 (0.25)	12.63 (0.21)	12.52 (0.24)
	Sig. Diff	0.875	p <0.001	p <0.001	p <0.001

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Table D.9: Mean Total Distance Travelled by the Object in Metres and Standard Deviation for Both Communication Strategies Different Sized Objects in Randomly Generated Environments

Object Size	Type	Randomly Generated Environment		
		1	2	3
Medium	Exp	6.11 (0.01)	7.99 (0.02)	4.43 (0.03)
	Exp Original	6.18 (0.03)	8.00 (0.09)	4.42 (0.04)
	Sig. Diff	p <0.001	0.055	p <0.001
	Imp	6.13 (0.04)	8.05 (0.06)	4.44 (0.04)
	Imp Original	6.16 (0.04)	7.97 (0.09)	4.39 (0.05)
	Sig. Diff	p <0.001	p <0.001	p <0.001
Large	Exp	6.18 (0.05)	8.21 (0.05)	4.47 (0.08)
	Exp Original	6.18 (0.03)	8.00 (0.09)	4.42 (0.04)
	Sig. Diff	0.007	p <0.001	p <0.001
	Imp	6.17 (0.05)	8.11 (0.06)	4.50 (0.08)
	Imp Original	6.16 (0.04)	7.97 (0.09)	4.39 (0.05)
	Sig. Diff	0.201	p <0.001	p <0.001

Table D.10: Mean and Standard Deviation Total Distance Travelled by Object in Metres for Both Communication Strategies Manipulating Different Shaped Objects in the Line Following Environmental Setup

Object Shape	Type	Line Following Environment Path		
		1	2	3
Cuboid	Exp	3.50 (0.06)	3.36 (0.06)	3.47 (0.09)
	Exp Original	3.51 (0.06)	3.33 (0.06)	3.42 (0.05)
	Sig. Diff.	0.226	0.003	p <0.001
	Imp	3.53 (0.07)	3.49 (0.09)	3.54 (0.08)
	Imp Original	3.66 (0.02)	3.48 (0.01)	3.59 (0.01)
	Sig. Diff	0.002	p <0.001	p <0.001
Cylinder	Exp	3.50 (0.06)	3.35 (0.06)	3.48 (0.08)
	Exp Original	3.51 (0.06)	3.33 (0.06)	3.42 (0.05)
	Sig. Diff.	0.336	0.108	p <0.001
	Imp	3.56 (0.09)	3.39 (0.08)	3.49 (0.11)
	Imp Original	3.66 (0.02)	3.48 (0.01)	3.59 (0.01)
	Sig. Diff	p <0.001	0.002	0.007
Sphere	Exp	3.50 (0.05)	3.38 (0.04)	3.41 (0.05)
	Exp Original	3.51 (0.06)	3.33 (0.06)	3.42 (0.05)
	Sig. Diff.	0.517	p <0.001	0.588
	Imp	3.49 (0.05)	3.51 (0.11)	3.43 (0.06)
	Imp Original	3.66 (0.02)	3.48 (0.01)	3.59 (0.01)
	Sig. Diff	p <0.001	p <0.001	0.981

Table D.11: Mean and Standard Deviation Total Distance Travelled by Object in Metres for Both Communication Strategies Manipulating Different Shaped Objects in the Simple and Cluttered Environmental Setups

Object Shape	Type	Path			
		1		2	3
		SE	CE	CE	CE
Cuboid	Exp	5.30 (0.09)	12.92 (0.04)	12.67 (0.01)	12.53 (0.04)
	Exp Original	5.27 (0.05)	12.82 (0.20)	12.51 (0.06)	12.40 (0.14)
	Sig. Diff.	0.036	p <0.001	p <0.001	p <0.001
	Imp	5.27 (0.07)	13.03 (0.13)	13.03 (0.07)	12.65 (0.14)
	Imp Original	5.37 (0.01)	13.02 (0.13)	12.64 (0.06)	12.52 (0.10)
	Sig. Diff	0.533	p <0.001	p <0.001	p <0.001
Cylinder	Exp	5.27 (0.05)	12.89 (0.06)	12.54 (0.01)	12.50 (0.08)
	Exp Original	5.27 (0.05)	12.82 (0.20)	12.51 (0.06)	12.40 (0.14)
	Sig. Diff.	0.994	0.013	0.332	p <0.001
	Imp	5.28 (0.07)	13.28 (0.23)	N/A	12.66 (0.16)
	Imp Original	5.37 (0.01)	13.02 (0.13)	12.64 (0.06)	12.52 (0.10)
	Sig. Diff	0.891	p <0.001	N/A	p <0.001
Sphere	Exp	5.26 (0.05)	12.83 (0.10)	12.51 (0.04)	12.42 (0.08)
	Exp Original	5.27 (0.05)	12.82 (0.20)	12.51 (0.06)	12.40 (0.14)
	Sig. Diff.	0.233	0.434	1.000	0.009
	Imp	5.28 (0.05)	12.94 (0.06)	12.69 (0.08)	12.50 (0.04)
	Imp Original	5.37 (0.01)	13.02 (0.13)	12.64 (0.06)	12.52 (0.10)
	Sig. Diff	0.981	p <0.001	p <0.001	0.004

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Table D.12: Mean Total Distance Travelled by the Object in Metres and Standard Deviation for Both Communication Strategies Manipulating Different Shaped Objects in Randomly Generated Environments

Object Shape	Type	Randomly Generated Environment		
		1	2	3
Cuboid	Exp	6.13 (0.05)	8.06 (0.03)	4.45 (0.05)
	Exp Original	6.18 (0.03)	8.00 (0.09)	4.42 (0.04)
	Sig. Diff	p <0.001	p <0.001	p <0.001
	Imp	6.16 (0.05)	8.12 (0.06)	4.51 (0.17)
	Imp Original	6.36 (0.04)	9.75 (2.84)	4.66 (0.03)
	Sig. Diff	0.699	p <0.001	p <0.001
Cylinder	Exp	6.14 (0.009)	8.07 (0.05)	4.44 (0.05)
	Exp Original	6.18 (0.03)	8.00 (0.09)	4.42 (0.04)
	Sig. Diff	p <0.001	p <0.001	p <0.001
	Imp	6.30 (0.12)	8.07 (0.06)	4.44 (0.05)
	Imp Original	6.36 (0.04)	9.75 (2.84)	4.66 (0.03)
	Sig. Diff	p <0.001	p <0.001	p <0.001
Sphere	Exp	6.13 (0.01)	7.99 (0.03)	4.44 (0.03)
	Exp Original	6.18 (0.03)	8.00 (0.09)	4.42 (0.04)
	Sig. Diff	p <0.001	0.629	p <0.001
	Imp	6.19 (0.04)	8.03 (0.04)	4.44 (0.05)
	Imp Original	6.36 (0.04)	9.75 (2.84)	4.66 (0.03)
	Sig. Diff	p <0.001	p <0.001	p <0.001

Table D.13: Mean Maximum Displacement and Standard Deviation of Object in Metres for Both Communication Strategies Manipulating a Medium Sized Object and a Large Sized Object in the Line Following Environmental Setups

Object Size	Type	Line Following Environments		
		1	2	3
Medium	Exp	0.019 (0.006)	0.020 (0.005)	0.020 (0.005)
	Exp Original	0.018 (0.006)	0.018 (0.006)	0.019 (0.005)
	Sig. Diff	0.157	0.005	0.218
	Imp	0.029 (0.006)	0.031 (0.005)	0.031 (0.004)
	Imp Original	0.029 (0.005)	0.031 (0.005)	0.033 (0.006)
	Sig. Diff	0.531	0.783	0.135
Large	Exp	0.022 (0.006)	0.021 (0.006)	0.022 (0.006)
	Exp Original	0.018 (0.006)	0.018 (0.006)	0.019 (0.005)
	Sig. Diff	p <0.001	p <0.001	p <0.001
	Imp	0.037 (0.001)	0.037 (0.002)	0.032 (0.004)
	Imp Original	0.029 (0.005)	0.031 (0.005)	0.033 (0.006)
	Sig. Diff	p <0.001	p <0.001	0.525

Table D.14: Mean Maximum Displacement and Standard Deviation of Object in Metres for Both Communication Strategies Manipulating a Medium Sized Object and a Large Sized Object in the Simple and Cluttered Environmental Setups

Object Size	Type	Path			
		1		2	3
		SE	CE	CE	CE
Medium	Exp	0.020 (0.006)	0.020 (0.005)	0.017 (0.003)	0.020 (0.005)
	Exp Original	0.018 (0.006)	0.019 (0.005)	0.016 (0.004)	0.017 (0.005)
	Sig. Diff.	0.023	0.013	p <0.001	0.002
	Imp	0.035 (0.004)	0.037 (0.004)	0.035 (0.003)	0.036 (0.003)
	Imp Original	0.031 (0.004)	0.037 (0.003)	0.038 (0.002)	0.038 (0.003)
	Sig. Diff	p <0.001	0.295	p <0.001	p <0.001
Large	Exp	0.020 (0.005)	0.020 (0.004)	0.016 (0.002)	0.020 (0.004)
	Exp Original	0.018 (0.006)	0.019 (0.005)	0.016 (0.004)	0.017 (0.005)
	Sig. Diff.	0.026	0.251	0.023	p <0.001
	Imp	0.036 (0.002)	0.039 (0.003)	0.038 (0.002)	0.039 (0.002)
	Imp Original	0.031 (0.004)	0.037 (0.003)	0.038 (0.002)	0.038 (0.003)
	Sig. Diff	p <0.001	0.001	0.698	0.741

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Table D.15: Mean Maximum Displacement and Standard Deviation of Object in Metres for Both Communication Strategies Different Sized Objects in Randomly Generated Environments

Object Size	Type	Randomly Generated Environment		
		1	2	3
Medium	Exp	0.021 (0.005)	0.021 (0.005)	0.020 (0.005)
	Exp Original	0.019 (0.005)	0.018 (0.006)	0.017 (0.005)
	Sig. Diff	p <0.001	0.001	p <0.001
	Imp	0.039 (0.003)	0.036 (0.004)	0.034 (0.004)
	Imp Original	0.034 (0.004)	0.034 (0.003)	0.033 (0.004)
	Sig. Diff	p <0.001	0.001	p <0.001
Large	Exp	0.020 (0.005)	0.018 (0.003)	0.019 (0.004)
	Exp Original	0.019 (0.005)	0.018 (0.006)	0.017 (0.005)
	Sig. Diff	0.001	0.405	p <0.001
	Imp	0.037 (0.003)	0.034 (0.004)	0.040 (0.001)
	Imp Original	0.034 (0.004)	0.034 (0.003)	0.033 (0.004)
	Sig. Diff	p <0.001	0.942	p <0.001

Table D.16: Mean Maximum Displacement and Standard Deviation of Object in Metres for Both Communication Strategies Manipulating Different Shaped Objects in the Line Following Environmental Setup

Object Shape	Type	Line Following Environment Path		
		1	2	3
Cuboid	Exp	0.020 (0.006)	0.021 (0.006)	0.021 (0.006)
	Exp Original	0.018 (0.006)	0.018 (0.006)	0.019 (0.005)
	Sig. Diff.	0.035	p <0.001	0.036
	Imp	0.039 (0.002)	0.040 (0.002)	0.031 (0.005)
	Imp Original	0.029 (0.005)	0.031 (0.005)	0.033 (0.006)
	Sig. Diff	p <0.001	p <0.001	0.011
Cylinder	Exp	0.020 (0.006)	0.020 (0.006)	0.021 (0.006)
	Exp Original	0.018 (0.006)	0.018 (0.006)	0.019 (0.005)
	Sig. Diff.	0.112	0.009	0.008
	Imp	0.038 (0.004)	0.037 (0.006)	0.036 (0.004)
	Imp Original	0.029 (0.005)	0.031 (0.005)	0.033 (0.006)
	Sig. Diff	p <0.001	p <0.001	p <0.001
Sphere	Exp	0.020 (0.006)	0.020 (0.006)	0.019 (0.005)
	Exp Original	0.018 (0.006)	0.018 (0.006)	0.019 (0.005)
	Sig. Diff.	0.022	0.006	0.508
	Imp	0.035 (0.005)	0.037 (0.005)	0.032 (0.005)
	Imp Original	0.029 (0.005)	0.031 (0.005)	0.033 (0.006)
	Sig. Diff	p <0.001	p <0.001	0.194

Table D.17: Mean Maximum Displacement and Standard Deviation of Object in Metres for Both Communication Strategies Manipulating Different Shaped Objects in the Simple and Cluttered Environmental Setups

Object Shape	Type	Path			
		1		2	3
		SE	CE	CE	CE
Cuboid	Exp	0.019 (0.005)	0.022 (0.004)	0.014 (0.001)	0.023 (0.005)
	Exp Original	0.018 (0.006)	0.019 (0.005)	0.016 (0.004)	0.017 (0.005)
	Sig. Diff.	0.179	$p < 0.001$	0.580	$p < 0.001$
	Imp	0.035 (0.002)	0.039 (0.003)	0.040 (0.003)	0.038 (0.003)
	Imp Original	0.031 (0.004)	0.037 (0.003)	0.038 (0.002)	0.038 (0.003)
	Sig. Diff	$p < 0.001$	$p < 0.001$	0.226	0.316
Cylinder	Exp	0.019 (0.006)	0.019 (0.004)	0.0136 (∼0.000)	0.020 (0.005)
	Exp Original	0.018 (0.006)	0.019 (0.005)	0.016 (0.004)	0.017 (0.005)
	Sig. Diff.	0.439	0.699	0.117	$p < 0.001$
	Imp	0.030 (0.005)	0.040 (0.005)	N/A	0.037 (0.005)
	Imp Original	0.031 (0.004)	0.037 (0.003)	0.038 (0.002)	0.038 (0.003)
	Sig. Diff	0.028	$p < 0.001$	N/A	0.390
Sphere	Exp	0.020 (0.005)	0.026 (0.005)	0.019 (0.004)	0.023 (0.006)
	Exp Original	0.018 (0.006)	0.019 (0.005)	0.016 (0.004)	0.017 (0.005)
	Sig. Diff.	0.043	$p < 0.001$	0.008	$p < 0.001$
	Imp	0.036 (0.005)	0.040 (0.005)	0.036 (0.003)	0.038 (0.004)
	Imp Original	0.031 (0.004)	0.037 (0.003)	0.038 (0.002)	0.038 (0.003)
	Sig. Diff	$p < 0.001$	0.002	$p < 0.001$	0.784

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Table D.18: Mean Maximum Displacement and Standard Deviation of Object in Metres for Both Communication Strategies Manipulating Different Shaped Objects in Randomly Generated Environments

Object Shape	Type	Randomly Generated Environment		
		1	2	3
Cuboid	Exp	0.022 (0.006)	0.022 (0.005)	0.020 (0.006)
	Exp Original	0.019 (0.005)	0.018 (0.006)	0.017 (0.005)
	Sig. Diff	0.002	p <0.001	0.002
	Imp	0.041 (0.003)	0.035 (0.003)	0.040 (0.002)
	Imp Original	0.034 (0.004)	0.034 (0.003)	0.033 (0.004)
	Sig. Diff	p <0.001	0.400	p <0.001
Cylinder	Exp	0.021 (0.006)	0.021 (0.05)	0.021 (0.006)
	Exp Original	0.019 (0.005)	0.018 (0.006)	0.017 (0.005)
	Sig. Diff	0.043	0.001	p <0.001
	Imp	0.043 (0.003)	0.034 (0.005)	0.041 (0.002)
	Imp Original	0.034 (0.004)	0.034 (0.003)	0.033 (0.004)
	Sig. Diff	p <0.001	0.555	p <0.001
Sphere	Exp	0.022 (0.007)	0.023 (0.006)	0.021 (0.007)
	Exp Original	0.019 (0.005)	0.018 (0.006)	0.017 (0.005)
	Sig. Diff	0.002	p <0.001	0.003
	Imp	0.040 (0.002)	0.037 (0.005)	0.035 (0.005)
	Imp Original	0.034 (0.004)	0.034 (0.003)	0.033 (0.004)
	Sig. Diff	p <0.001	p <0.001	p <0.001

Table D.19: Percentage Mean and Standard Deviation Path Fidelity for Both Communication Strategies Manipulating a Medium Sized Object and a Large Sized Object in the Line Following Environmental Setup

Object Size	Type	Line Following Environment Path		
		1	2	3
Medium	Exp	91.75% (13.79%)	100% (0%)	94.80% (8.82%)
	Exp Original	90.75% (14.93%)	100% (∼0%)	99.40% (3.43%)
	Sig. Diff.	0.704	1	p <0.001
	Imp	96.50% (9.41%)	94.67% (9.73%)	92.53% (10.91%)
	Imp Original	93.00 (12.35%)	89.67% (14.17%)	96.57% (9.49%)
	Sig. Diff	0.021	0.011	0.001
Large	Exp	88.00% (17.94%)	80.33% (11.21%)	96.60% (7.55%)
	Exp Original	90.75% (14.93%)	100% (∼0%)	99.40% (3.43%)
	Sig. Diff.	0.327	p <0.001	0.001
	Imp	83.25% (19.15%)	74.33% (21.51%)	83.26% (18.10%)
	Imp Original	93.00 (12.35%)	89.67% (14.17%)	96.57% (9.49%)
	Sig. Diff	p <0.001	p <0.001	p <0.001

Table D.20: Percentage Mean and Standard Deviation Path Fidelity for Both Communication Strategies Manipulating a Medium Sized Object and a Large Sized Object in the Simple and Cluttered Environmental Setups

Object Size	Type	Path			
		1		2	3
		SE	CE	CE	CE
Medium	Exp	90.89% (1.60%)	73.07% (9.82%)	77.67% (4.52%)	75.20% (10.06%)
	Exp Original	91.00% (2.12%)	64.09% (15.65%)	72.96% (8.33%)	69.04 (15.25%)
	Sig. Diff.	0.392	p <0.001	p <0.001	p <0.001
	Imp	91.56% (1.14%)	73.03% (5.38%)	70.90% (6.79%)	74.34% (5.52%)
	Imp Original	91.79% (1.60%)	70.78% (3.55%)	69.44% (2.80%)	70.56% (3.35%)
	Sig. Diff	0.277	0.015	p <0.001	p <0.001
Large	Exp	92.10% (1.11%)	84.34% (6.74%)	87.90% (2.59%)	82.39% (7.33%)
	Exp Original	91.00% (2.12%)	64.09% (15.65%)	72.96% (8.33%)	69.04 (15.25%)
	Sig. Diff.	p <0.001	p <0.001	p <0.001	p <0.001
	Imp	91.05% (1.13%)	69.14% (6.01%)	75.13% (2.18%)	71.43% (8.13%)
	Imp Original	91.79% (1.60%)	70.78% (3.55%)	69.44% (2.80%)	70.56% (3.35%)
	Sig. Diff	p <0.001	0.001	p <0.001	0.040

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Table D.21: Mean Percentage Path Fidelity and Standard Deviation for Both Communication Strategies Different Sized Objects in Randomly Generated Environments

Object Size	Type	Randomly Generated Environment		
		1	2	3
Medium	Exp	68.88% (12.96%)	69.43% (9.93%)	61.06% (14.64%)
	Exp Original	54.36% (23.85%)	56.36% (21.46%)	49.84% (23.26%)
	Sig. Diff	p <0.001	p <0.001	p <0.001
	Imp	75.61% (7.52%)	71.93% (6.13%)	65.89% (10.41%)
	Imp Original	75.31% (9.04%)	68.40% (5.61%)	61.80% (14.57%)
	Sig. Diff	0.928	p <0.001	0.390
Large	Exp	85.95% (6.79%)	86.83% (5.13%)	81.35% (12.28%)
	Exp Original	54.36% (23.85%)	56.36% (21.46%)	49.84% (23.26%)
	Sig. Diff	p <0.001	p <0.001	p <0.001
	Imp	70.33% (8.93%)	71.74% (5.13%)	59.65% (8.86%)
	Imp Original	75.31% (9.04%)	68.40% (5.61%)	61.80% (14.57%)
	Sig. Diff	p <0.001	p <0.001	0.012

Table D.22: Percentage Mean and Standard Deviation Path Fidelity for Both Communication Strategies Manipulating Different Shaped Objects in the Line Following Environmental Setup

Object Shape	Type	Line Following Environment Path		
		1	2	3
Cuboid	Exp	95.00% (11.24%)	69.67% (19.73%)	94.40% (10.67%)
	Exp Original	90.75% (14.93%)	100% (∼0%)	99.40% (3.43%)
	Sig. Diff.	0.028	p <0.001	p <0.001
	Imp	84.50% (16.20%)	82.33% (16.21%)	86.29% (16.40%)
	Imp Original	93.00 (12.35%)	89.67% (14.17%)	96.57% (9.49%)
	Sig. Diff	p <0.001	p <0.001	p <0.001
Cylinder	Exp	97.00% (8.16%)	80.17% (15.30%)	93.80% (11.62%)
	Exp Original	90.75% (14.93%)	100% (∼0%)	99.40% (3.43%)
	Sig. Diff.	p <0.001	p <0.001	p <0.001
	Imp	87.00% (16.85%)	91.17% (12.64%)	83.02% (19.37%)
	Imp Original	93.00 (12.35%)	89.67% (14.17%)	96.57% (9.49%)
	Sig. Diff	0.009	0.568	p <0.001
Sphere	Exp	95.75% (10.08%)	91.50% (10.19%)	99.80% (20.00%)
	Exp Original	90.75% (14.93%)	100% (∼0%)	99.40% (3.43%)
	Sig. Diff.	0.010	p <0.001	0.316
	Imp	93.50% (12.62%)	80.17% (21.67%)	97.00% (8.23%)
	Imp Original	93.00 (12.35%)	89.67% (14.17%)	96.57% (9.49%)
	Sig. Diff	0.663	0.002	0.816

Table D.23: Percentage Mean and Standard Deviation Path Fidelity for Both Communication Strategies Manipulating Different Shaped Objects in the Simple and Cluttered Environmental Setups

Object Shape	Type	Path			
		1		2	3
		SE	CE	CE	CE
Cuboid	Exp	93.00% (1.15%)	75.73% (8.16%)	86.12% (1.18%)	75.12% (10.63%)
	Exp Original	91.00% (2.12%)	64.09% (15.65%)	72.96% (8.33%)	69.04 (15.25%)
	Sig. Diff.	p <0.001	p <0.001	p <0.001	0.003
	Imp	92.20% (1.08%)	68.57% (5.34%)	75.17% (1.79%)	72.68% (7.45%)
	Imp Original	91.79% (1.60%)	70.78% (3.55%)	69.44% (2.80%)	70.56% (3.35%)
	Sig. Diff	0.236	0.001	p <0.001	0.003
Cylinder	Exp	92.74% (1.03%)	76.22% (6.42%)	82.13% (0.77%)	75.68% (9.41%)
	Exp Original	91.00% (2.12%)	64.09% (15.65%)	72.96% (8.33%)	69.04 (15.25%)
	Sig. Diff.	p <0.001	p <0.001	0.022	0.007
	Imp	92.50% (1.19%)	67.09% (7.11%)	N/A	67.09% (9.45%)
	Imp Original	91.79% (1.60%)	70.78% (3.55%)	69.44% (2.80%)	70.56% (3.35%)
	Sig. Diff	0.004	p <0.001	N/A	0.002
Sphere	Exp	90.68% (2.01%)	70.25% (9.78%)	76.14% (5.91%)	71.38% (11.63%)
	Exp Original	91.00% (2.12%)	64.09% (15.65%)	72.96% (8.33%)	69.04 (15.25%)
	Sig. Diff.	0.266	0.003	0.008	0.437
	Imp	91.77% (1.38%)	63.60% (6.18%)	67.87% (5.93%)	63.58% (7.38%)
	Imp Original	91.79% (1.60%)	70.78% (3.55%)	69.44% (2.80%)	70.56% (3.35%)
	Sig. Diff	0.653	p <0.001	0.353	p <0.001

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Table D.24: Mean Percentage Path Fidelity and Standard Deviation for Both Communication Strategies Manipulating Different Shaped Objects in Randomly Generated Environments

Object Shape	Type	Randomly Generated Environment		
		1	2	3
Cuboid	Exp	74.97% (10.54%)	75.40% (8.64%)	65.87% (17.54%)
	Exp Original	54.36% (23.85%)	56.36% (21.46%)	49.84% (23.26%)
	Sig. Diff	p <0.001	p <0.001	p <0.001
	Imp	73.07% (7.93%)	69.73% (6.57%)	57.92% (8.35%)
	Imp Original	75.31% (9.04%)	68.40% (5.61%)	61.80% (14.57%)
	Sig. Diff	0.036	0.064	0.330
Cylinder	Exp	71.11% (11.37%)	70.55% (9.48%)	56.24% (15.13%)
	Exp Original	54.36% (23.85%)	56.36% (21.46%)	49.84% (23.26%)
	Sig. Diff	p <0.001	p <0.001	0.006
	Imp	63.55% (11.27%)	66.19% (6.58%)	58.27% (9.52%)
	Imp Original	75.31% (9.04%)	68.40% (5.61%)	61.80% (14.57%)
	Sig. Diff	p <0.001	0.029	0.432
Sphere	Exp	68.73% (16.01%)	68.70% (12.18%)	61.21% (21.32%)
	Exp Original	54.36% (23.85%)	56.36% (21.46%)	49.84% (23.26%)
	Sig. Diff	p <0.001	p <0.001	0.001
	Imp	64.27% (10.10%)	61.98% (8.62%)	51.58% (10.21%)
	Imp Original	75.31% (9.04%)	68.40% (5.61%)	61.80% (14.57%)
	Sig. Diff	p <0.001	p <0.001	p <0.001

Appendix E

Experimental Data from Chapter 6: Fault Tolerance of Implicit and Explicit Communication in Object Manipulation Tasks

E.1 Vision Sensor Fault

Table E.1: Mean Time Taken in Seconds and Standard Deviation for Both Strategies in the Line Following Environment in the presence of Vision Sensor Faults

Vision Sensor Fault	Type	Line Following Environment Paths		
		1	2	3
Left	Exp	N/A	119.87 (38.55)	N/A
	Exp Original	121.81 (46.49)	119.22 (40.55)	121.15 (35.70)
	Sig Diff.	N/A	p <0.001	N/A
	Imp	219.40 (49.54)	79.03 (14.36)	N/A
	Imp Original	80.25 (18.25)	79.18 (18.89)	81.45 (19.03)
	Sig Diff.	p <0.001	0.837	N/A
Middle	Exp	116.03 (37.21)	114.32 (40.40)	123.55 (41.75)
	Exp Original	121.81 (46.49)	119.22 (40.55)	121.15 (35.70)
	Sig Diff.	0.736	0.361	0.950
	Imp	77.76 (18.82)	77.43 (16.85)	83.21 (22.52)
	Imp Original	80.25 (18.25)	79.18 (18.89)	81.45 (19.03)
	Sig Diff.	0.305	0.334	0.980
Right	Exp	116.09 (36.69)	N/A	120.18 (40.20)
	Exp Original	121.81 (46.49)	119.22 (40.55)	121.15 (35.70)
	Sig Diff.	0.700	N/A	0.499
	Imp	80.02 (19.72)	N/A	84.53 (20.58)
	Imp Original	80.25 (18.25)	79.18 (18.89)	81.45 (19.03)
	Sig Diff.	0.760	N/A	0.328

Table E.2: Mean Total Distance Travelled in Metres by the Object and Standard Deviation for Both Strategies in the Line Following Environment in the presence of Vision Sensor Faults

Vision Sensor Fault	Type	Line Following Environment Paths		
		1	2	3
Left	Exp	N/A	3.34 (0.06)	N/A
	Exp Original	3.51 (0.06)	3.33 (0.06)	3.42 (0.05)
	Sig Diff.	N/A	p <0.001	N/A
	Imp	4.84 (0.13)	3.35 (0.05)	N/A
	Imp Original	3.50 (0.05)	3.36 (0.07)	3.45 (0.06)
	Sig Diff.	p <0.001	0.742	N/A
Middle	Exp	3.51 (0.05)	3.33 (0.06)	3.45 (0.05)
	Exp Original	3.51 (0.06)	3.33 (0.06)	3.42 (0.05)
	Sig Diff.	0.872	0.492	p <0.001
	Imp	3.49 (0.06)	3.34 (0.06)	3.48 (0.08)
	Imp Original	3.50 (0.05)	3.36 (0.07)	3.45 (0.06)
	Sig Diff.	0.282	0.241	p <0.001
Right	Exp	3.50 (0.05)	N/A	3.41 (0.05)
	Exp Original	3.50 (0.05)	3.36 (0.07)	3.45 (0.06)
	Sig Diff.	0.720	N/A	0.187
	Imp	3.50 (0.06)	N/A	3.45 (0.07)
	Imp Original	3.50 (0.05)	3.36 (0.07)	3.45 (0.06)
	Sig Diff.	0.581	N/A	0.769

Table E.3: Mean Maximum Displacement in Metres of the Object and Standard Deviation for Both Strategies in the Line Following Environment in the presence of Vision Sensor Faults

Vision Sensor Fault	Type	Line Following Environment Paths		
		1	2	3
Left	Exp	N/A	0.018 (0.005)	N/A
	Exp Original	0.018 (0.006)	0.018 (0.006)	0.019 (0.005)
	Sig Diff.	N/A	0.736	N/A
	Imp	0.028 (0.005)	0.031 (0.005)	N/A
	Imp Original	0.029 (0.005)	0.031 (0.005)	0.033 (0.006)
	Sig Diff.	0.155	0.264	N/A
Middle	Exp	0.018 (0.005)	0.018 (0.005)	0.018 (0.006)
	Exp Original	0.018 (0.006)	0.018 (0.006)	0.019 (0.005)
	Sig Diff.	0.885	0.688	0.622
	Imp	0.030 (0.005)	0.031 (0.005)	0.033 (0.005)
	Imp Original	0.029 (0.005)	0.031 (0.005)	0.033 (0.006)
	Sig Diff.	0.2636	0.324	0.673
Right	Exp	0.018 (0.005)	N/A	0.019 (0.006)
	Exp Original	0.018 (0.006)	0.018 (0.006)	0.019 (0.005)
	Sig Diff.	0.702	N/A	0.551
	Imp	0.030 (0.05)	N/A	0.031 (0.006)
	Imp Original	0.029 (0.005)	0.031 (0.005)	0.033 (0.006)
	Sig Diff.	0.812	N/A	0.169

Table E.4: Mean Percentage Path Fidelity and Standard Deviation for Both Strategies in the Line Following Environment in the presence of Vision Sensor Faults

Vision Sensor Fault	Type	Line Following Environment Paths		
		1	2	3
Left	Exp	N/A	100% (∼0%)	N/A
	Exp Original	90.75% (14.93%)	100% (∼0%)	99.40% (3.43%)
	Sig Diff.	N/A	1.00	N/A
	Imp	21.63% (8.62%)	82.33% (20.21%)	N/A
	Imp Original	93.00 (12.35%)	89.67% (14.17%)	96.57% (9.49%)
	Sig Diff.	p <0.001	0.010	N/A
Middle	Exp	99.00% (4.92%)	73.33% (12.08%)	99.80% (2.00%)
	Exp Original	90.75% (14.93%)	100% (∼0%)	99.40% (3.43%)
	Sig Diff.	p <0.001	p <0.001	0.316
	Imp	97.25% (7.86%)	91.83% (12.19%)	97.76% (6.35%)
	Imp Original	93.00 (12.35%)	89.67% (14.17%)	96.57% (9.49%)
	Sig Diff.	0.006	0.362	0.510
Right	Exp	90.50% (14.12%)	N/A	99.80% (2.00%)
	Exp Original	90.75% (14.93%)	100% (∼0%)	99.40% (3.43%)
	Sig Diff.	0.744	N/A	0.316
	Imp	91.00% (15.29%)	N/A	86.87% (14.61%)
	Imp Original	93.00 (12.35%)	89.67% (14.17%)	96.57% (9.49%)
	Sig Diff.	0.462	N/A	p <0.001

E.2 Partial Motor Fault

E.2.1 Leader Wheels

Table E.5: Percentage Task Completion for Both Strategies in the Line Following Environment in the presence of Partial Motor Faults in Leader Wheels

Partial Motor Fault	Type	Line Following Environment Path		
		1	2	3
Left Wheel	Exp	85.00%	73.00%	86.00%
	Exp Original	100.00%	100.00%	100.00%
	Imp	85.00%	93.00%	97.00%
	Imp Original	100.00%	100.00%	99.00%
Right Wheel	Exp	100.00%	67.00%	63.00%
	Exp Original	100.00%	100.00%	100.00%
	Imp	100.00%	84.00%	3.00%
	Imp Original	100.00%	100.00%	99.00%

Table E.6: Percentage Task Completion for Both Strategies in Simple (SE) and Cluttered (CE) Environments in the presence of Partial Motor Faults in Leader Wheels

Partial Motor Fault	Type	Path			
		SE	CE	CE	CE
		1	1	2	3
Left Wheel	Exp	99.00%	32.00%	63.00%	69.00%
	Exp Original	100.00%	100.00%	60.00%	100.00%
	Imp	100.00%	43.00%	93.00%	93.00%
	Imp Original	100.00%	100.00%	100.00%	100.00%
Right Wheel	Exp	92.00%	60.00%	32.00%	68.00%
	Exp Original	100.00%	100.00%	60.00%	100.00%
	Imp	100.00%	67.00%	38.00%	92.00%
	Imp Original	100.00%	100.00%	100.00%	100.00%

Table E.7: Percentage Task Completion for Both Strategies in Randomly Generated Environments in the presence of Partial Motor Faults in Leader Wheels

Partial Motor Fault	Type	Randomly Generated Environment		
		1	2	3
Left Wheel	Exp	94.00%	72.00%	0.00%
	Exp Original	100.00%	100.00%	93.00%
	Imp	100.00%	95.00%	14.00%
	Imp Original	100.00%	100.00%	100.00%
Right Wheel	Exp	98.00%	90.00%	86.00%
	Exp Original	100.00%	100.00%	93.00%
	Imp	100.00%	100.00%	94.00%
	Imp Original	100.00%	100.00%	100.00%

Table E.8: Mean Time Taken in Seconds and Standard Deviation for Both Strategies in the Line Following Environment in the presence of Partial Motor Faults in Leader Wheels

Partial Motor Fault	Type	Line Following Environment		
		1	2	3
Left Wheel	Exp	332.03 (184.73)	296.67 (155.93)	330.82 (201.08)
	Exp Original	121.81 (46.49)	119.22 (40.55)	121.15 (35.70)
	Sig Diff.	p <0.001	p <0.001	p <0.001
	Imp	150.95 (44.70)	150.14 (44.02)	185.03 (99.72)
	Imp Original	80.25 (18.25)	79.18 (18.89)	81.45 (19.03)
	Sig Diff.	p <0.001	p <0.001	p <0.001
Right Wheel	Exp	256.55 (119.29)	243.59 (93.56)	319.11 (128.61)
	Exp Original	121.81 (46.49)	119.22 (40.55)	121.15 (35.70)
	Sig Diff.	p <0.001	p <0.001	p <0.001
	Imp	118.89 (26.00)	216.52 (125.29)	138.92 (39.27)
	Imp Original	80.25 (18.25)	79.18 (18.89)	81.45 (19.03)
	Sig Diff.	p <0.001	p <0.001	0.008

Table E.9: Mean Time Taken in Seconds and Standard Deviation for Both Strategies in Simple (SE) and Cluttered (CE) Environments in the presence of Partial Motor Faults in Leader Wheels

Partial Motor Fault	Type	Path			
		SE 1	CE 1	CE 2	CE 3
Left Wheel	Exp	346.95 (162.98)	443.72 (133.00)	569.82 (101.33)	558.93 (102.58)
	Exp Original	170.98 (62.64)	414.36 (127.10)	445.31 (113.61)	431.18 (120.53)
	Sig Diff.	$p < 0.001$	0.070	$p < 0.001$	$p < 0.001$
	Imp	174.40 (44.54)	438.26 (106.24)	409.67 (92.03)	371.83 (79.76)
	Imp Original	118.84 (26.18)	271.44 (67.54)	257.93 (58.21)	263.55 (65.87)
	Sig Diff.	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$
Right Wheel	Exp	311.86 (125.04)	561.63 (96.89)	635.68 (81.65)	553.33 (85.80)
	Exp Original	170.98 (62.64)	414.36 (127.10)	445.31 (113.61)	431.18 (120.53)
	Sig Diff.	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$
	Imp	179.89 (45.98)	421.21 (88.53)	523.86 (84.72)	431.05 (97.74)
	Imp Original	118.84 (26.18)	271.44 (67.54)	257.93 (58.21)	263.55 (65.87)
	Sig Diff.	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$

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Table E.10: Mean Time Taken in Seconds and Standard Deviation for Both Strategies in Randomly Generated Environments in the presence of Partial Motor Faults in Leader Wheels

Partial Motor Fault	Type	Randomly Generated Environment		
		1	2	3
Left Wheel	Exp	343.31 (138.33)	461.13 (130.61)	N/A
	Exp Original	189.45 (57.78)	266.01 (80.07)	181.78 (94.63)
	Sig Diff.	p <0.001	p <0.001	N/A
	Imp	196.03 (45.56)	254.15 (56.13)	114.28 (37.26)
	Imp Original	137.92 (34.28)	168.28 (41.27)	95.06 (20.45)
	Sig Diff.	p <0.001	p <0.001	p <0.001
Right Wheel	Exp	326.09 (142.97)	406.50 (123.61)	337.22 (137.54)
	Exp Original	189.45 (57.78)	266.01 (80.07)	181.78 (94.63)
	Sig Diff.	p <0.001	p <0.001	p <0.001
	Imp	199.69 (46.72)	272.46 (67.86)	157.39 (28.73)
	Imp Original	137.92 (34.28)	168.28 (41.27)	95.06 (20.45)
	Sig Diff.	p <0.001	p <0.001	p <0.001

Table E.11: Mean Total Distance Travelled by Object in Metres and Standard Deviation for Both Strategies in the Line Following Environment in the presence of Partial Motor Faults in Leader Wheels

Partial Motor Fault	Type	Line Following Environment		
		1	2	3
Left Wheel	Exp	3.92 (0.57)	3.64 (0.44)	3.87 (0.06)
	Exp Original	3.51 (0.06)	3.33 (0.06)	3.42 (0.05)
	Sig Diff.	p <0.001	p <0.001	p <0.001
	Imp	4.12 (1.10)	3.80 (0.75)	5.77 (4.43)
	Imp Original	3.50 (0.05)	3.36 (0.07)	3.45 (0.06)
	Sig Diff.	p <0.001	p <0.001	p <0.001
Right Wheel	Exp	3.60 (0.05)	3.59 (0.33)	3.83 (0.47)
	Exp Original	3.50 (0.05)	3.36 (0.07)	3.45 (0.06)
	Sig Diff.	p <0.001	p <0.001	p <0.001
	Imp	3.92 (0.35)	6.70 (5.25)	4.55 (1.52)
	Imp Original	3.50 (0.05)	3.36 (0.07)	3.45 (0.06)
	Sig Diff.	p <0.001	p <0.001	0.003

Table E.12: Mean Total Distance Travelled by Object in Metres and Standard Deviation for Both Strategies in Simple (SE) and Cluttered (CE) Environments in the presence of Partial Motor Faults in Leader Wheels

Partial Motor Fault	Type	Path			
		SE	CE	CE	CE
		1	1	2	3
Left Wheel	Exp	5.36 (0.03)	12.62 (0.03)	12.36 (0.04)	12.23 (0.08)
	Exp Original	5.27 (0.05)	12.82 (0.20)	12.51 (0.06)	12.40 (0.14)
	Sig Diff.	p <0.001	p <0.001	p <0.001	p <0.001
	Imp	5.45 (0.12)	13.83 (0.94)	13.33 (0.87)	12.89 (0.68)
	Imp Original	5.28 (0.06)	12.85 (0.25)	12.63 (0.21)	12.52 (0.24)
	Sig Diff.	p <0.001	p <0.001	p <0.001	p <0.001
Right Wheel	Exp	5.37 (0.03)	13.12 (0.13)	12.87 (0.06)	11.79 (1.84)
	Exp Original	5.28 (0.06)	12.85 (0.25)	12.63 (0.21)	12.52 (0.24)
	Sig Diff.	p <0.001	p <0.001	p <0.001	0.003
	Imp	5.45 (0.12)	14.04 (0.78)	14.68 (0.97)	13.88 (0.91)
	Imp Original	5.28 (0.06)	12.85 (0.25)	12.63 (0.21)	12.52 (0.24)
	Sig Diff.	p <0.001	p <0.001	p <0.001	p <0.001

Table E.13: Mean Total Distance Travelled by Object in Metres and Standard Deviation for Both Strategies in Randomly Generated Environments in the presence of Partial Motor Faults in Leader Wheels

Partial Motor Fault	Type	Randomly Generated Environment		
		1	2	3
Left Wheel	Exp	6.37 (0.05)	7.97 (0.03)	N/A
	Exp Original	6.18 (0.03)	8.00 (0.09)	4.42 (0.04)
	Sig Diff.	p <0.001	0.209	N/A
	Imp	6.50 (0.12)	8.27 (0.27)	4.65 (0.05)
	Imp Original	6.16 (0.04)	7.97 (0.09)	4.39 (0.05)
	Sig Diff.	p <0.001	p <0.001	p <0.001
Right Wheel	Exp	6.07 (0.01)	8.21 (0.09)	4.45 (0.01)
	Exp Original	6.16 (0.04)	7.97 (0.09)	4.39 (0.05)
	Sig Diff.	p <0.001	p <0.001	p <0.001
	Imp	6.18 (0.21)	8.67 (0.41)	4.51 (0.06)
	Imp Original	6.16 (0.04)	7.97 (0.09)	4.39 (0.05)
	Sig Diff.	0.007	p <0.001	p <0.001

Table E.14: Mean Maximum Displacement of Object in Metres and Standard Deviation for Both Strategies in the Line Following Environment in the presence of Partial Motor Faults in Leader Wheels

Partial Motor Fault	Type	Line Following Environment		
		1	2	3
Left Wheel	Exp	0.012 (0.003)	0.013 (0.002)	0.012 (0.003)
	Exp Original	0.018 (0.006)	0.018 (0.006)	0.019 (0.005)
	Sig Diff.	p <0.001	p <0.001	p <0.001
	Imp	0.033 (0.003)	0.032 (0.003)	0.032 (0.005)
	Imp Original	0.029 (0.005)	0.031 (0.005)	0.033 (0.006)
	Sig Diff.	p <0.001	0.115	0.469
Right Wheel	Exp	0.010 (0.003)	0.014 (0.002)	0.013 (0.002)
	Exp Original	0.018 (0.006)	0.018 (0.006)	0.019 (0.005)
	Sig Diff.	p <0.001	p <0.001	p <0.001
	Imp	0.032 (0.003)	0.034 (0.004)	0.033 (0.001)
	Imp Original	0.029 (0.005)	0.031 (0.005)	0.033 (0.006)
	Sig Diff.	p <0.001	p <0.001	0.953

Table E.15: Mean Maximum Displacement of Object in Metres and Standard Deviation for Both Strategies in Simple (SE) and Cluttered (CE) Environments in the presence of Partial Motor Faults in Leader Wheels

Partial Motor Fault	Type	Path			
		SE	CE	CE	CE
		1	1	2	3
Left Wheel	Exp	0.010 (0.004)	0.012 (0.001)	0.014 (0.002)	0.013 (0.002)
	Exp Original	0.018 (0.006)	0.019 (0.005)	0.016 (0.004)	0.017 (0.005)
	Sig Diff.	p <0.001	p <0.001	p <0.001	p <0.001
	Imp	0.036 (0.003)	0.036 (0.003)	0.035 (0.002)	0.035 (0.002)
	Imp Original	0.031 (0.004)	0.037 (0.003)	0.038 (0.002)	0.038 (0.003)
	Sig Diff.	p <0.001	p <0.001	p <0.001	p <0.001
Right Wheel	Exp	0.011 (0.003)	0.014 (0.002)	0.012 (0.001)	0.012 (0.004)
	Exp Original	0.018 (0.006)	0.019 (0.005)	0.016 (0.004)	0.017 (0.005)
	Sig Diff.	p <0.001	p <0.001	p <0.001	p <0.001
	Imp	0.027 (0.004)	0.035 (0.002)	0.035 (0.003)	0.035 (0.003)
	Imp Original	0.031 (0.004)	0.037 (0.003)	0.038 (0.002)	0.038 (0.003)
	Sig Diff.	p <0.001	p <0.001	p <0.001	p <0.001

Table E.16: Mean Maximum Displacement of Object in Metres and Standard Deviation for Both Strategies in Randomly Generated Environments in the presence of Partial Motor Faults in Leader Wheels

Partial Motor Fault	Type	Randomly Generated Environment		
		1	2	3
Left Wheel	Exp	0.012 (0.003)	0.011 (0.002)	N/A
	Exp Original	0.019 (0.005)	0.018 (0.006)	0.017 (0.005)
	Sig Diff.	p <0.001	p <0.001	N/A
	Imp	0.032 (0.003)	0.031 (0.002)	0.028 (0.004)
	Imp Original	0.034 (0.004)	0.034 (0.003)	0.033 (0.004)
	Sig Diff.	0.002	p <0.001	p <0.001
Right Wheel	Exp	0.013 (0.003)	0.013 (0.003)	0.011 (0.003)
	Exp Original	0.019 (0.005)	0.018 (0.006)	0.017 (0.005)
	Sig Diff.	p <0.001	p <0.001	p <0.001
	Imp	0.028 (0.002)	0.032 (0.002)	0.027 (0.003)
	Imp Original	0.034 (0.004)	0.034 (0.003)	0.033 (0.004)
	Sig Diff.	p <0.001	p <0.001	p <0.001

Table E.17: Mean Percentage Path Fidelity and Standard Deviation for Both Strategies in the Line Following Environment in the presence of Partial Motor Faults in Leader Wheels

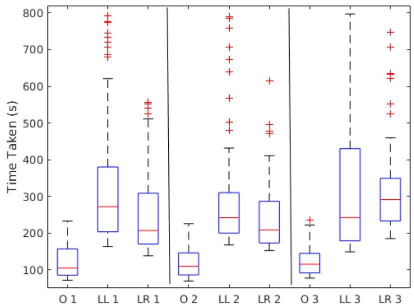
Partial Motor Fault	Type	Line Following Environment		
		1	2	3
Left Wheel	Exp	90.59% (21.47%)	93.84% (15.84%)	74.88% (14.12%)
	Exp Original	90.75% (14.93%)	100% (∼0%)	99.40% (3.43%)
	Sig Diff.	0.208	p <0.001	p <0.001
	Imp	87.35% (19.14%)	97.85% (5.62%)	77.32% (19.07%)
	Imp Original	93.00 (12.35%)	89.67% (14.17%)	96.57% (9.49%)
	Sig Diff.	0.053	p <0.001	p <0.001
Right Wheel	Exp	100% (∼0%)	19.15% (24.32%)	86.67% (27.12%)
	Exp Original	90.75% (14.93%)	100% (∼0%)	99.40% (3.43%)
	Sig Diff.	p <0.001	p <0.001	p <0.001
	Imp	86.25% (17.54%)	35.71% (19.56%)	66.67% (11.55%)
	Imp Original	93.00 (12.35%)	89.67% (14.17%)	96.57% (9.49%)
	Sig Diff.	0.004	p <0.001	p <0.001

Table E.18: Mean Percentage Path Fidelity and Standard Deviation for Both Strategies in Simple (SE) and Cluttered (CE) Environments in the presence of Partial Motor Faults in Leader Wheels

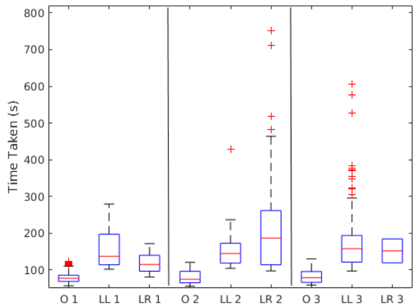
Partial Motor Fault	Type	Path			
		SE	CE	CE	CE
		1	1	2	3
Left Wheel	Exp	0.93%(0.55%)	4.43% (0.57%)	3.10% (0.98%)	4.60% (0.44%)
	Exp Original	91.00% (2.12%)	64.09% (15.65%)	72.96% (8.33%)	69.04 (15.25%)
	Sig Diff.	p <0.001	p <0.001	p <0.001	p <0.001
	Imp	0.66% (0.63%)	8.75% (4.77%)	7.70% (4.50%)	6.29% (4.30%)
	Imp Original	91.79% (1.60%)	70.78% (3.55%)	69.44% (2.80%)	70.56% (3.35%)
	Sig Diff.	p <0.001	p <0.001	p <0.001	p <0.001
Right Wheel	Exp	0% (0%)	2.41% (0.50%)	0.55% (0.54%)	1.66% (1.46%)
	Exp Original	91.00% (2.12%)	64.09% (15.65%)	72.96% (8.33%)	69.04 (15.25%)
	Sig Diff.	p <0.001	p <0.001	p <0.001	p <0.001
	Imp	∼0% (0.12%)	1.64% (2.20%)	1.51% (2.00%)	1.86% (2.40%)
	Imp Original	91.79% (1.60%)	70.78% (3.55%)	69.44% (2.80%)	70.56% (3.35%)
	Sig Diff.	p <0.001	p <0.001	p <0.001	p <0.001

Table E.19: Mean Percentage Path Fidelity and Standard Deviation for Both Strategies in Randomly Generated Environments in the presence of Partial Motor Faults in Leader Wheels

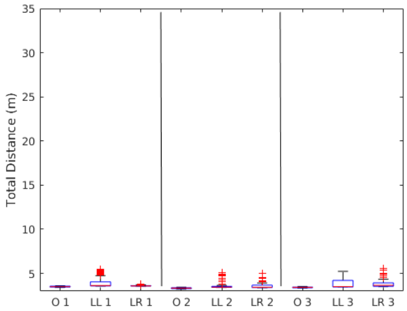
Partial Motor Fault	Type	Randomly Generated Environment		
		1	2	3
Left Wheel	Exp	1.27% (0.42%)	5.21% (1.51%)	N/A
	Exp Original	54.36% (23.85%)	56.36% (21.46%)	49.84% (23.26%)
	Sig Diff.	p <0.001	p <0.001	N/A
	Imp	1.27% (0.75%)	5.47% (2.56%)	0% (0%)
	Imp Original	75.31% (9.04%)	68.40% (5.61%)	61.80% (14.57%)
	Sig Diff.	p <0.001	p <0.001	p <0.001
Right Wheel	Exp	4.04% (2.78%)	2.96% (1.23%)	1.46% (0.26%)
	Exp Original	54.36% (23.85%)	56.36% (21.46%)	49.84% (23.26%)
	Sig Diff.	p <0.001	p <0.001	p <0.001
	Imp	2.54% (2.12%)	3.12% (1.27%)	1.02% (0.63%)
	Imp Original	75.31% (9.04%)	68.40% (5.61%)	61.80% (14.57%)
	Sig Diff.	p <0.001	p <0.001	p <0.001



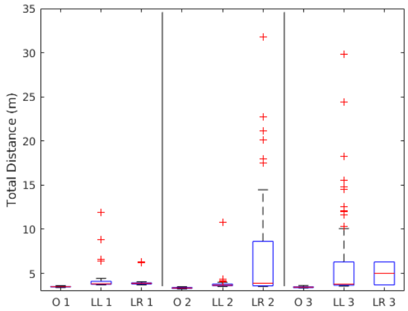
(a) Explicit: Mean Time Taken and Standard Deviation



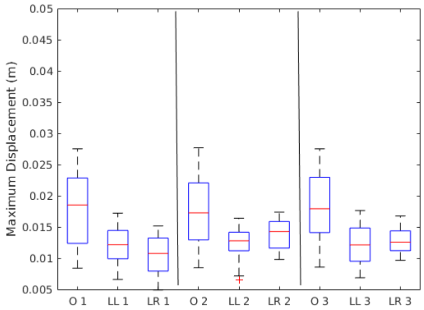
(b) Implicit: Mean Time Taken and Standard Deviation



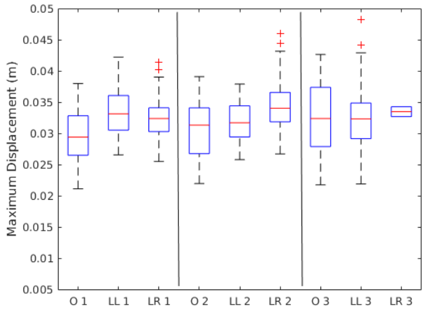
(c) Explicit: Mean Total Distance Travelled and Standard Deviation



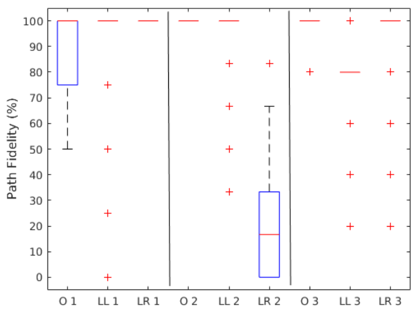
(d) Implicit: Mean Total Distance Travelled and Standard Deviation



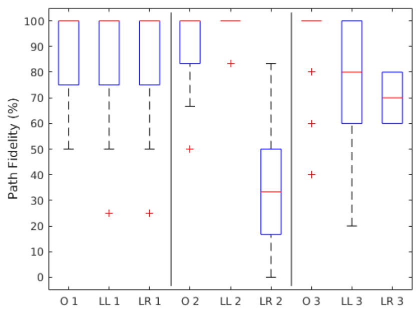
(e) Explicit: Mean Maximum Displacement and Standard Deviation



(f) Implicit: Mean Maximum Displacement and Standard Deviation

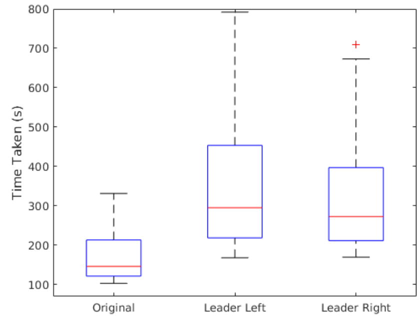


(g) Explicit: Mean Percentage Path Fidelity and Standard Deviation

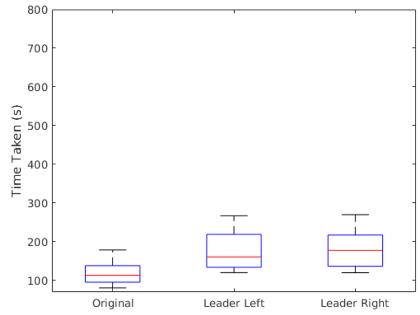


(h) Implicit: Mean Percentage Path Fidelity and Standard Deviation

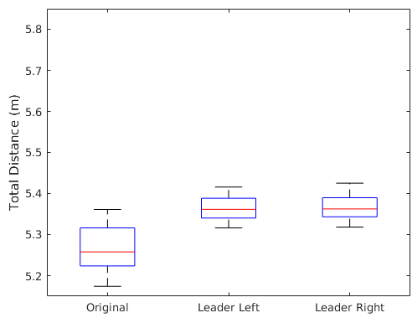
Figure E.1: Performance of both communication strategies in the Line Following Environment for partial motor faults in the Leader's wheels



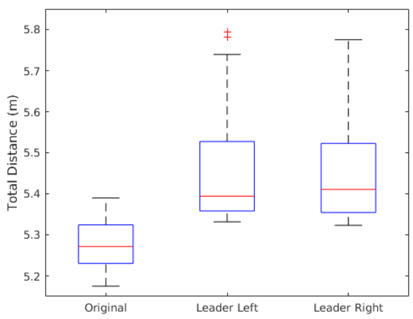
(a) Explicit: Mean Time Taken and Standard Deviation



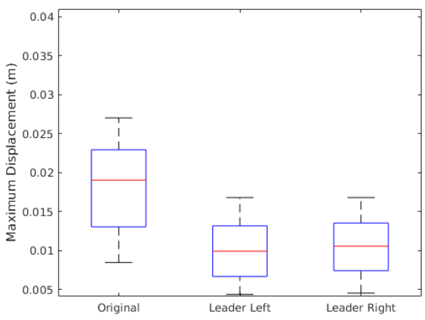
(b) Implicit: Mean Time Taken and Standard Deviation



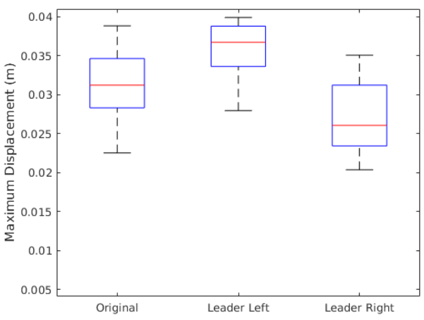
(c) Explicit: Mean Total Distance Travelled and Standard Deviation



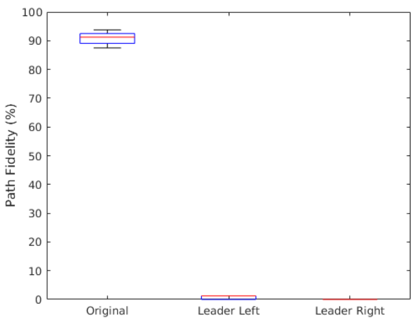
(d) Implicit: Mean Total Distance Travelled and Standard Deviation



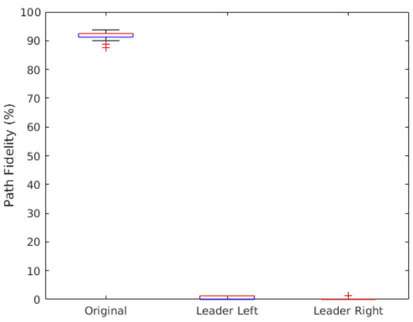
(e) Explicit: Mean Maximum Displacement and Standard Deviation



(f) Implicit: Mean Maximum Displacement and Standard Deviation

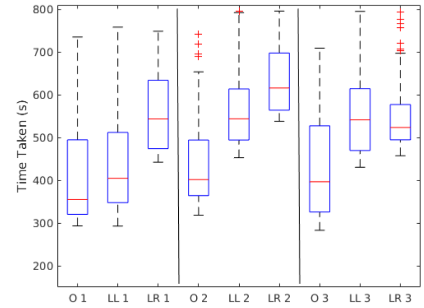


(g) Explicit: Mean Percentage Path Fidelity and Standard Deviation

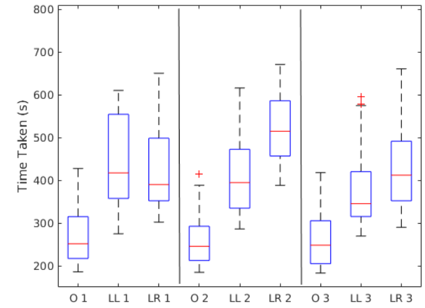


(h) Implicit: Mean Percentage Path Fidelity and Standard Deviation

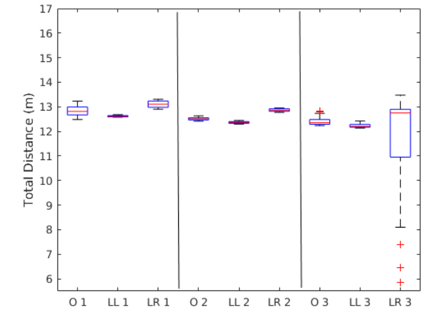
Figure E.2: Performance of both communication strategies in the Simple Environment for partial motor faults in the Leader's wheels



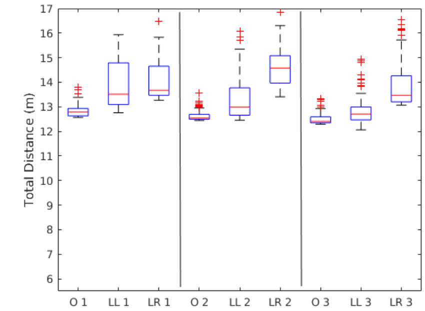
(a) Explicit: Mean Time Taken and Standard Deviation



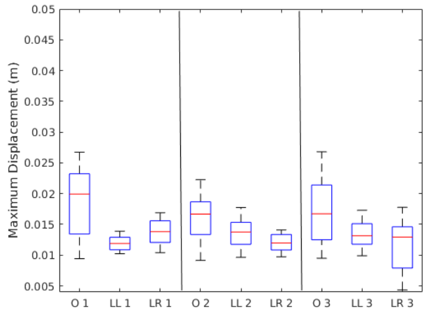
(b) Implicit: Mean Time Taken and Standard Deviation



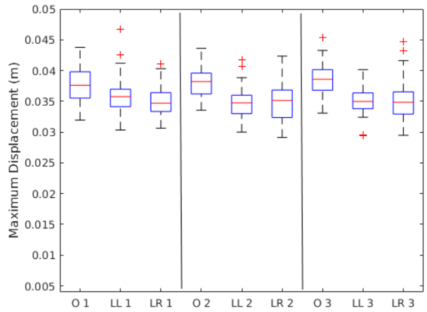
(c) Explicit: Mean Total Distance Travelled and Standard Deviation



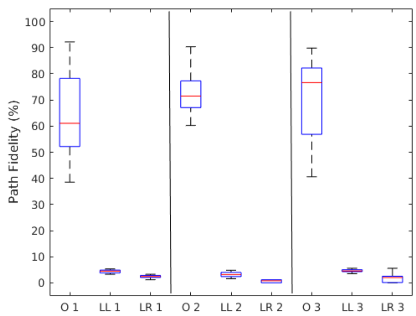
(d) Implicit: Mean Total Distance Travelled and Standard Deviation



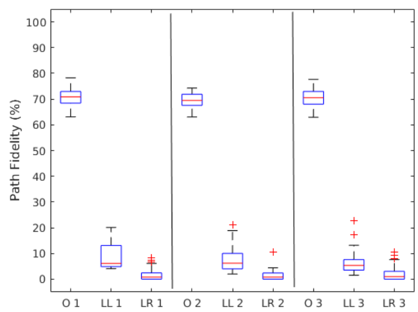
(e) Explicit: Mean Maximum Displacement and Standard Deviation



(f) Implicit: Mean Maximum Displacement and Standard Deviation

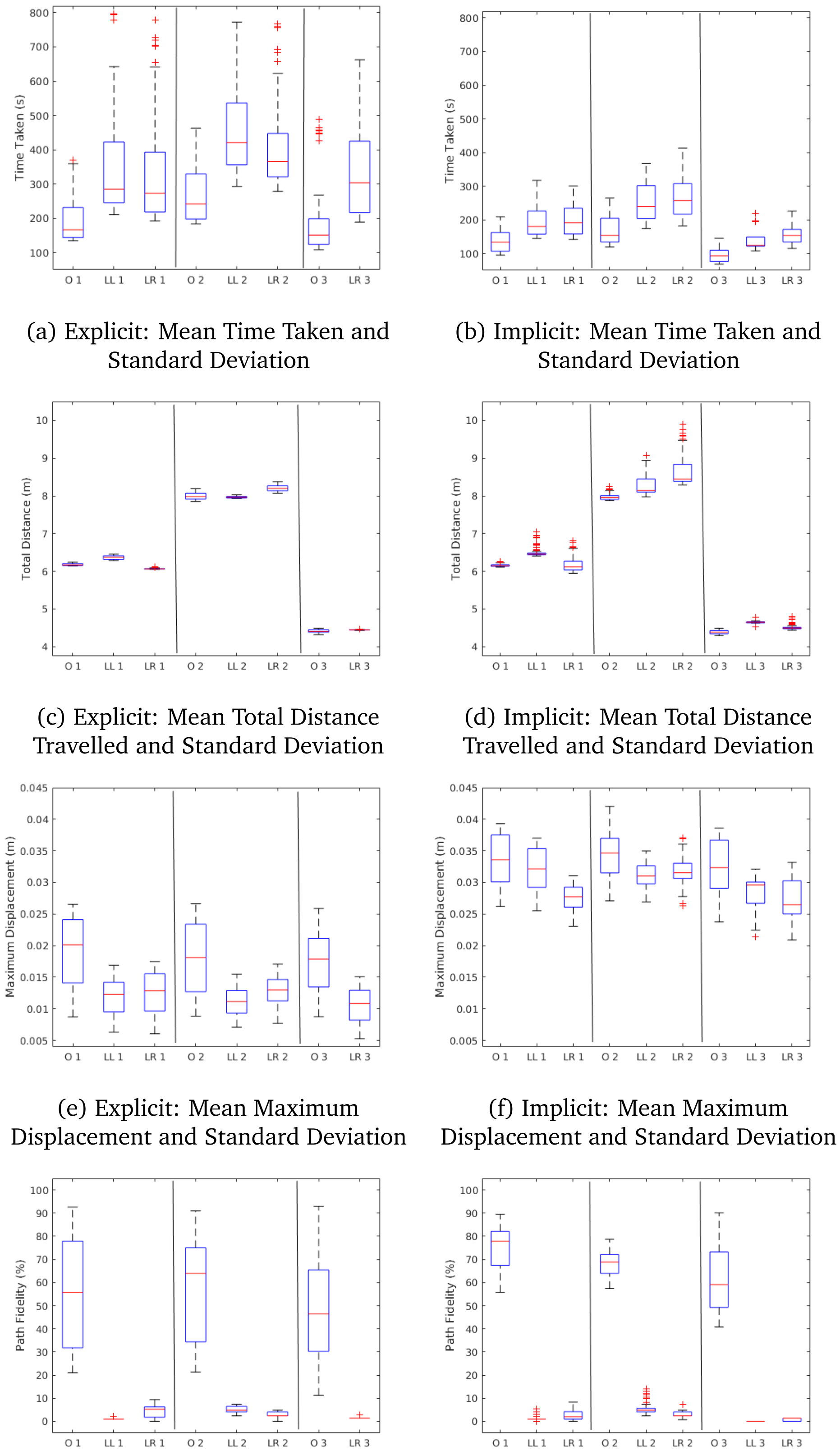


(g) Explicit: Mean Percentage Path Fidelity and Standard Deviation



(h) Implicit: Mean Percentage Path Fidelity and Standard Deviation

Figure E.3: Performance of both communication strategies in the Cluttered Environment for partial motor faults in the Leader's wheels



(a) Explicit: Mean Time Taken and Standard Deviation

(b) Implicit: Mean Time Taken and Standard Deviation

(c) Explicit: Mean Total Distance Travelled and Standard Deviation

(d) Implicit: Mean Total Distance Travelled and Standard Deviation

(e) Explicit: Mean Maximum Displacement and Standard Deviation

(f) Implicit: Mean Maximum Displacement and Standard Deviation

(g) Explicit: Mean Percentage Path Fidelity and Standard Deviation

(h) Implicit: Mean Percentage Path Fidelity and Standard Deviation

Figure E.4: Performance of both communication strategies in the Randomly Generated Environments for partial motor faults in the Leader's wheels

E.2.2 Follower Wheels

Table E.20: Percentage Task Completion for Both Strategies in the Line Following Environment in the presence of Partial Motor Faults in Follower Wheels

Partial Motor Fault	Type	Line Following Environment Paths		
		1	2	3
Wheel 1	Exp	100.00%	100.00%	100.00%
	Exp Original	100.00%	100.00%	100.00%
	Imp	100.00%	100.00%	100.00%
	Imp Original	100.00%	100.00%	99.00%
Wheel 2	Exp	100.00%	100.00%	100.00%
	Exp Original	100.00%	100.00%	100.00%
	Imp	100.00%	100.00%	95.00%
	Imp Original	100.00%	100.00%	99.00%
Wheel 3	Exp	100.00%	100.00%	100.00%
	Exp Original	100.00%	100.00%	100.00%
	Imp	100.00%	100.00%	100.00%
	Imp Original	100.00%	100.00%	99.00%

Table E.21: Percentage Task Completion for Both Strategies in Simple (SE) and Cluttered (CE) Environments in the presence of Partial Motor Faults in Follower Wheels

Partial Motor Fault	Type	Path			
		SE	CE	CE	CE
		1	1	2	3
Wheel 1	Exp	100.00%	35.00%	73.00%	100.00%
	Exp Original	100.00%	100.00%	60.00%	100.00%
	Imp	100.00%	80.00%	100.00%	100.00%
	Imp Original	100.00%	100.00%	100.00%	100.00%
Wheel 2	Exp	100.00%	22.00%	67.00%	100.00%
	Exp Original	100.00%	100.00%	60.00%	100.00%
	Imp	100.00%	77.00%	100.00%	100.00%
	Imp Original	100.00%	100.00%	100.00%	100.00%
Wheel 3	Exp	100.00%	34.00%	64.00%	100.00%
	Exp Original	100.00%	100.00%	60.00%	100.00%
	Imp	100.00%	75.00%	100.00%	100.00%
	Imp Original	100.00%	100.00%	100.00%	100.00%

Table E.22: Percentage Task Completion for Both Strategies in Randomly Generated Environments in the presence of Partial Motor Faults in Follower Wheels

Partial Motor Fault	Type	Randomly Generated Environment		
		1	2	3
Wheel 1	Exp	100.00%	100.00%	86.00%
	Exp Original	100.00%	100.00%	93.00%
	Imp	100.00%	100.00%	100.00%
	Imp Original	100.00%	100.00%	100.00%
Wheel 2	Exp	100.00%	100.00%	87.00%
	Exp Original	100.00%	100.00%	93.00%
	Imp	100.00%	100.00%	100.00%
	Imp Original	100.00%	100.00%	100.00%
Wheel 3	Exp	100.00%	100.00%	90.00%
	Exp Original	100.00%	100.00%	93.00%
	Imp	100.00%	100.00%	100.00%
	Imp Original	100.00%	100.00%	100.00%

Table E.23: Mean Time Taken in Seconds and Standard Deviation for Both Strategies in the Line Following Environment in the presence of Partial Motor Faults in Follower Wheels

Partial Motor Fault	Type	Line Following Environment Paths		
		1	2	3
Wheel 1	Exp	129.56 (46.06)	111.24 (40.16)	128.38 (43.97)
	Exp Original	121.81 (46.49)	119.22 (40.55)	121.15 (35.70)
	Sig Diff.	$p < 0.001$	0.083	0.442
	Imp	85.52 (18.98)	83.66 (21.10)	88.17 (21.01)
	Imp Original	80.25 (18.25)	79.18 (18.89)	81.45 (19.03)
	Sig Diff.	0.053	0.245	0.013
Wheel 2	Exp	111.78 (39.95)	116.91 (49.30)	121.00 (41.92)
	Exp Original	121.81 (46.49)	119.22 (40.55)	121.15 (35.70)
	Sig Diff.	0.133	0.336	0.454
	Imp	80.68 (18.78)	81.55 (20.04)	82.84 (19.88)
	Imp Original	80.25 (18.25)	79.18 (18.89)	81.45 (19.03)
	Sig Diff.	0.919	0.661	0.607
Wheel 3	Exp	118.91 (40.71)	122.26 (43.46)	133.27 (43.76)
	Exp Original	121.81 (46.49)	119.22 (40.55)	121.15 (35.70)
	Sig Diff.	0.951	0.742	0.056
	Imp	82.30 (19.13)	81.51 (20.08)	85.98 (20.04)
	Imp Original	80.25 (18.25)	79.18 (18.89)	81.45 (19.03)
	Sig Diff.	0.463	0.678	0.082

Table E.24: Mean Time Taken in Seconds and Standard Deviation for Both Strategies in Simple (SE) and Cluttered (CE) Environments in the presence of Partial Motor Faults in Follower Wheels

Partial Motor Fault	Type	Path			
		SE	CE	CE	CE
		1	1	2	3
Wheel 1	Exp	177.24 (60.42)	323.34 (30.55)	448.86 (118.90)	384.18 (102.
	Exp Original	170.98 (62.64)	414.36 (127.10)	445.31 (113.61)	431.18 (120.
	Sig Diff.	0.237	p <0.001	0.991	0.003
	Imp	115.05 (27.85)	258.10 (50.82)	274.78 (67.70)	260.59 (59.
	Imp Original	118.84 (26.18)	271.44 (67.54)	257.93 (58.21)	263.55 (65.
	Sig Diff.	0.217	0.403	0.094	0.958
Wheel 2	Exp	169.41 (57.63)	325.50 (10.43)	471.95 (116.26)	392.30 (106.
	Exp Original	170.98 (62.64)	414.36 (127.10)	445.31 (113.61)	431.18 (120.
	Sig Diff.	0.846	0.005	0.145	0.009
	Imp	120.02 (27.00)	257.17 (65.18)	269.19 (65.82)	261.18 (60.
	Imp Original	118.84 (26.18)	271.44 (67.54)	257.93 (58.21)	263.55 (65.
	Sig Diff.	0.759	0.105	0.267	0.919
Wheel 3	Exp	164.20 (57.19)	327.85 (14.78)	484.70 (117.83)	407.64 (124.
	Exp Original	170.98 (62.64)	414.36 (127.10)	445.31 (113.61)	431.18 (120.
	Sig Diff.	0.511	0.002	0.046	0.065
	Imp	114.72 (28.57)	271.27 (63.19)	271.78 (66.85)	272.53 (65.
	Imp Original	118.84 (26.18)	271.44 (67.54)	257.93 (58.21)	263.55 (65.
	Sig Diff.	0.165	0.821	0.204	0.325

Table E.25: Mean Time Taken in Seconds and Standard Deviation for Both Strategies in Randomly Generated Environments in the presence of Partial Motor Faults in Follower Wheels

Partial Motor Fault	Type	Randomly Generated Environment		
		1	2	3
Wheel 1	Exp	199.88 (63.39)	266.17 (79.51)	166.66 (73.40)
	Exp Original	189.45 (57.78)	266.01 (80.07)	181.78 (94.63)
	Sig Diff.	0.199	0.872	0.226
	Imp	136.05 (31.14)	170.64 (39.61)	100.95 (22.68)
	Imp Original	137.92 (34.28)	168.28 (41.27)	95.06 (20.45)
	Sig Diff.	0.931	0.356	0.070
Wheel 2	Exp	204.76 (64.02)	264.01 (75.65)	167.71 (77.77)
	Exp Original	189.45 (57.78)	266.01 (80.07)	181.78 (94.63)
	Sig Diff.	0.050	0.726	0.370
	Imp	139.19 (31.91)	164.56 (40.32)	100.74 (24.56)
	Imp Original	137.92 (34.28)	168.28 (41.27)	95.06 (20.45)
	Sig Diff.	0.661	0.513	0.140
Wheel 3	Exp	199.92 (59.51)	274.52 (86.33)	192.85 (99.87)
	Exp Original	189.45 (57.78)	266.01 (80.07)	181.78 (94.63)
	Sig Diff.	0.088	0.352	0.417
	Imp	139.07 (30.64)	178.92 (42.27)	102.65 (21.37)
	Imp Original	137.92 (34.28)	168.28 (41.27)	95.06 (20.45)
	Sig Diff.	0.576	0.054	0.010

Table E.26: Mean Total Distance Travelled By Object in Metres and Standard Deviation for Both Strategies in the Line Following Environment in the presence of Partial Motor Faults in Follower Wheels

Partial Motor Fault	Type	Line Following Environment Paths		
		1	2	3
Wheel 1	Exp	3.52 (0.06)	3.32 (0.06)	3.43 (0.05)
	Exp Original	3.51 (0.06)	3.33 (0.06)	3.42 (0.05)
	Sig Diff.	0.135	0.072	0.294
	Imp	3.51 (0.05)	3.34 (0.007)	3.45 (0.06)
	Imp Original	3.50 (0.05)	3.36 (0.07)	3.45 (0.06)
	Sig Diff.	0.430	0.044	0.965
Wheel 2	Exp	3.49 (0.06)	3.32 (0.06)	3.42 (0.05)
	Exp Original	3.51 (0.06)	3.33 (0.06)	3.42 (0.05)
	Sig Diff.	0.091	0.061	0.843
	Imp	3.50 (0.06)	3.35 (0.07)	3.45 (0.06)
	Imp Original	3.50 (0.05)	3.36 (0.07)	3.45 (0.06)
	Sig Diff.	0.925	0.819	0.656
Wheel 3	Exp	3.50 (0.06)	3.34 (0.06)	3.43 (0.05)
	Exp Original	3.50 (0.05)	3.36 (0.07)	3.45 (0.06)
	Sig Diff.	0.439	0.743	0.214
	Imp	3.51 (0.06)	3.36 (0.06)	3.46 (0.06)
	Imp Original	3.50 (0.05)	3.36 (0.07)	3.45 (0.06)
	Sig Diff.	0.652	0.848	0.137

Table E.27: Mean Total Distance Travelled by Object in Metres and Standard Deviation for Both Strategies in Simple (SE) and Cluttered (CE) Environments in the presence of Partial Motor Faults in Follower Wheels

Partial Motor Fault	Type	Path			
		SE	CE	CE	CE
		1	1	2	3
Wheel 1	Exp	5.27 (0.05)	13.04 (0.11)	12.50 (0.06)	12.42 (0.14)
	Exp Original	5.27 (0.05)	12.82 (0.20)	12.51 (0.06)	12.40 (0.14)
	Sig Diff.	0.368	p <0.001	0.281	0.215
	Imp	5.26 (0.06)	12.73 (0.03)	12.49 (0.08)	12.30 (0.06)
	Imp Original	5.28 (0.06)	12.85 (0.25)	12.63 (0.21)	12.52 (0.24)
	Sig Diff.	0.005	p <0.001	p <0.001	p <0.001
Wheel 2	Exp	5.27 (0.05)	13.03 (0.07)	12.49 (0.06)	12.43 (0.14)
	Exp Original	5.27 (0.05)	12.82 (0.20)	12.51 (0.06)	12.40 (0.14)
	Sig Diff.	0.910	p <0.001	0.042	0.150
	Imp	5.28 (0.06)	12.83 (0.18)	12.62 (0.22)	12.42 (0.17)
	Imp Original	5.28 (0.06)	12.85 (0.25)	12.63 (0.21)	12.52 (0.24)
	Sig Diff.	0.805	0.376	0.041	p <0.001
Wheel 3	Exp	5.26 (0.05)	13.03 (0.09)	12.49 (0.06)	12.42 (0.15)
	Exp Original	5.28 (0.06)	12.85 (0.25)	12.63 (0.21)	12.52 (0.24)
	Sig Diff.	0.319	p <0.001	0.0103	0.454
	Imp	5.26 (0.06)	12.87 (0.21)	12.63 (0.22)	12.47 (0.20)
	Imp Original	5.28 (0.06)	12.85 (0.25)	12.63 (0.21)	12.52 (0.24)
	Sig Diff.	0.049	0.482	0.334	0.016

Table E.28: Mean Total Distance Travelled by Object in Metres and Standard Deviation for Both Strategies in Randomly Generated Environments in the presence of Partial Motor Faults in Follower Wheels

Partial Motor Fault	Type	Randomly Generated Environment		
		1	2	3
Wheel 1	Exp	6.17 (0.03)	8.02 (0.08)	4.38 (0.02)
	Exp Original	6.18 (0.03)	8.00 (0.09)	4.42 (0.04)
	Sig Diff.	0.0576	0.0236	p <0.001
	Imp	6.14 (0.01)	7.93 (0.02)	4.35 (0.04)
	Imp Original	6.16 (0.04)	7.97 (0.09)	4.39 (0.05)
	Sig Diff.	p <0.001	p <0.001	p <0.001
Wheel 2	Exp	6.17 (0.03)	8.03 (0.08)	4.38 (0.02)
	Exp Original	6.18 (0.03)	8.00 (0.09)	4.42 (0.04)
	Sig Diff.	0.723	0.011	p <0.001
	Imp	6.15 (0.03)	7.98 (0.06)	4.36 (0.04)
	Imp Original	6.16 (0.04)	7.97 (0.09)	4.39 (0.05)
	Sig Diff.	0.622	0.074	p <0.001
Wheel 3	Exp	6.17 (0.03)	8.02 (0.08)	4.39 (0.01)
	Exp Original	6.16 (0.04)	7.97 (0.09)	4.39 (0.05)
	Sig Diff.	0.443	0.024	p <0.001
	Imp	6.15 (0.03)	7.99 (0.07)	4.37 (0.03)
	Imp Original	6.16 (0.04)	7.97 (0.09)	4.39 (0.05)
	Sig Diff.	0.404	0.003	0.007

Table E.29: Mean Maximum Displacement of Object in Metres and Standard Deviation for Both Strategies in the Line Following Environment in the presence of Partial Motor Faults in Follower Wheels

Partial Motor Fault	Type	Line Following Environment Paths		
		1	2	3
Wheel 1	Exp	0.017 (0.006)	0.019 (0.006)	0.018 (0.006)
	Exp Original	0.018 (0.006)	0.018 (0.006)	0.019 (0.005)
	Sig Diff.	0.123	0.084	0.459
	Imp	0.026 (0.005)	0.027 (0.005)	0.029 (0.005)
	Imp Original	0.029 (0.005)	0.031 (0.005)	0.033 (0.006)
	Sig Diff.	p <0.001	p <0.001	p <0.001
Wheel 2	Exp	0.019 (0.006)	0.019 (0.006)	0.019 (0.006)
	Exp Original	0.018 (0.006)	0.018 (0.006)	0.019 (0.005)
	Sig Diff.	0.290	0.132	0.832
	Imp	0.029 (0.005)	0.030 (0.005)	0.032 (0.006)
	Imp Original	0.029 (0.005)	0.031 (0.005)	0.033 (0.006)
	Sig Diff.	0.308	0.485	0.475
Wheel 3	Exp	0.019 (0.005)	0.017 (0.006)	0.018 (0.005)
	Exp Original	0.018 (0.006)	0.018 (0.006)	0.019 (0.005)
	Sig Diff.	0.575	0.417	0.194
	Imp	0.029 (0.005)	0.030 (0.005)	0.031 (0.005)
	Imp Original	0.029 (0.005)	0.031 (0.005)	0.033 (0.006)
	Sig Diff.	0.315	0.577	0.028

Table E.30: Mean Maximum Displacement of Object in Metres and Standard Deviation for Both Strategies in Simple (SE) and Cluttered (CE) Environments in the presence of Partial Motor Faults in Follower Wheels

Partial Motor Fault	Type	Path			
		SE	CE	CE	CE
		1	1	2	3
Wheel 1	Exp	0.017 (0.005)	0.023 (0.002)	0.016 (0.004)	0.019 (0.005)
	Exp Original	0.018 (0.006)	0.019 (0.005)	0.016 (0.004)	0.017 (0.005)
	Sig Diff.	0.225	p <0.001	0.980	0.005
	Imp	0.027 (0.005)	0.031 (0.004)	0.029 (0.004)	0.030 (0.004)
	Imp Original	0.031 (0.004)	0.037 (0.003)	0.038 (0.002)	0.038 (0.003)
	Sig Diff.	p <0.001	p <0.001	p <0.001	p <0.001
Wheel 2	Exp	0.018 (0.005)	0.023 (0.001)	0.015 (0.004)	0.019 (0.005)
	Exp Original	0.018 (0.006)	0.019 (0.005)	0.016 (0.004)	0.017 (0.005)
	Sig Diff.	0.812	p <0.001	0.155	0.011
	Imp	0.032 (0.004)	0.038 (0.003)	0.038 (0.003)	0.038 (0.003)
	Imp Original	0.031 (0.004)	0.037 (0.003)	0.038 (0.002)	0.038 (0.003)
	Sig Diff.	0.608	0.863	0.209	0.066
Wheel 3	Exp	0.019 (0.005)	0.023 (0.002)	0.015 (0.004)	0.019 (0.006)
	Exp Original	0.018 (0.006)	0.019 (0.005)	0.016 (0.004)	0.017 (0.005)
	Sig Diff.	0.530	p <0.001	0.052	0.067
	Imp	0.031 (0.004)	0.037 (0.003)	0.038 (0.003)	0.037 (0.003)
	Imp Original	0.031 (0.004)	0.037 (0.003)	0.038 (0.002)	0.038 (0.003)
	Sig Diff.	0.549	0.493	0.489	0.013

Table E.31: Mean Maximum Displacement of Object in Metres and Standard Deviation for Both Strategies in Randomly Generated Environments in the presence of Partial Motor Faults in Follower Wheels

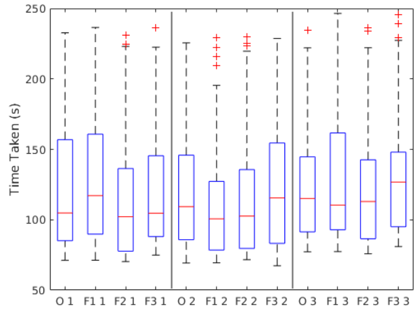
Partial Motor Fault	Type	Randomly Generated Environment		
		1	2	3
Wheel 1	Exp	0.018 (0.005)	0.018 (0.006)	0.017 (0.005)
	Exp Original	0.019 (0.005)	0.018 (0.006)	0.017 (0.005)
	Sig Diff.	0.199	0.974	0.886
	Imp	0.027 (0.005)	0.028 (0.005)	0.026 (0.005)
	Imp Original	0.034 (0.004)	0.034 (0.003)	0.033 (0.004)
	Sig Diff.	p <0.001	p <0.001	p <0.001
Wheel 2	Exp	0.018 (0.006)	0.018 (0.005)	0.017 (0.005)
	Exp Original	0.019 (0.005)	0.018 (0.006)	0.017 (0.005)
	Sig Diff.	0.077	0.967	0.867
	Imp	0.033 (0.004)	0.035 (0.003)	0.031 (0.005)
	Imp Original	0.034 (0.004)	0.034 (0.003)	0.033 (0.004)
	Sig Diff.	0.041	0.785	0.054
Wheel 3	Exp	0.018 (0.005)	0.018 (0.006)	0.017 (0.005)
	Exp Original	0.019 (0.005)	0.018 (0.006)	0.017 (0.005)
	Sig Diff.	0.128	0.591	0.737
	Imp	0.033 (0.004)	0.034 (0.003)	0.030 (0.005)
	Imp Original	0.034 (0.004)	0.034 (0.003)	0.033 (0.004)
	Sig Diff.	0.065	0.070	0.001

Table E.32: Mean Percentage Path Fidelity and Standard Deviation for Both Strategies in the Line Following Environment in the presence of Partial Motor Faults in Follower Wheels

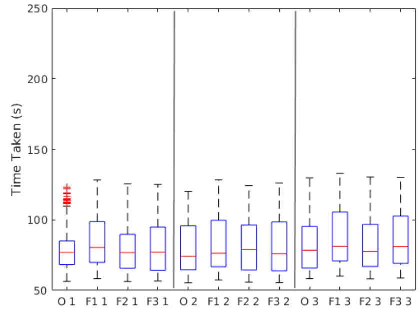
Partial Motor Fault	Type	Line Following Environment Paths		
		1	2	3
Wheel 1	Exp	94.75% (11.4%)	99.83% (1.67%)	100% (∼0%)
	Exp Original	90.75% (14.93%)	100% (∼0%)	99.40% (3.43%)
	Sig Diff.	0.0427	0.322	0.083
	Imp	90.50% (13.19%)	99.67% (2.35%)	65.00% (9.59%)
	Imp Original	93.00 (12.35%)	89.67% (14.17%)	96.57% (9.49%)
	Sig Diff.	0.137	p <0.001	0.119
Wheel 2	Exp	99.75% (2.50%)	100% (∼0%)	99.80% (2.00%)
	Exp Original	90.75% (14.93%)	100% (∼0%)	99.40% (3.43%)
	Sig Diff.	p <0. 001	1	0.316
	Imp	98.00% (6.82(%)	92.17% (13.29%)	97.26% (6.91%)
	Imp Original	93.00 (12.35%)	89.67% (14.17%)	96.57% (9.49%)
	Sig Diff.	p <0.001	0.148	0.885
Wheel 3	Exp	90.50% (14.98%)	89.00% (10.11%)	99.80% (2.00%)
	Exp Original	90.75% (14.93%)	100% (∼0%)	99.40% (3.43%)
	Sig Diff.	0.889	p <0.001	0.316
	Imp	91.25% (13.47%)	88.83% (14.03%)	96.60% (8.07%)
	Imp Original	93.00 (12.35%)	89.67% (14.17%)	96.57% (9.49%)
	Sig Diff.	0.343	0.576	0.745

Table E.33: Mean Percentage Path Fidelity and Standard Deviation for Both Strategies in Simple (SE) and Cluttered (CE) Environments in the presence of Partial Motor Faults in Follower Wheels

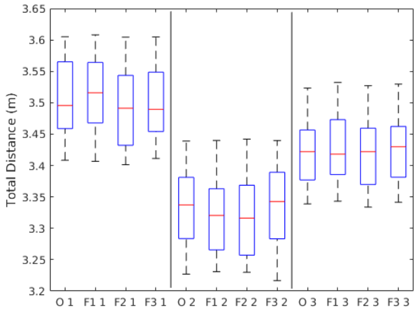
Partial Motor Fault	Type	Path			
		SE	CE	CE	CE
		1	1	2	3
Wheel 1	Exp	91.08% (1.93%)	50.25% (7.99%)	72.87% (9.01%)	62.85% (15.72
	Exp Original	91.00% (2.12%)	64.09% (15.65%)	72.96% (8.33%)	69.04 (15.25%
	Sig Diff.	0.846	p <0.001	0.915	0.004
	Imp	90.71% (1.92%)	73.57% (5.20%)	74.99% (5.28%)	76.60% (5.36
	Imp Original	91.79% (1.60%)	70.78% (3.55%)	69.44% (2.80%)	70.56% (3.35
	Sig Diff.	p <0.001	0.002	p <0.001	p <0.001
Wheel 2	Exp	90.66% (2.28%)	49.31% (5.21%)	74.15% (9.01%)	62.40% (16.83
	Exp Original	91.00% (2.12%)	64.09% (15.65%)	72.96% (8.33%)	69.04 (15.25%
	Sig Diff.	0.343	p <0.001	0.381	0.002
	Imp	90.66 (2.28%)	71.48% (4.31%)	71.36% (3.59%)	73.27% (3.84
	Imp Original	91.79% (1.60%)	70.78% (3.55%)	69.44% (2.80%)	70.56% (3.35
	Sig Diff.	p <0.001	0.852	p <0.001	p <0.001
Wheel 3	Exp	90.39% (2.18%)	49.07% (6.67%)	74.64% (9.27%)	63.36% (17.54
	Exp Original	91.00% (2.12%)	64.09% (15.65%)	72.96% (8.33%)	69.04 (15.25%
	Sig Diff.	0.051	p <0.001	0.188	0.013
	Imp	91.00% (1.92%)	72.15% (3.29%)	70.35% (2.99%)	72.02% (3.60
	Imp Original	91.79% (1.60%)	70.78% (3.55%)	69.44% (2.80%)	70.56% (3.35
	Sig Diff.	0.004	0.012	0.048	0.002



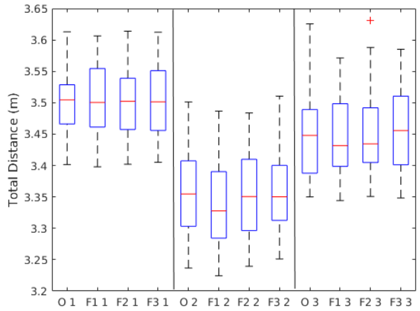
(a) Explicit: Mean Time Taken and Standard Deviation



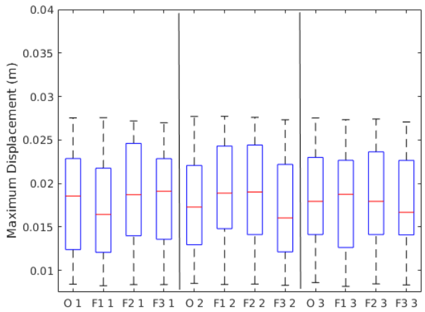
(b) Implicit: Mean Time Taken and Standard Deviation



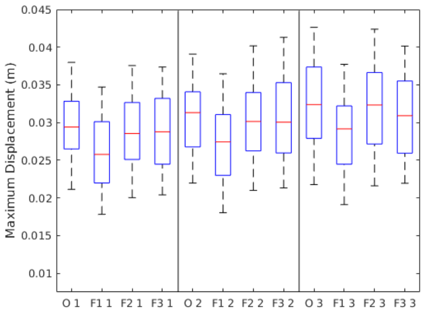
(c) Explicit: Mean Total Distance Travelled and Standard Deviation



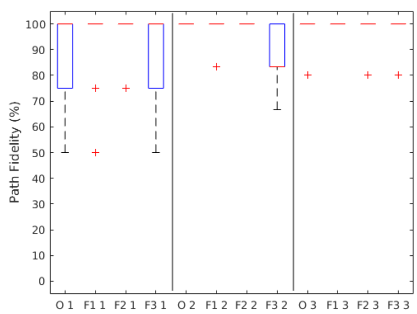
(d) Implicit: Mean Total Distance Travelled and Standard Deviation



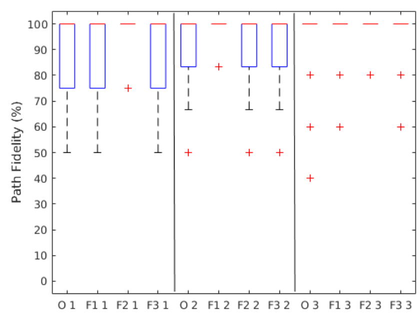
(e) Explicit: Mean Maximum Displacement and Standard Deviation



(f) Implicit: Mean Maximum Displacement and Standard Deviation

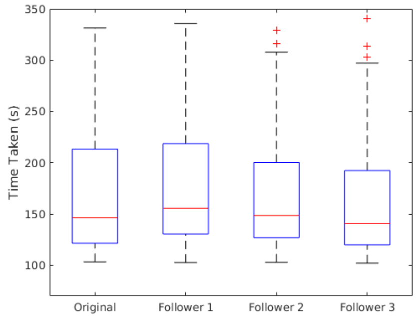


(g) Explicit: Mean Percentage Path Fidelity and Standard Deviation

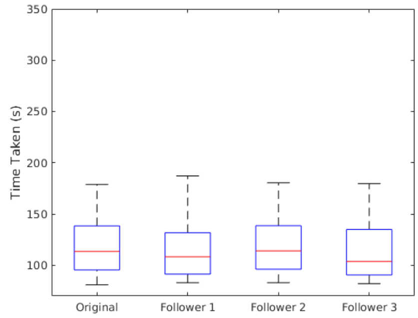


(h) Implicit: Mean Percentage Path Fidelity and Standard Deviation

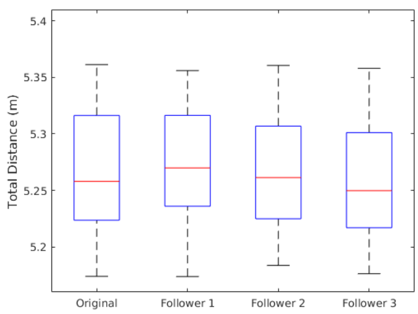
Figure E.5: Performance of both communication strategies in the Line Following Environment for partial motor faults in the Follower's wheels



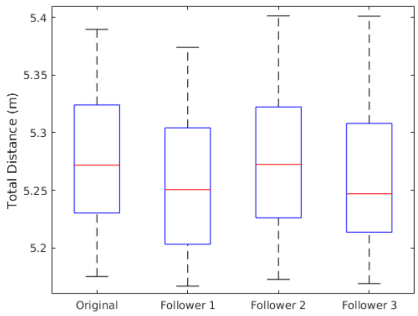
(a) Explicit: Mean Time Taken and Standard Deviation



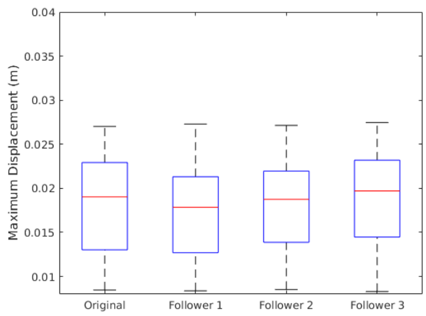
(b) Implicit: Mean Time Taken and Standard Deviation



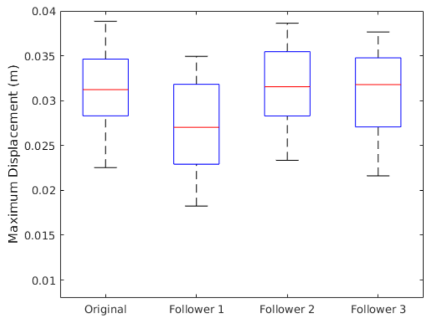
(c) Explicit: Mean Total Distance Travelled and Standard Deviation



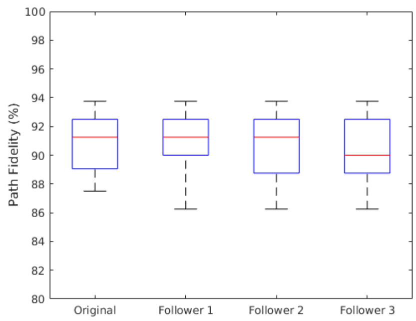
(d) Implicit: Mean Total Distance Travelled and Standard Deviation



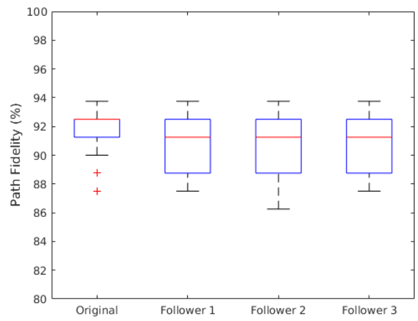
(e) Explicit: Mean Maximum Displacement and Standard Deviation



(f) Implicit: Mean Maximum Displacement and Standard Deviation

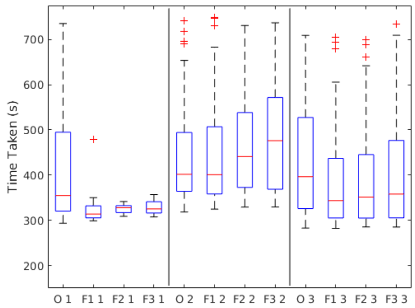


(g) Explicit: Mean Percentage Path Fidelity and Standard Deviation

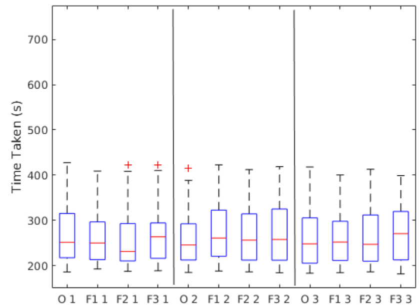


(h) Implicit: Mean Percentage Path Fidelity and Standard Deviation

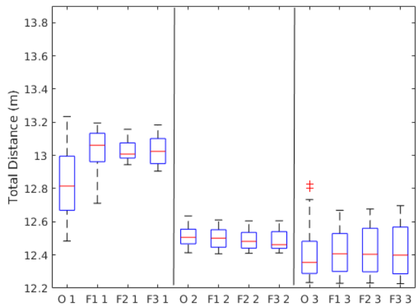
Figure E.6: Performance of both communication strategies in the Simple Environment for partial motor faults in the Follower's wheels



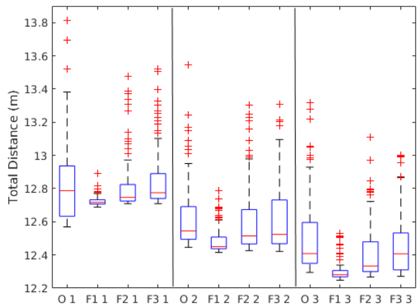
(a) Explicit: Mean Time Taken and Standard Deviation



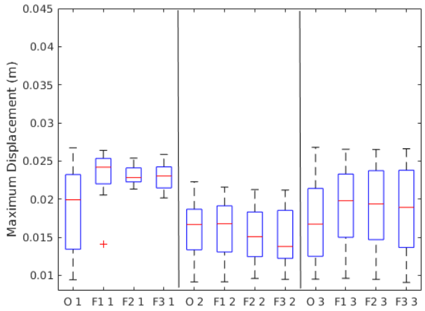
(b) Implicit: Mean Time Taken and Standard Deviation



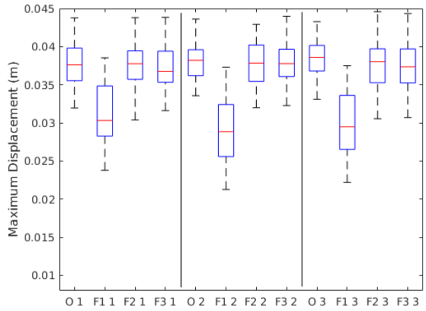
(c) Explicit: Mean Total Distance Travelled and Standard Deviation



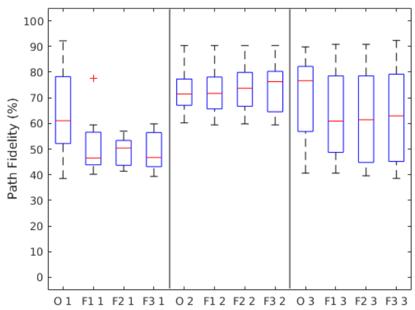
(d) Implicit: Mean Total Distance Travelled and Standard Deviation



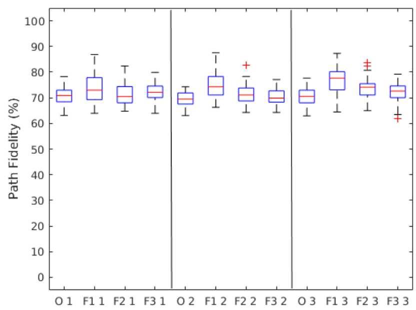
(e) Explicit: Mean Maximum Displacement and Standard Deviation



(f) Implicit: Mean Maximum Displacement and Standard Deviation

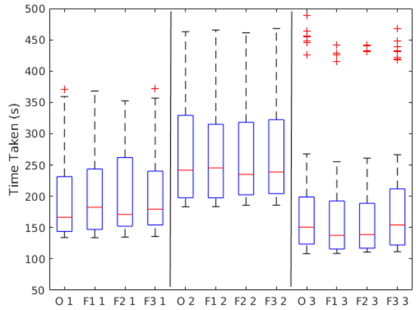


(g) Explicit: Mean Percentage Path Fidelity and Standard Deviation

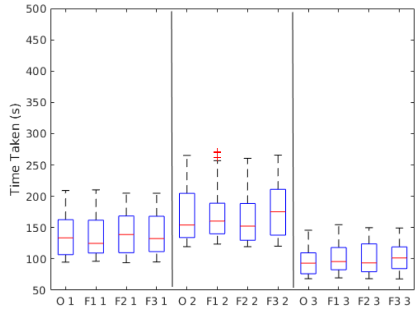


(h) Implicit: Mean Percentage Path Fidelity and Standard Deviation

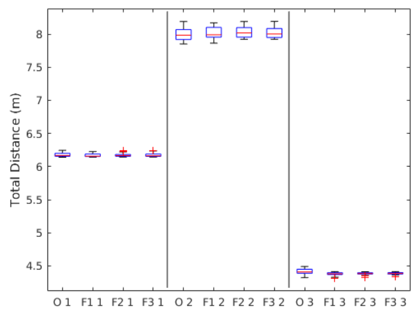
Figure E.7: Performance of both communication strategies in the Cluttered Environment for partial motor faults in the Follower's wheels



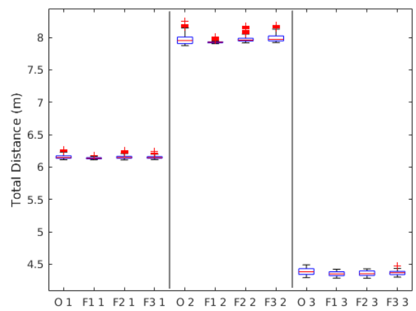
(a) Explicit: Mean Time Taken and Standard Deviation



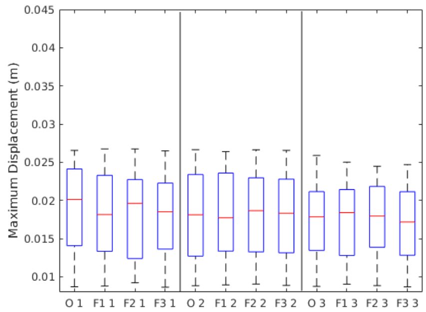
(b) Implicit: Mean Time Taken and Standard Deviation



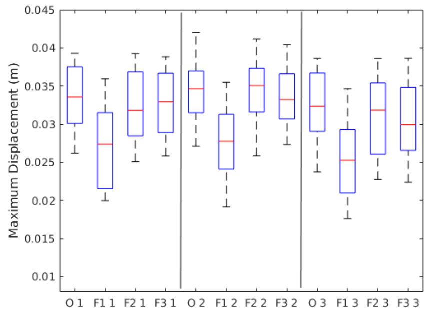
(c) Explicit: Mean Total Distance Travelled and Standard Deviation



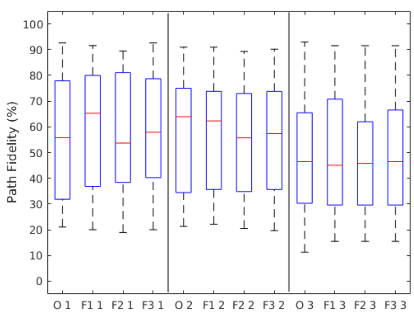
(d) Implicit: Mean Total Distance Travelled and Standard Deviation



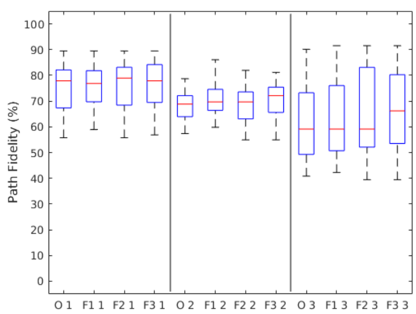
(e) Explicit: Mean Maximum Displacement and Standard Deviation



(f) Implicit: Mean Maximum Displacement and Standard Deviation



(g) Explicit: Mean Percentage Path Fidelity and Standard Deviation



(h) Implicit: Mean Percentage Path Fidelity and Standard Deviation

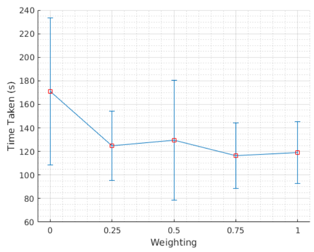
Figure E.8: Performance of both communication strategies in the Randomly Generated Environments for partial motor faults in the Follower's wheels

Table E.34: Mean Percentage Path Fidelity and Standard Deviation for Both Strategies in Randomly Generated Environments in the presence of Partial Motor Faults in Follower Wheels

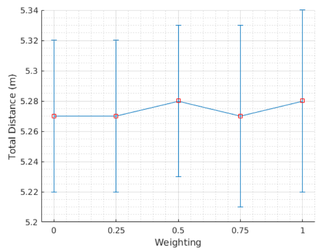
Partial Motor Fault	Type	Randomly Generated Environment		
		1	2	3
Wheel 1	Exp	58.62% (24.18%)	57.15% (21.08%)	50.31% (23.85%)
	Exp Original	54.36% (23.85%)	56.36% (21.46%)	49.84% (23.26%)
	Sig Diff.	0.257	0.834	0.819
	Imp	75.66% (7.99%)	70.80% (6.45%)	63.30% (15.26%)
	Imp Original	75.31% (9.04%)	68.40% (5.61%)	61.80% (14.57%)
	Sig Diff.	0.990	0.045	0.512
Wheel 2	Exp	57.01% (24.05%)	54.25% (21.31%)	47.94% (21.94%)
	Exp Original	54.36% (23.85%)	56.36% (21.46%)	49.84% (23.26%)
	Sig Diff.	0.345	0.510	0.442
	Imp	76.20% (8.83%)	68.84 (6.57%)	65.08% (17.01%)
	Imp Original	75.31% (9.04%)	68.40% (5.61%)	61.80% (14.57%)
	Sig Diff.	0.443	0.596	0.172
Wheel 3	Exp	57.24% (23.22%)	55.95% (22.47%)	48.81% (23.74%)
	Exp Original	54.36% (23.85%)	56.36% (21.46%)	49.84% (23.26%)
	Sig Diff.	0.484	0.880	0.680
	Imp	76.28% (8.37%)	70.66% (5.91%)	66.61% (15.05%)
	Imp Original	75.31% (9.04%)	68.40% (5.61%)	61.80% (14.57%)
	Sig Diff.	0.489	0.005	0.020

Appendix F

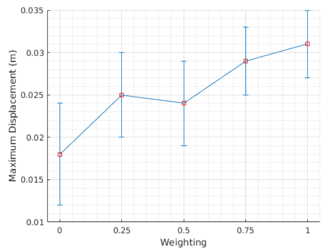
Experimental Data Results from Chapter 7.2: Hybrid System with Original Object



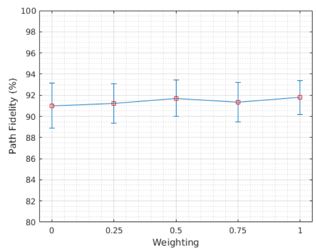
(a) Mean Time Taken and Standard Deviation



(b) Mean Total Distance Travelled and Standard Deviation

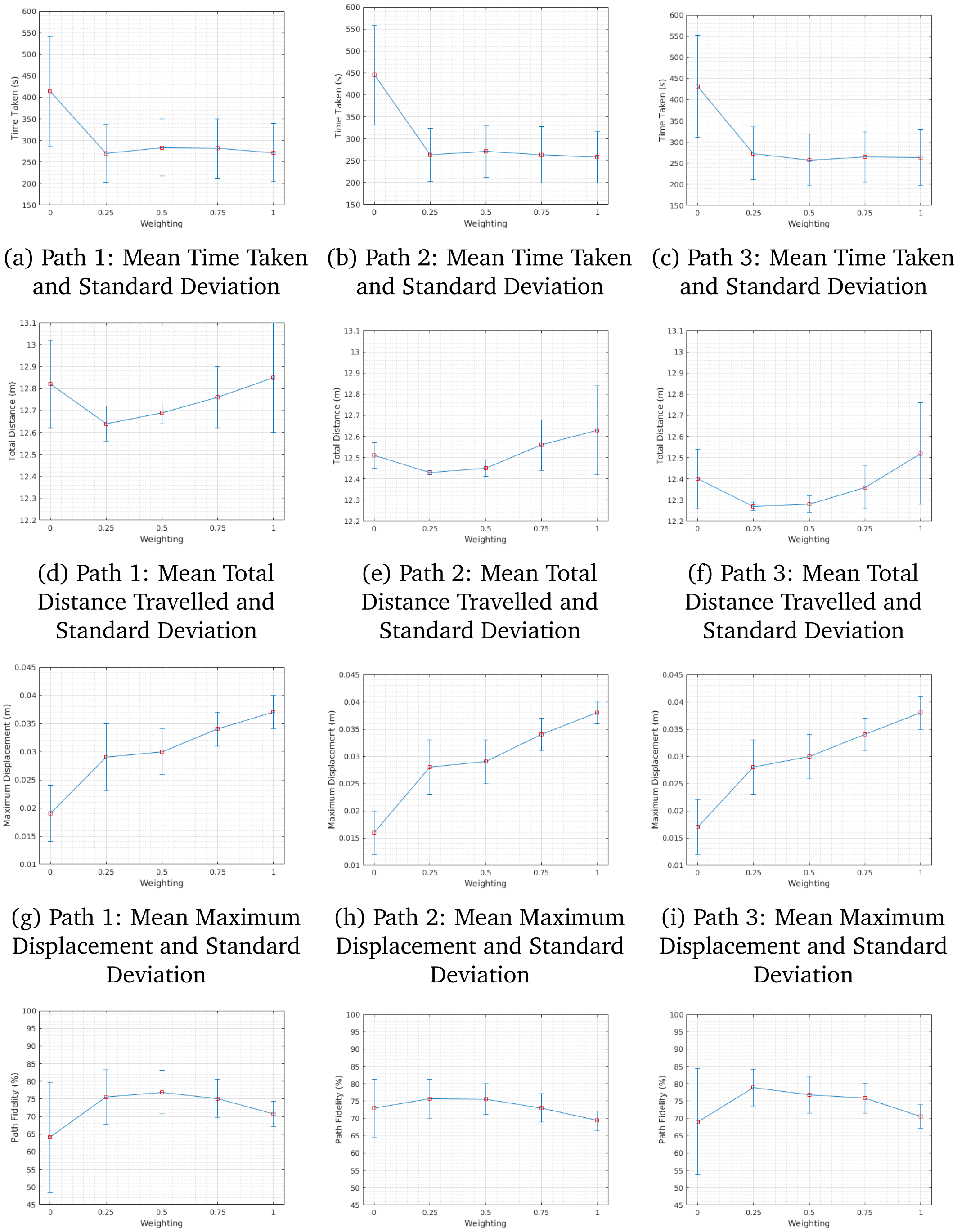


(c) Mean Maximum Displacement and Standard Deviation



(d) Mean Percentage Path Fidelity and Standard Deviation

Figure F.1: Performance for the Hybrid System across all design requirement metrics in the Simple Environment



(a) Path 1: Mean Time Taken and Standard Deviation

(b) Path 2: Mean Time Taken and Standard Deviation

(c) Path 3: Mean Time Taken and Standard Deviation

(d) Path 1: Mean Total Distance Travelled and Standard Deviation

(e) Path 2: Mean Total Distance Travelled and Standard Deviation

(f) Path 3: Mean Total Distance Travelled and Standard Deviation

(g) Path 1: Mean Maximum Displacement and Standard Deviation

(h) Path 2: Mean Maximum Displacement and Standard Deviation

(i) Path 3: Mean Maximum Displacement and Standard Deviation

(j) Path 1: Mean Percentage Path Fidelity and Standard Deviation

(k) Path 2: Mean Percentage Path Fidelity and Standard Deviation

(l) Path 3: Mean Percentage Path Fidelity and Standard Deviation

Figure F.2: Performance for the Hybrid System across all design requirement metrics in the Cluttered Environment

Table F.1: Mean Time Taken in Seconds and Standard Deviation to Complete Task for the Hybrid System in the Line Following Environmental Setup

Weighting	Line Following Paths		
	1	2	3
w = 0.25	**134.35 (103.35)**	**206.05 (214.39)**	**118.71 (32.50)**
Exp	121.81 (46.49)	119.22 (40.55)	121.15 (35.70)
Sig. Diff	0.673	0.135	0.897
Imp	80.25 (18.25)	79.18 (18.89)	81.45 (19.03)
Sig. Diff	p <0.001	p <0.001	p <0.001
w = 0.5	**131.89 (147.99)**	**118.76 (101.62)**	**107.65 (19.52)**
Exp	121.81 (46.49)	119.22 (40.55)	121.15 (35.70)
Sig. Diff	0.006	0.005	0.071
Imp	80.25 (18.25)	79.18 (18.89)	81.45 (19.03)
Sig. Diff	p <0.001	p <0.001	p <0.001
w = 0.75	**90.46 (21.63)**	**77.43 (17.20)**	**94.37 (21.03)**
Exp	121.81 (46.49)	119.22 (40.55)	121.15 (35.70)
Sig. Diff	p <0.001	p <0.001	1.69E-07
Imp	80.25 (18.25)	79.18 (18.89)	81.45 (19.03)
Sig. Diff	p <0.001	0.289	p <0.001

Table F.2: Mean Time Taken in Seconds and Standard Deviation to Complete Task for the Hybrid System in the Simple (SE) and Cluttered (CE) Environments

Weighting	Paths			
	1		2	3
	SE	CE	CE	CE
w = 0.25	**124.66 (29.48)**	**270.09 (67.01)**	**263.68 (60.60)**	**273.22 (65.83)**
Exp	170.98 (62.64)	414.36 (127.10)	445.31 (113.61)	431.18 (120.53)
Sig. Diff	p <0.001	p <0.001	p <0.001	p <0.001
Imp	118.84 (26.18)	271.44 (67.54)	257.93 (58.21)	263.55 (65.87)
Sig. Diff	0.023	0.651	0.019	0.128
w = 0.5	**129.72 (50.93)**	**283.73 (66.40)**	**270.75 (58.86)**	**257.41 (61.12)**
Exp	170.98 (62.64)	414.36 (127.10)	445.31 (113.61)	431.18 (120.53)
Sig. Diff	p <0.001	p <0.001	p <0.001	p <0.001
Imp	118.84 (26.18)	271.44 (67.54)	257.93 (58.21)	263.55 (65.87)
Sig. Diff	0.579	0.521	0.295	0.443
w = 0.75	**116.27 (27.92)**	**281.52 (68.64)**	**263.25 (63.95)**	**264.54 (59.27)**
Exp	170.98 (62.64)	414.36 (127.10)	445.31 (113.61)	431.18 (120.53)
Sig. Diff	p <0.001	p <0.001	p <0.001	p <0.001
Imp	118.84 (26.18)	271.44 (67.54)	257.93 (58.21)	263.55 (65.87)
Sig. Diff	0.681	0.656	0.182	0.394

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Table F.3: Mean Time Taken in Seconds and Standard Deviation to Complete Task for the Hybrid System in the Randomly Generated Environments

Weighting	Randomly Generated Environment		
	1	2	3
w = 0.25	**138.24 (29.51)**	**172.47 (40.02)**	**104.11 (24.81)**
Exp	189.45 (57.78)	266.01 (80.07)	181.78 (94.63)
Sig. Diff	p <0.001	p <0.001	p <0.001
Imp	137.92 (34.28)	168.28 (41.27)	95.06 (20.45)
Sig. Diff	0.079	0.018	0.027
w = 0.5	**140.64 (30.78)**	**173.53 (38.21)**	**105.65 (22.36)**
Exp	189.45 (57.78)	266.01 (80.07)	181.78 (94.63)
Sig. Diff	p <0.001	p <0.001	p <0.001
Imp	137.92 (34.28)	168.28 (41.27)	95.06 (20.45)
Sig. Diff	0.476	0.714	0.708
w = 0.75	**137.31 (31.90)**	**174.68 (42.70)**	**100.78 (24.22)**
Exp	189.45 (57.78)	266.01 (80.07)	181.78 (94.63)
Sig. Diff	p <0.001	p <0.001	p <0.001
Imp	137.92 (34.28)	168.28 (41.27)	95.06 (20.45)
Sig. Diff	0.778	0.806	0.226

Table F.4: Mean and Standard Deviation Total Distance Travelled by Object in Metres for the Hybrid System in the Line Following Environmental Setup

Weighting	Line Following Paths		
	1	2	3
w = 0.25	**3.80 (0.99)**	**4.32 (1.83)**	**3.51 (0.08)**
Exp	3.51 (0.06)	3.33 (0.06)	3.42 (0.05)
Sig. Diff	p <0.001	p <0.001	p <0.001
Imp	3.50 (0.05)	3.36 (0.07)	3.45 (0.06)
Sig. Diff	p <0.001	p <0.001	p <0.001
w = 0.5	**3.89 (1.46)**	**3.63 (0.91)**	**3.52 (0.07)**
Exp	3.51 (0.06)	3.33 (0.06)	3.42 (0.05)
Sig. Diff	0.023	p <0.001	p <0.001
Imp	3.50 (0.05)	3.36 (0.07)	3.45 (0.06)
Sig. Diff	0.008	p <0.001	p <0.001
w = 0.75	**3.52 (0.06)**	**3.32 (0.06)**	**3.49 (0.07)**
Exp	3.51 (0.06)	3.33 (0.06)	3.42 (0.05)
Sig. Diff	0.124	0.018	p <0.001
Imp	3.50 (0.05)	3.36 (0.07)	3.45 (0.06)
Sig. Diff	0.063	p <0.001	p <0.001

Table F.5: Mean and Standard Deviation Total Distance Travelled by Object in Metres for the Hybrid System in the Simple (SE) and Cluttered (CE) Environments

Weighting	Paths			
	1		2	3
	SE	CE	CE	CE
w = 0.25	**5.27 (0.05)**	**12.64 (0.08)**	**12.43 (0.01)**	**12.27 (0.02)**
Exp	5.27 (0.05)	12.82 (0.20)	12.51 (0.06)	12.40 (0.14)
Sig. Diff	0.711	p <0.001	p <0.001	p <0.001
Imp	5.28 (0.06)	12.85 (0.25)	12.63 (0.21)	12.52 (0.24)
Sig. Diff	0.964	p <0.001	p <0.001	p <0.001
w = 0.5	**5.28 (0.05)**	**12.69 (0.05)**	**12.45 (0.04)**	**12.28 (0.04)**
Exp	5.27 (0.05)	12.82 (0.20)	12.51 (0.06)	12.40 (0.14)
Sig. Diff	0.854	p <0.001	p <0.001	p <0.001
Imp	5.28 (0.06)	12.85 (0.25)	12.63 (0.21)	12.52 (0.24)
Sig. Diff	0.306	p <0.001	p <0.001	p <0.001
w = 0.75	**5.27 (0.06)**	**12.76 (0.14)**	**12.53 (0.12)**	**12.36 (0.10)**
Exp	5.27 (0.05)	12.82 (0.20)	12.51 (0.06)	12.40 (0.14)
Sig. Diff	0.552	0.002	0.711	0.028
Imp	5.28 (0.06)	12.85 (0.25)	12.63 (0.21)	12.52 (0.24)
Sig. Diff	0.258	p <0.001	p <0.001	p <0.001

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Table F.6: Mean and Standard Deviation Total Distance Travelled by Object in Metres for the Hybrid System in the Randomly Generated Environments

Weighting	Randomly Generated Environment		
	1	2	3
w = 0.25	**6.14 (0.01)**	**7.90 (0.03)**	**4.38 (0.04)**
Exp	6.18 (0.03)	8.00 (0.09)	4.42 (0.04)
Sig. Diff	p <0.001	p <0.001	p <0.001
Imp	6.16 (0.04)	7.97 (0.09)	4.39 (0.05)
Sig. Diff	0.001	p <0.001	0.066
w = 0.5	**6.14 (0.01)**	**7.90 (0.04)**	**4.39 (0.04)**
Exp	6.18 (0.03)	8.00 (0.09)	4.42 (0.04)
Sig. Diff	p <0.001	p <0.001	0.011
Imp	6.16 (0.04)	7.97 (0.09)	4.39 (0.05)
Sig. Diff	p <0.001	p <0.001	p <0.001
w = 0.75	**6.14 (0.02)**	**7.92 (0.05)**	**4.39 (0.05)**
Exp	6.18 (0.03)	8.00 (0.09)	4.42 (0.04)
Sig. Diff	p <0.001	p <0.001	0.005
Imp	6.16 (0.04)	7.97 (0.09)	4.39 (0.05)
Sig. Diff	p <0.001	p <0.001	0.028

Table F.7: Mean Maximum Displacement and Standard Deviation of Object in Metres for the Hybrid System in the Line Following Environmental Setup

Weighting	Line Following Paths		
	1	2	3
w = 0.25	**0.027 (0.008)**	**0.034 (0.009)**	**0.031 (0.009)**
Exp	0.018 (0.006)	0.018 (0.006)	0.019 (0.005)
Sig. Diff	p <0.001	p <0.001	p <0.001
Imp	0.029 (0.005)	0.031 (0.005)	0.033 (0.006)
Sig. Diff	0.001	0.130	0.005
w = 0.5	**0.028 (0.007)**	**0.031 (0.006)**	**0.031 (0.006)**
Exp	0.018 (0.006)	0.018 (0.006)	0.019 (0.005)
Sig. Diff	p <0.001	p <0.001	3.18E-23
Imp	0.029 (0.005)	0.031 (0.005)	0.033 (0.006)
Sig. Diff	0.008	0.654	0.009
w = 0.75	**0.028 (0.006)**	**0.032 (0.004)**	**0.032 (0.006)**
Exp	0.018 (0.006)	0.018 (0.006)	0.019 (0.005)
Sig. Diff	p <0.001	p <0.001	p <0.001
Imp	0.029 (0.005)	0.031 (0.005)	0.033 (0.006)
Sig. Diff	0.006	0.005	0.580

Table F.8: Mean Maximum Displacement and Standard Deviation of Object in Metres for the Hybrid System in the Simple (SE) and Cluttered (CE) Environments

Weighting	Paths			
	1		2	3
	SE	CE	CE	CE
w = 0.25	**0.025 (0.005)**	**0.029 (0.006)**	**0.028 (0.005)**	**0.028 (0.005)**
Exp	0.018 (0.006)	0.019 (0.005)	0.016 (0.004)	0.017 (0.005)
Sig. Diff	p <0.001	p <0.001	p <0.001	p <0.001
Imp	0.031 (0.004)	0.037 (0.003)	0.038 (0.002)	0.038 (0.003)
Sig. Diff	p <0.001	p <0.001	p <0.001	p <0.001
w = 0.5	**0.024 (0.005)**	**0.030 (0.004)**	**0.029 (0.004)**	**0.030 (0.004)**
Exp	0.018 (0.006)	0.019 (0.005)	0.016 (0.004)	0.017 (0.005)
Sig. Diff	p <0.001	p <0.001	p <0.001	p <0.001
Imp	0.031 (0.004)	0.037 (0.003)	0.038 (0.002)	0.038 (0.003)
Sig. Diff	p <0.001	p <0.001	p <0.001	p <0.001
w = 0.75	**0.029 (0.004)**	**0.034 (0.003)**	**0.034 (0.003)**	**0.034 (0.003)**
Exp	0.018 (0.006)	0.019 (0.005)	0.016 (0.004)	0.017 (0.005)
Sig. Diff	p <0.001	p <0.001	p <0.001	p <0.001
Imp	0.031 (0.004)	0.037 (0.003)	0.038 (0.002)	0.038 (0.003)
Sig. Diff	0.001	p <0.001	p <0.001	p <0.001

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Table F.9: Mean Maximum Displacement and Standard Deviation of Object in Metres for the Hybrid System in the Randomly Generated Environments

Weighting	Randomly Generated Environment		
	1	2	3
w = 0.25	**0.027 (0.005)**	**0.027 (0.006)**	**0.025 (0.006)**
Exp	0.019 (0.005)	0.018 (0.006)	0.017 (0.005)
Sig. Diff	p <0.001	p <0.001	p <0.001
Imp	0.034 (0.004)	0.034 (0.003)	0.033 (0.004)
Sig. Diff	p <0.001	p <0.001	p <0.001
w = 0.5	**0.026 (0.005)**	**0.027 (0.005)**	**0.025 (0.005)**
Exp	0.019 (0.005)	0.018 (0.006)	0.017 (0.005)
Sig. Diff	p <0.001	p <0.001	p <0.001
Imp	0.034 (0.004)	0.034 (0.003)	0.033 (0.004)
Sig. Diff	p <0.001	p <0.001	p <0.001
w = 0.75	**0.030 (0.003)**	**0.030 (0.003)**	**0.029 (0.004)**
Exp	0.019 (0.005)	0.018 (0.006)	0.017 (0.005)
Sig. Diff	p <0.001	p <0.001	p <0.001
Imp	0.034 (0.004)	0.034 (0.003)	0.033 (0.004)
Sig. Diff	p <0.001	p <0.001	0.005

Table F.10: Percentage Mean and Standard Deviation Path Fidelity for the Hybrid System in the Line Following Environmental Setup

Weighting	Line Following Paths		
	1	2	3
w = 0.25	**78.02 (27.09%)**	**56.58% (25.54%)**	**79.35% (19.15%)**
Exp	90.75% (14.93%)	100% (∼0%)	99.40% (3.43%)
Sig. Diff	0.001	p <0.001	p <0.001
Imp	93.00 (12.35%)	89.67% (14.17%)	96.57% (9.49%)
Sig. Diff	p <0.001	p <0.001	p <0.001
w = 0.5	**86.48% (22.47%)**	**71.56% (25.02%)**	**90.18% (15.64%)**
Exp	90.75% (14.93%)	100% (∼0%)	99.40% (3.43%)
Sig. Diff	0.444	p <0.001	p <0.001
Imp	93.00 (12.35%)	89.67% (14.17%)	96.57% (9.49%)
Sig. Diff	0.109	p <0.001	0.002
w = 0.75	**93.25% (13.23%)**	**99.50% (2.86%)**	**91.65% (14.18%)**
Exp	90.75% (14.93%)	100% (∼0%)	99.40% (3.43%)
Sig. Diff	0.224	0.083	p <0.001
Imp	93.00 (12.35%)	89.67% (14.17%)	96.57% (9.49%)
Sig. Diff	0.754	p <0.001	0.007

Table F.11: Percentage Mean and Standard Deviation Path Fidelity for the Hybrid System in the Simple (SE) and Cluttered (CE) Environments

Weighting	Randomly Generated Environment			
	1		2	3
	SE	CE	CE	CE
w = 0.25	**91.24% (1.87%)**	**75.61% (7.70%)**	**75.69% (5.67%)**	**78.94% (5.27%)**
Exp	91.00% (2.12%)	64.09% (15.65%)	72.96% (8.33%)	69.04 (15.25%)
Sig. Diff	0.157	p <0.001	0.002	p <0.001
Imp	91.79% (1.60%)	70.78% (3.55%)	69.44% (2.80%)	70.56% (3.35%)
Sig. Diff	0.057	p <0.001	p <0.001	p <0.001
w = 0.5	**91.72% (1.71%)**	**76.90% (6.14%)**	**75.59% (4.38%)**	**76.78% (5.26%)**
Exp	91.00% (2.12%)	64.09% (15.65%)	72.96% (8.33%)	69.04 (15.25%)
Sig. Diff	0.110	p <0.001	0.045	p <0.001
Imp	91.79% (1.60%)	70.78% (3.55%)	69.44% (2.80%)	70.56% (3.35%)
Sig. Diff	0.043	p <0.001	p <0.001	p <0.001
w = 0.75	**91.33% (1.88%)**	**75.09% (5.39%)**	**73.03% (4.04%)**	**75.83% (4.32%)**
Exp	91.00% (2.12%)	64.09% (15.65%)	72.96% (8.33%)	69.04 (15.25%)
Sig. Diff	0.100	p <0.001	0.390	0.003
Imp	91.79% (1.60%)	70.78% (3.55%)	69.44% (2.80%)	70.56% (3.35%)
Sig. Diff	0.058	p <0.001	p <0.001	p <0.001

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Table F.12: Percentage Mean and Standard Deviation Path Fidelity for the Hybrid System in the Randomly Generated Environments

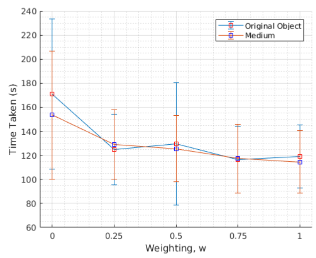
Weighting	Paths		
	1	2	3
w = 0.25	**74.08% (8.48%)**	**71.04% (7.16%)**	**63.48% (14.71%)**
Exp	54.36% (23.85%)	56.36% (21.46%)	49.84% (23.26%)
Sig. Diff	p <0.001	p <0.001	p <0.001
Imp	75.31% (9.04%)	68.40% (5.61%)	61.80% (14.57%)
Sig. Diff	0.998	0.001	0.586
w = 0.5	**76.73% (8.01%)**	**71.77% (6.66%)**	**66.30% (15.08%)**
Exp	54.36% (23.85%)	56.36% (21.46%)	49.84% (23.26%)
Sig. Diff	p <0.001	p <0.001	p <0.001
Imp	75.31% (9.04%)	68.40% (5.61%)	61.80% (14.57%)
Sig. Diff	0.666	0.031	0.447
w = 0.75	**75.83% (8.16%)**	**71.61% (7.05%)**	**64.37% (17.10%)**
Exp	54.36% (23.85%)	56.36% (21.46%)	49.84% (23.26%)
Sig. Diff	p <0.001	p <0.001	p <0.001
Imp	75.31% (9.04%)	68.40% (5.61%)	61.80% (14.57%)
Sig. Diff	0.812	0.222	0.158

Appendix G

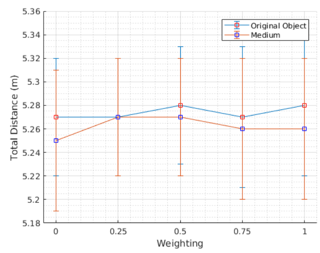
Graphical Results of Performance of Hybrid System with Objects of Different Size and Shape

G.1 Size

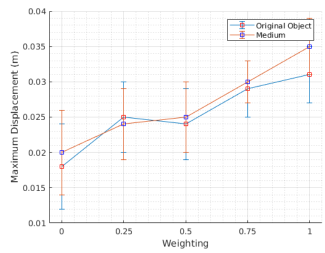
G.1.1 Medium



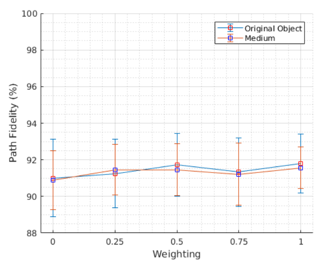
(a) Mean Time Taken and Standard Deviation



(b) Mean Total Distance Travelled and Standard Deviation

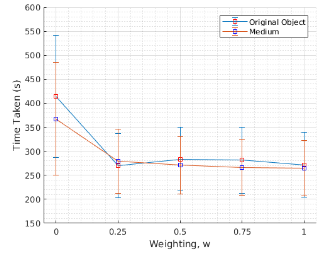


(c) Mean Maximum Displacement and Standard Deviation

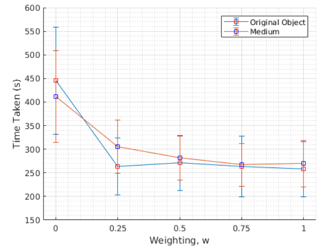


(d) Mean Percentage Path Fidelity and Standard Deviation

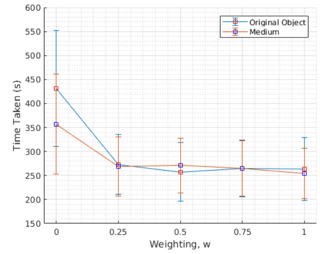
Figure G.1: Performance for the Hybrid System across all design requirement metrics in the Simple Environment for the Medium Object



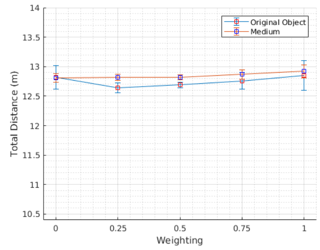
(a) Path 1: Mean Time Taken and Standard Deviation



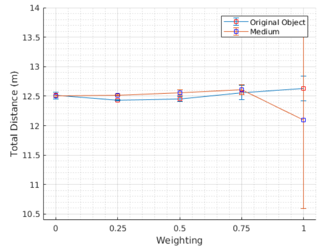
(b) Path 2: Mean Time Taken and Standard Deviation



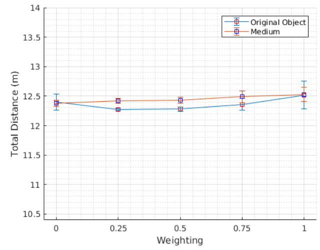
(c) Path 3: Mean Time Taken and Standard Deviation



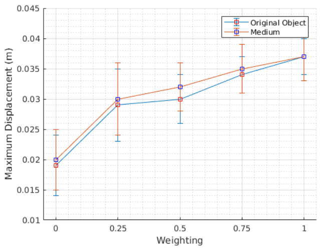
(d) Path 1: Mean Total Distance Travelled and Standard Deviation



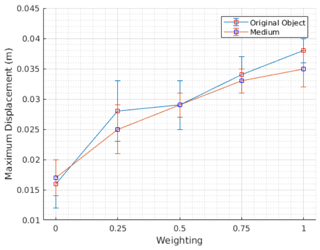
(e) Path 2: Mean Total Distance Travelled and Standard Deviation



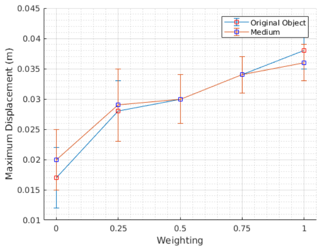
(f) Path 3: Mean Total Distance Travelled and Standard Deviation



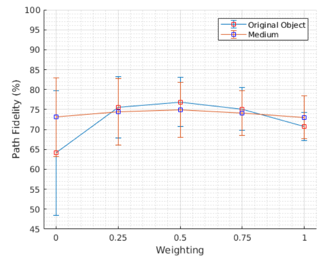
(g) Path 1: Mean Maximum Displacement and Standard Deviation



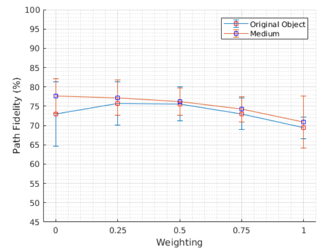
(h) Path 2: Mean Maximum Displacement and Standard Deviation



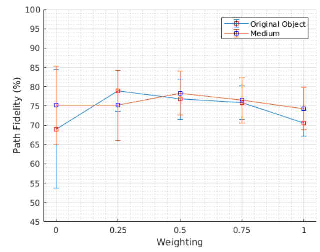
(i) Path 3: Mean Maximum Displacement and Standard Deviation



(j) Path 1: Mean Percentage Path Fidelity and Standard Deviation



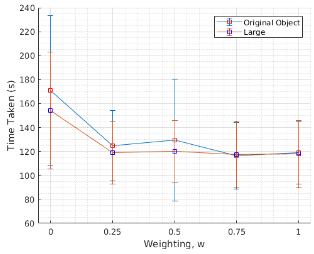
(k) Path 2: Mean Percentage Path Fidelity and Standard Deviation



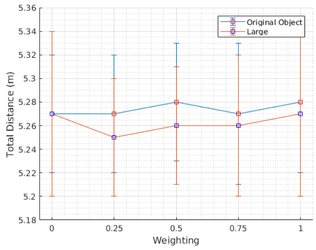
(l) Path 3: Mean Percentage Path Fidelity and Standard Deviation

Figure G.2: Performance for the Hybrid System across all design requirement metrics in the Cluttered Environment for the Medium Object

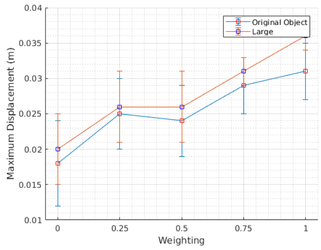
G.1.2 Large



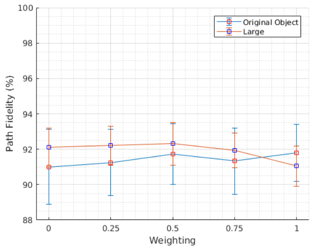
(a) Mean Time Taken and Standard Deviation



(b) Mean Total Distance Travelled and Standard Deviation

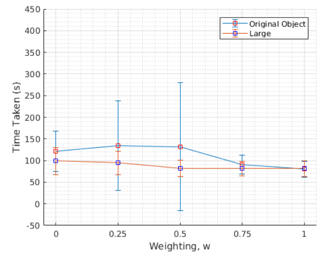


(c) Mean Maximum Displacement and Standard Deviation

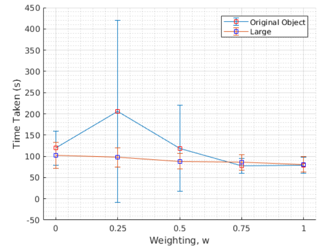


(d) Mean Percentage Path Fidelity and Standard Deviation

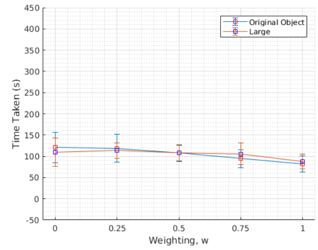
Figure G.3: Performance for the Hybrid System across all design requirement metrics in the Simple Environment for the Large Object



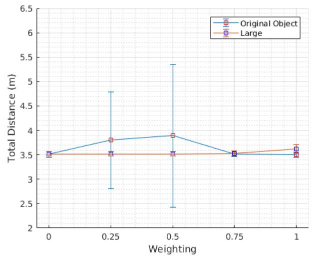
(a) Path 1: Mean Time Taken and Standard Deviation



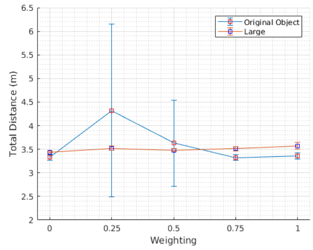
(b) Path 2: Mean Time Taken and Standard Deviation



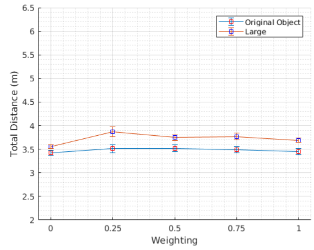
(c) Path 3: Mean Time Taken and Standard Deviation



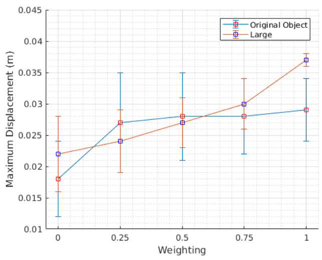
(d) Path 1: Mean Total Distance Travelled and Standard Deviation



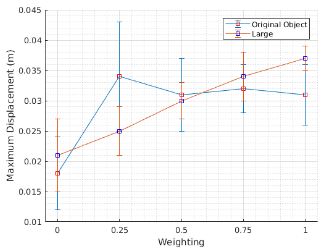
(e) Path 2: Mean Total Distance Travelled and Standard Deviation



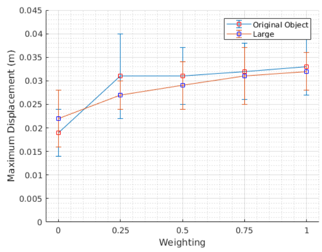
(f) Path 3: Mean Total Distance Travelled and Standard Deviation



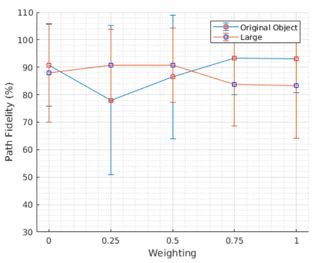
(g) Path 1: Mean Maximum Displacement and Standard Deviation



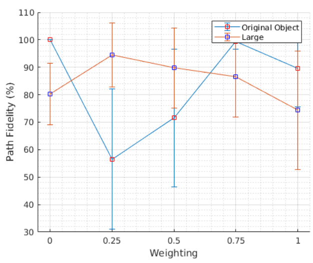
(h) Path 2: Mean Maximum Displacement and Standard Deviation



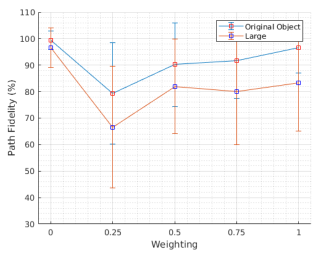
(i) Path 3: Mean Maximum Displacement and Standard Deviation



(j) Path 1: Mean Percentage Path Fidelity and Standard Deviation

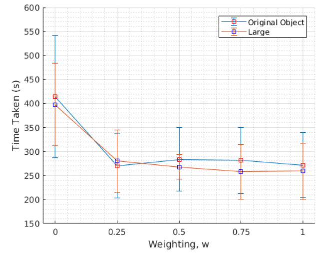


(k) Path 2: Mean Percentage Path Fidelity and Standard Deviation

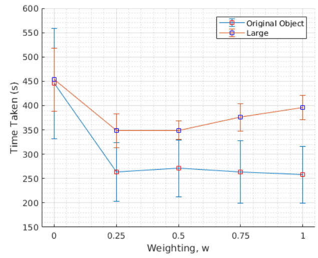


(l) Path 3: Mean Percentage Path Fidelity and Standard Deviation

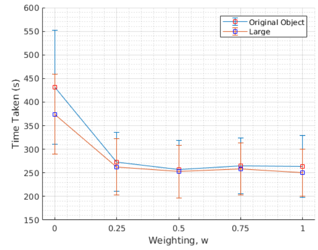
Figure G.4: Performance for the Hybrid System across all design requirement metrics in the Line Following Environmental Setup for the Large Object



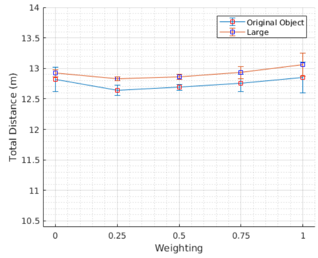
(a) Path 1: Mean Time Taken and Standard Deviation



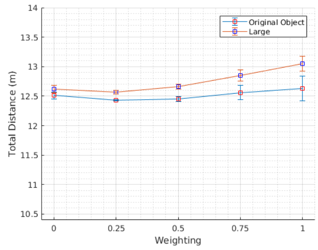
(b) Path 2: Mean Time Taken and Standard Deviation



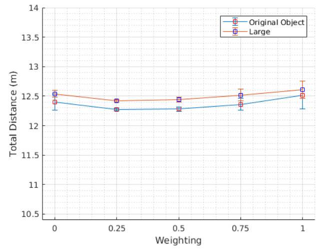
(c) Path 3: Mean Time Taken and Standard Deviation



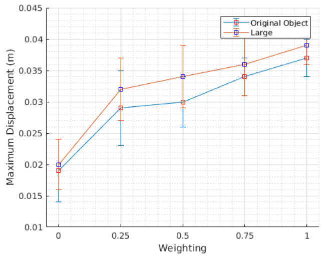
(d) Path 1: Mean Total Distance Travelled and Standard Deviation



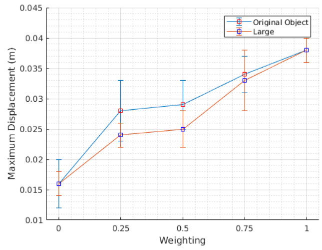
(e) Path 2: Mean Total Distance Travelled and Standard Deviation



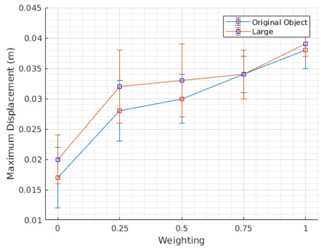
(f) Path 3: Mean Total Distance Travelled and Standard Deviation



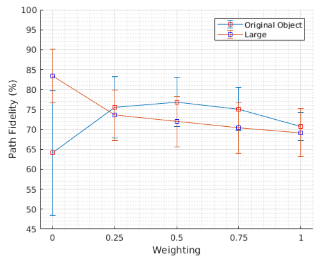
(g) Path 1: Mean Maximum Displacement and Standard Deviation



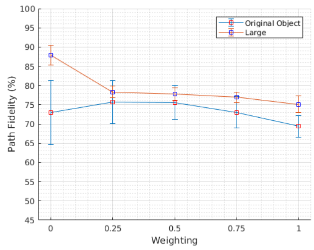
(h) Path 2: Mean Maximum Displacement and Standard Deviation



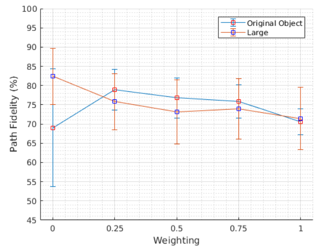
(i) Path 3: Mean Maximum Displacement and Standard Deviation



(j) Path 1: Mean Percentage Path Fidelity and Standard Deviation

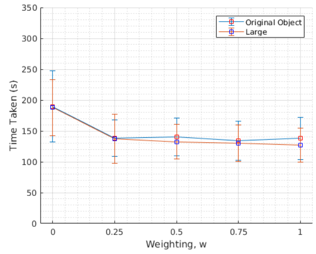


(k) Path 2: Mean Percentage Path Fidelity and Standard Deviation

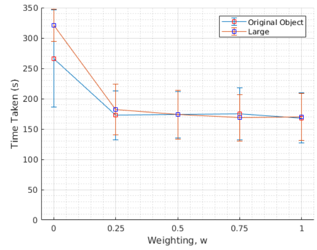


(l) Path 3: Mean Percentage Path Fidelity and Standard Deviation

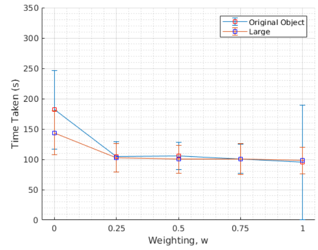
Figure G.5: Performance for the Hybrid System across all design requirement metrics in the Cluttered Environment for the Large Object



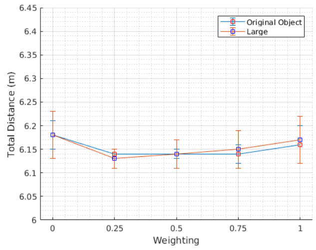
(a) Path 1: Mean Time Taken and Standard Deviation



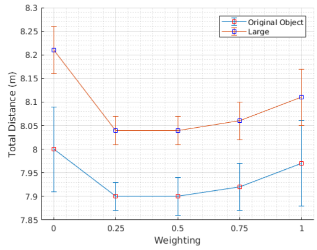
(b) Path 2: Mean Time Taken and Standard Deviation



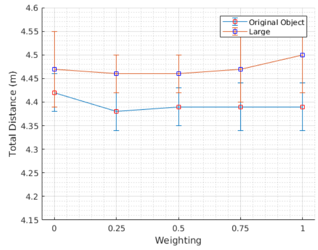
(c) Path 3: Mean Time Taken and Standard Deviation



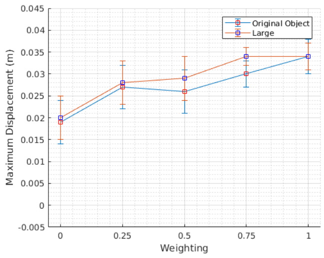
(d) Path 1: Mean Total Distance Travelled and Standard Deviation



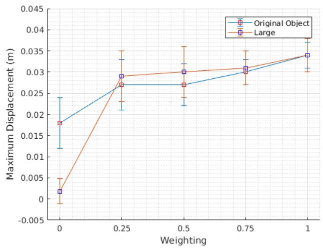
(e) Path 2: Mean Total Distance Travelled and Standard Deviation



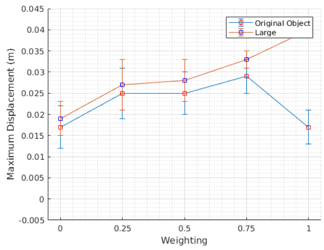
(f) Path 3: Mean Total Distance Travelled and Standard Deviation



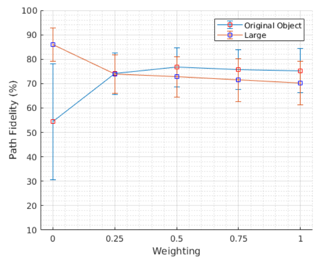
(g) Path 1: Mean Maximum Displacement and Standard Deviation



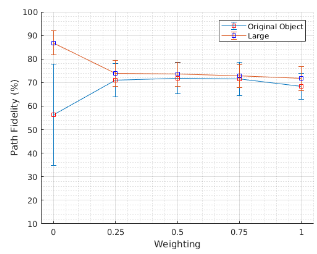
(h) Path 2: Mean Maximum Displacement and Standard Deviation



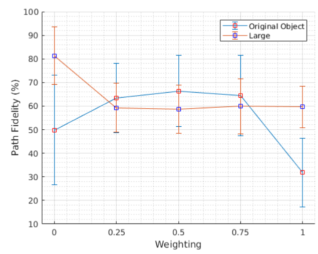
(i) Path 3: Mean Maximum Displacement and Standard Deviation



(j) Path 1: Mean Percentage Path Fidelity and Standard Deviation



(k) Path 2: Mean Percentage Path Fidelity and Standard Deviation

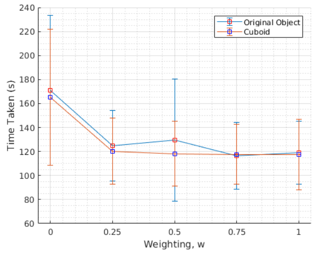


(l) Path 3: Mean Percentage Path Fidelity and Standard Deviation

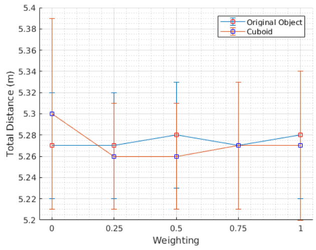
Figure G.6: Performance for the Hybrid System across all design requirement metrics in the Randomly Generated Environments for the Large Object

G.2 Shape

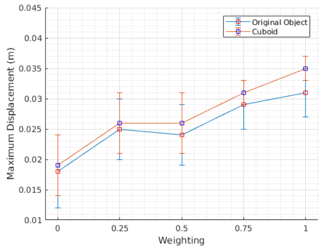
G.2.1 Cuboid



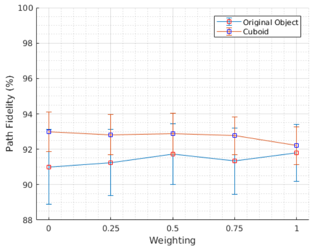
(a) Mean Time Taken and Standard Deviation



(b) Mean Total Distance Travelled and Standard Deviation

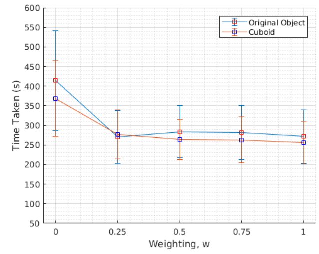


(c) Mean Maximum Displacement and Standard Deviation

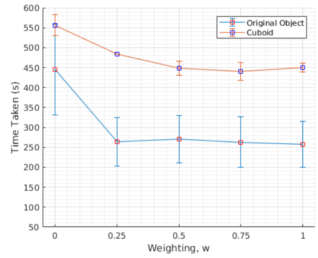


(d) Mean Percentage Path Fidelity and Standard Deviation

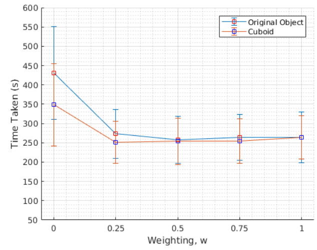
Figure G.7: Performance for the Hybrid System across all design requirement metrics in the Simple Environment for the Cuboid



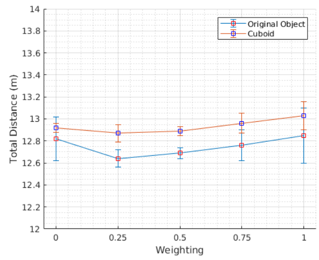
(a) Path 1: Mean Time Taken and Standard Deviation



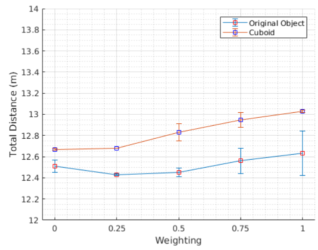
(b) Path 2: Mean Time Taken and Standard Deviation



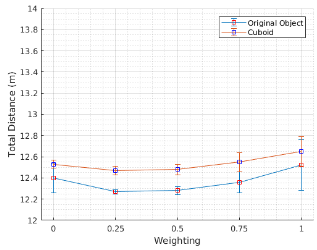
(c) Path 3: Mean Time Taken and Standard Deviation



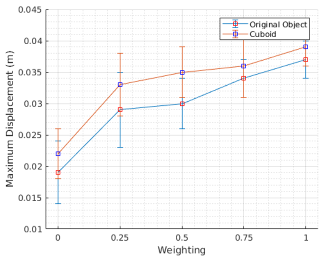
(d) Path 1: Mean Total Distance Travelled and Standard Deviation



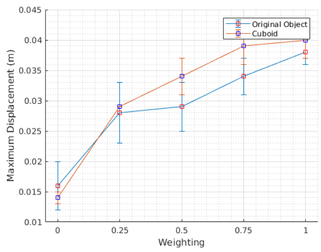
(e) Path 2: Mean Total Distance Travelled and Standard Deviation



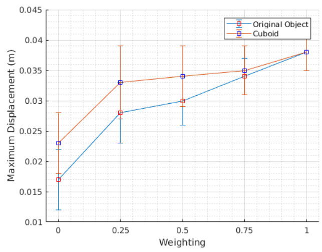
(f) Path 3: Mean Total Distance Travelled and Standard Deviation



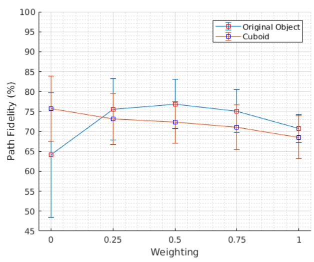
(g) Path 1: Mean Maximum Displacement and Standard Deviation



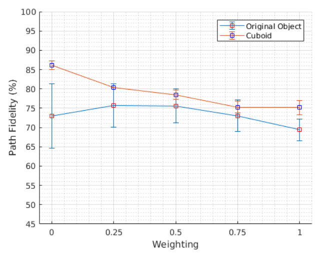
(h) Path 2: Mean Maximum Displacement and Standard Deviation



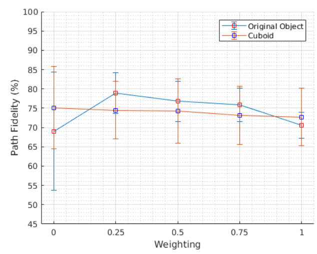
(i) Path 3: Mean Maximum Displacement and Standard Deviation



(j) Path 1: Mean Percentage Path Fidelity and Standard Deviation



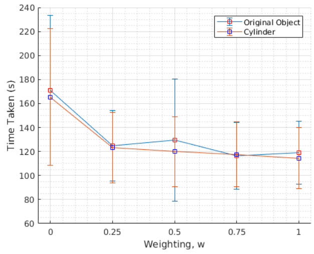
(k) Path 2: Mean Percentage Path Fidelity and Standard Deviation



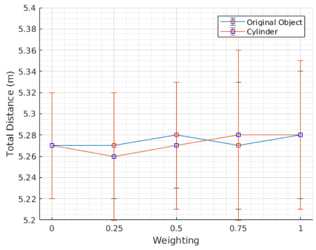
(l) Path 3: Mean Percentage Path Fidelity and Standard Deviation

Figure G.8: Performance for the Hybrid System across all design requirement metrics in the Cluttered Environment for the Cuboid

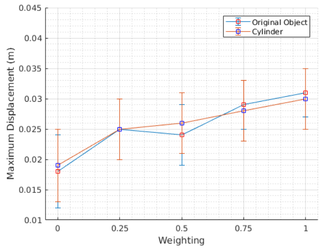
G.2.2 Cylinder



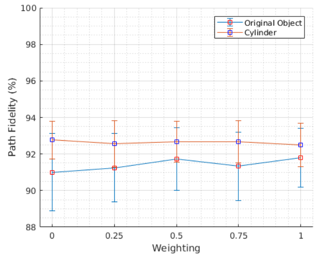
(a) Mean Time Taken and Standard Deviation



(b) Mean Total Distance Travelled and Standard Deviation

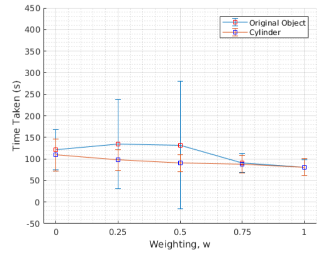


(c) Mean Maximum Displacement and Standard Deviation

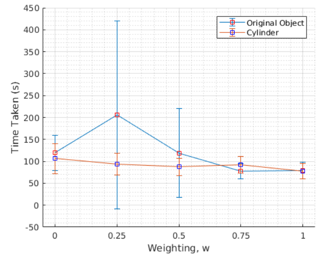


(d) Mean Percentage Path Fidelity and Standard Deviation

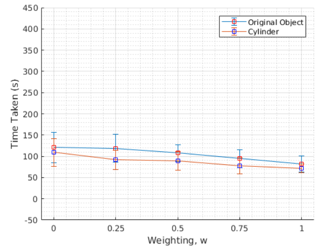
Figure G.9: Performance for the Hybrid System across all design requirement metrics in the Simple Environment for the Cylinder.



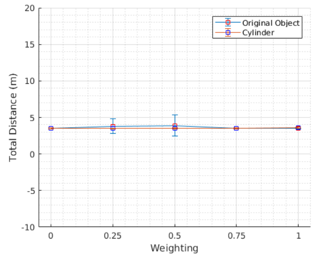
(a) Path 1: Mean Time Taken and Standard Deviation



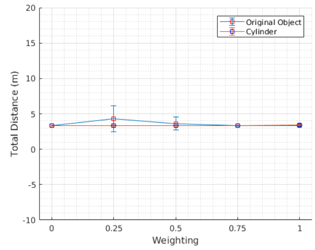
(b) Path 2: Mean Time Taken and Standard Deviation



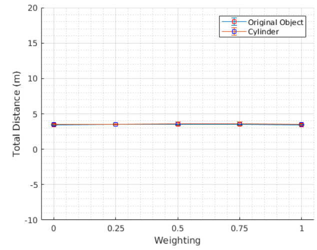
(c) Path 3: Mean Time Taken and Standard Deviation



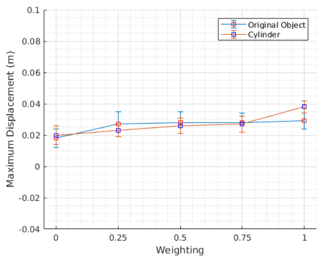
(d) Path 1: Mean Total Distance Travelled and Standard Deviation



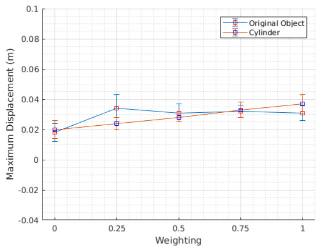
(e) Path 2: Mean Total Distance Travelled and Standard Deviation



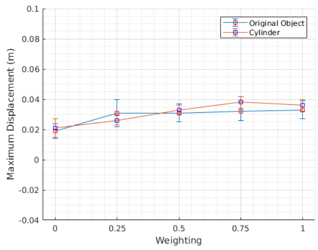
(f) Path 3: Mean Total Distance Travelled and Standard Deviation



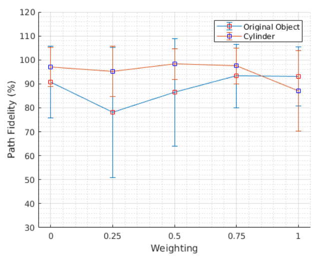
(g) Path 1: Mean Maximum Displacement and Standard Deviation



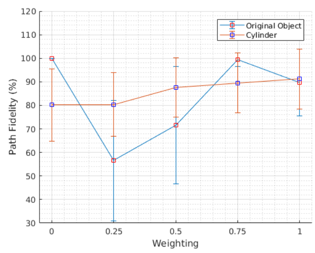
(h) Path 2: Mean Maximum Displacement and Standard Deviation



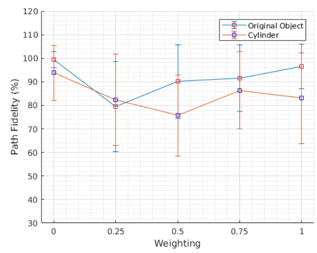
(i) Path 3: Mean Maximum Displacement and Standard Deviation



(j) Path 1: Mean Percentage Path Fidelity and Standard Deviation

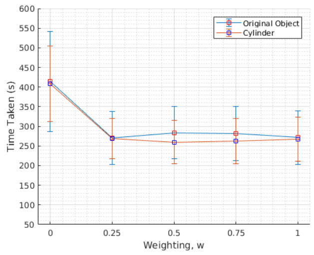


(k) Path 2: Mean Percentage Path Fidelity and Standard Deviation

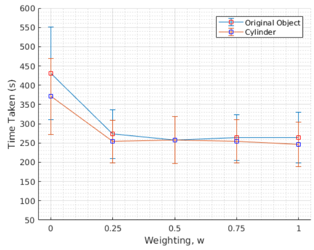


(l) Path 3: Mean Percentage Path Fidelity and Standard Deviation

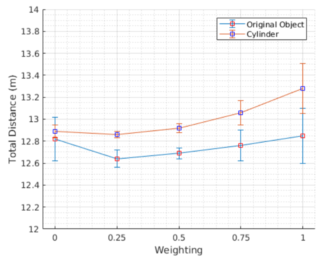
Figure G.10: Performance for the Hybrid System across all design requirement metrics in the Line Following Environmental Setup for the Cylinder.



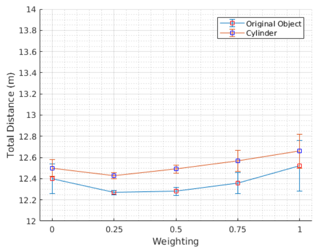
(a) Path 1: Mean Time Taken and Standard Deviation



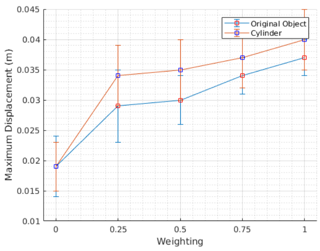
(b) Path 3: Mean Time Taken and Standard Deviation



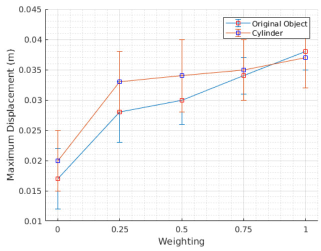
(c) Path 1: Mean Total Distance Travelled and Standard Deviation



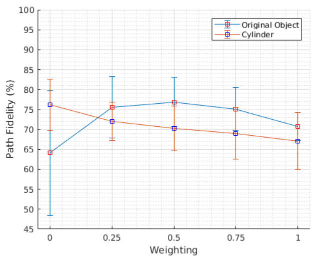
(d) Path 3: Mean Total Distance Travelled and Standard Deviation



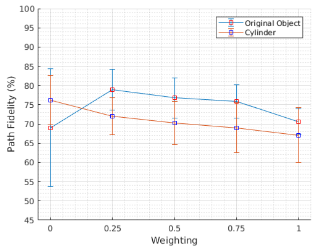
(e) Path 1: Mean Maximum Displacement and Standard Deviation



(f) Path 3: Mean Maximum Displacement and Standard Deviation

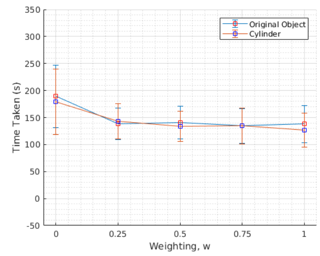


(g) Path 1: Mean Percentage Path Fidelity and Standard Deviation

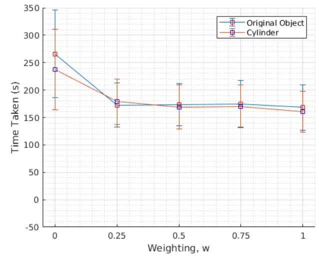


(h) Path 3: Mean Percentage Path Fidelity and Standard Deviation

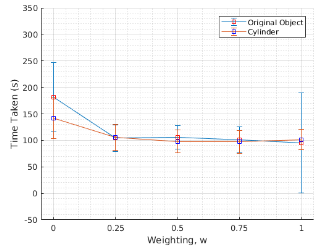
Figure G.11: Performance for the Hybrid System across all design requirement metrics in the Cluttered Environment for the Cylinder. No results for the cylinder in path 2 are shown due to task failure across all weightings.



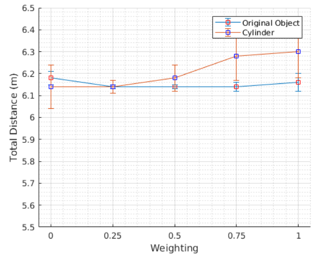
(a) Path 1: Mean Time Taken and Standard Deviation



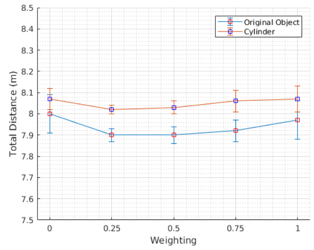
(b) Path 2: Mean Time Taken and Standard Deviation



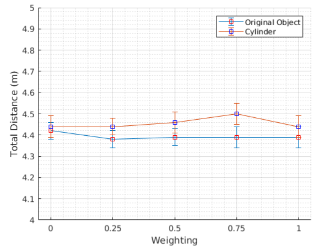
(c) Path 3: Mean Time Taken and Standard Deviation



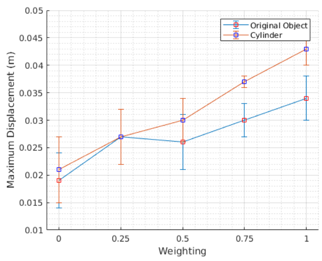
(d) Path 1: Mean Total Distance Travelled and Standard Deviation



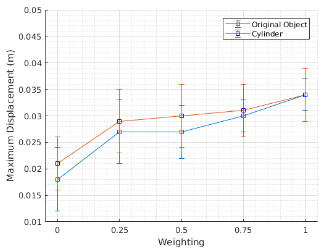
(e) Path 2: Mean Total Distance Travelled and Standard Deviation



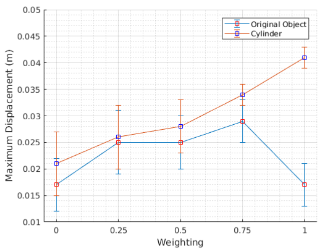
(f) Path 3: Mean Total Distance Travelled and Standard Deviation



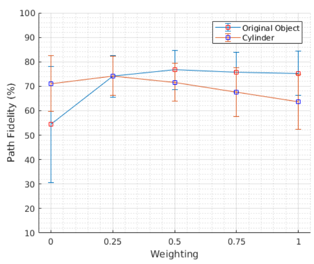
(g) Path 1: Mean Maximum Displacement and Standard Deviation



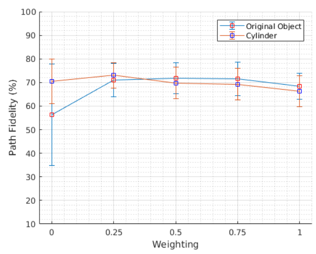
(h) Path 2: Mean Maximum Displacement and Standard Deviation



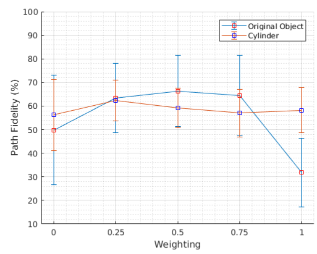
(i) Path 3: Mean Maximum Displacement and Standard Deviation



(j) Path 1: Mean Percentage Path Fidelity and Standard Deviation



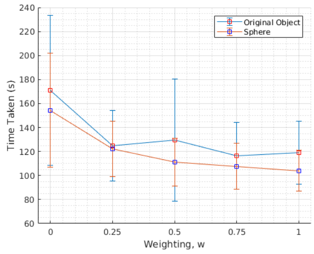
(k) Path 2: Mean Percentage Path Fidelity and Standard Deviation



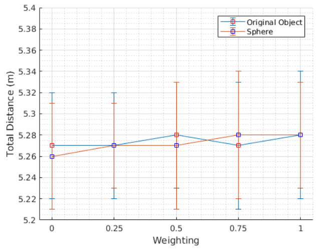
(l) Path 3: Mean Percentage Path Fidelity and Standard Deviation

Figure G.12: Performance for the Hybrid System across all design requirement metrics in the Randomly Generated Environments for the Cylinder.

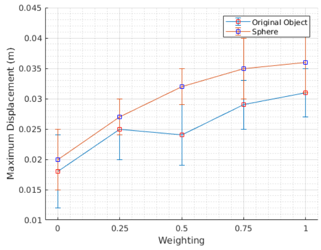
G.2.3 Sphere



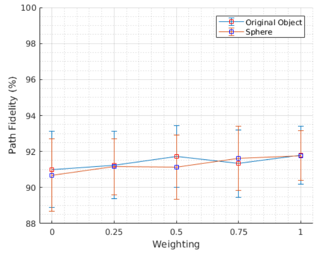
(a) Mean Time Taken and Standard Deviation



(b) Mean Total Distance Travelled and Standard Deviation

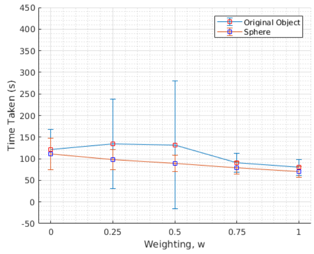


(c) Mean Maximum Displacement and Standard Deviation

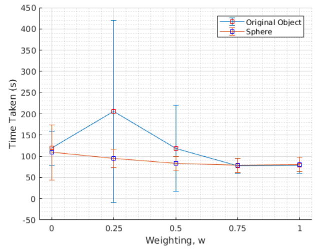


(d) Mean Percentage Path Fidelity and Standard Deviation

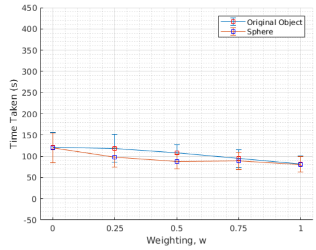
Figure G.13: Performance for the Hybrid System across all design requirement metrics in the Simple Environment for the Sphere.



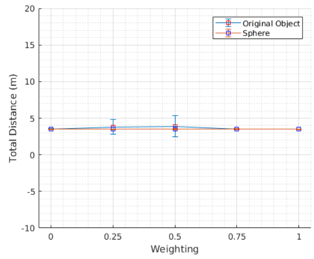
(a) Path 1: Mean Time Taken and Standard Deviation



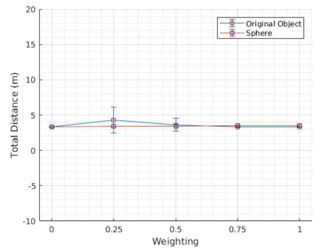
(b) Path 2: Mean Time Taken and Standard Deviation



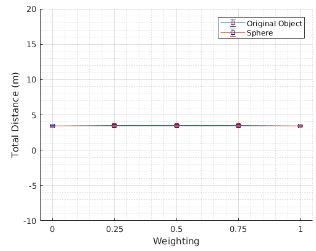
(c) Path 3: Mean Time Taken and Standard Deviation



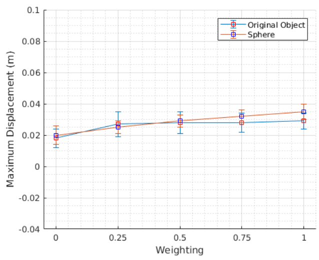
(d) Path 1: Mean Total Distance Travelled and Standard Deviation



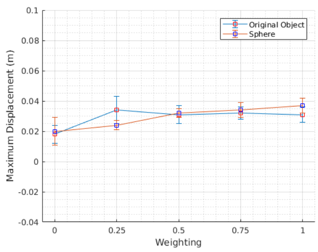
(e) Path 2: Mean Total Distance Travelled and Standard Deviation



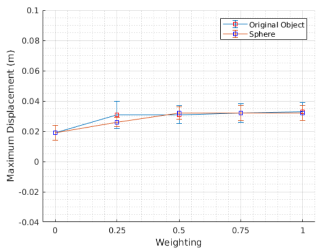
(f) Path 3: Mean Total Distance Travelled and Standard Deviation



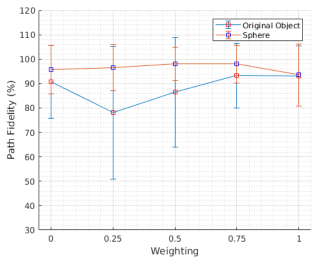
(g) Path 1: Mean Maximum Displacement and Standard Deviation



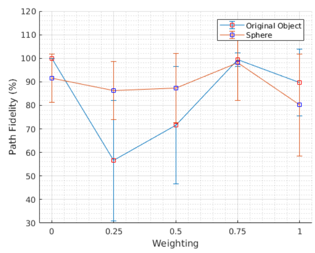
(h) Path 2: Mean Maximum Displacement and Standard Deviation



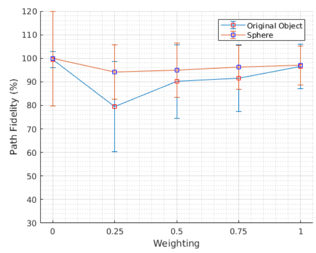
(i) Path 3: Mean Maximum Displacement and Standard Deviation



(j) Path 1: Mean Percentage Path Fidelity and Standard Deviation

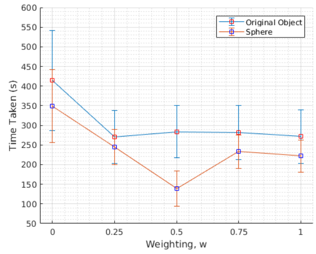


(k) Path 2: Mean Percentage Path Fidelity and Standard Deviation

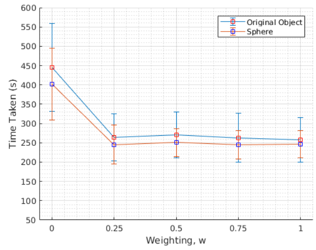


(l) Path 3: Mean Percentage Path Fidelity and Standard Deviation

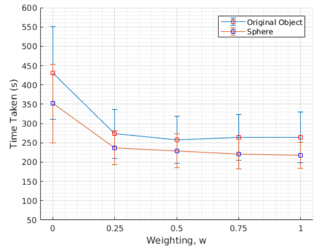
Figure G.14: Performance for the Hybrid System across all design requirement metrics in the Line Following Environmental Setup for the Sphere.



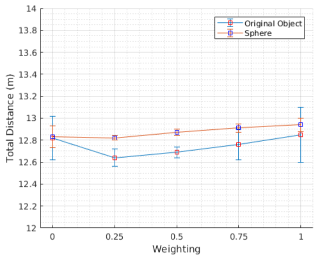
(a) Path 1: Mean Time Taken and Standard Deviation



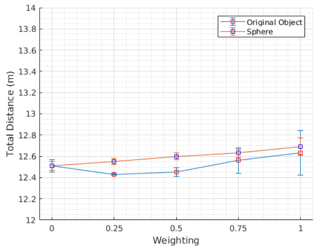
(b) Path 2: Mean Time Taken and Standard Deviation



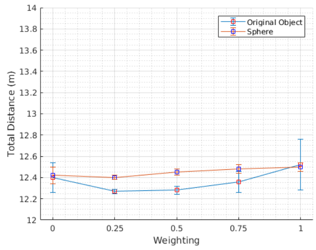
(c) Path 3: Mean Time Taken and Standard Deviation



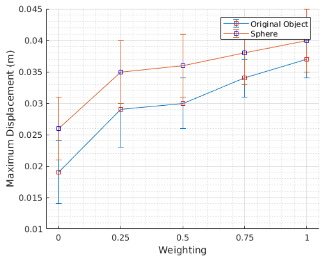
(d) Path 1: Mean Total Distance Travelled and Standard Deviation



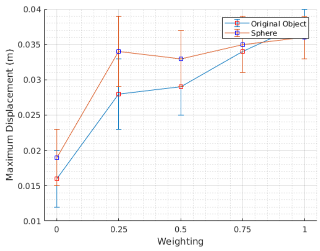
(e) Path 2: Mean Total Distance Travelled and Standard Deviation



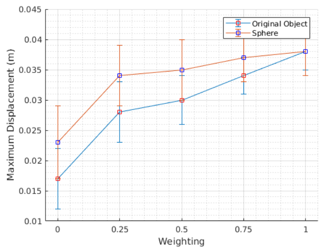
(f) Path 3: Mean Total Distance Travelled and Standard Deviation



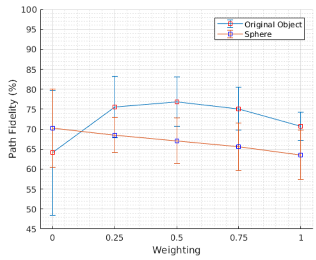
(g) Path 1: Mean Maximum Displacement and Standard Deviation



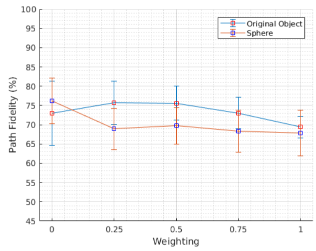
(h) Path 2: Mean Maximum Displacement and Standard Deviation



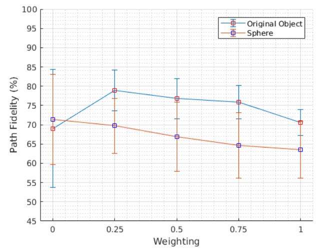
(i) Path 3: Mean Maximum Displacement and Standard Deviation



(j) Path 1: Mean Percentage Path Fidelity and Standard Deviation

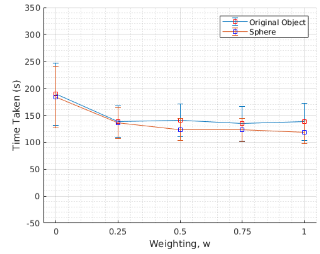


(k) Path 2: Mean Percentage Path Fidelity and Standard Deviation

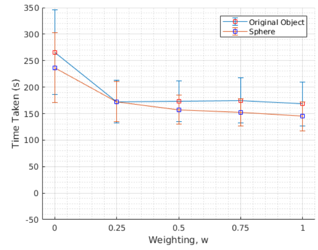


(l) Path 3: Mean Percentage Path Fidelity and Standard Deviation

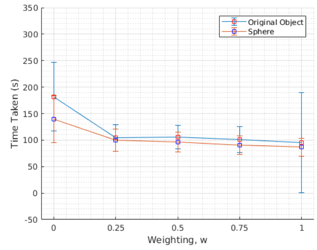
Figure G.15: Performance for the Hybrid System across all design requirement metrics in the Cluttered Environment for the Sphere.



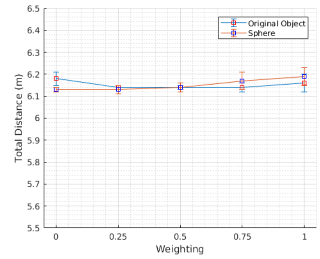
(a) Path 1: Mean Time Taken and Standard Deviation



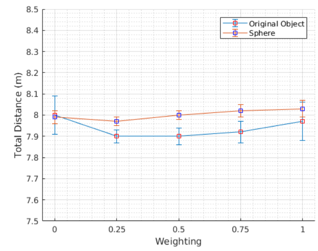
(b) Path 2: Mean Time Taken and Standard Deviation



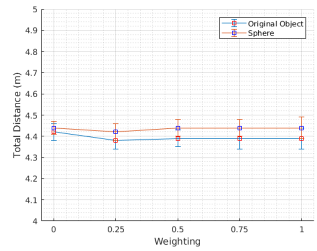
(c) Path 3: Mean Time Taken and Standard Deviation



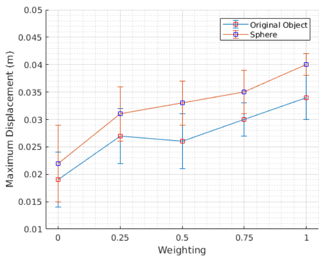
(d) Path 1: Mean Total Distance Travelled and Standard Deviation



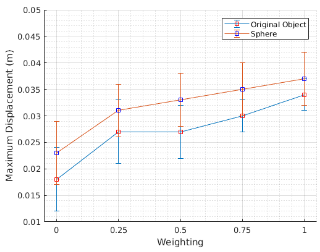
(e) Path 2: Mean Total Distance Travelled and Standard Deviation



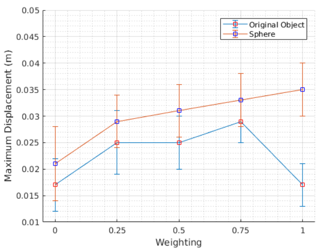
(f) Path 3: Mean Total Distance Travelled and Standard Deviation



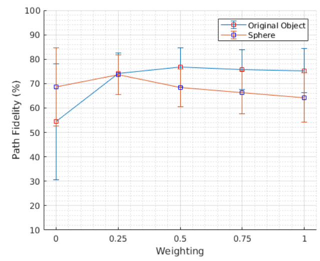
(g) Path 1: Mean Maximum Displacement and Standard Deviation



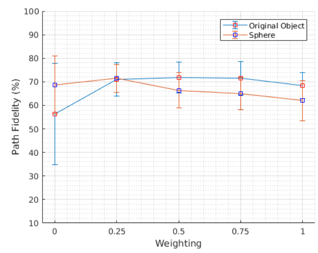
(h) Path 2: Mean Maximum Displacement and Standard Deviation



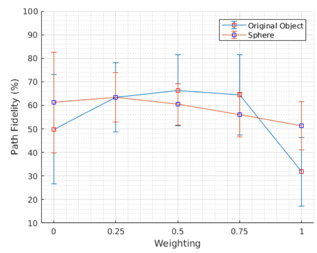
(i) Path 3: Mean Maximum Displacement and Standard Deviation



(j) Path 1: Mean Percentage Path Fidelity and Standard Deviation



(k) Path 2: Mean Percentage Path Fidelity and Standard Deviation



(l) Path 3: Mean Percentage Path Fidelity and Standard Deviation

Figure G.16: Performance for the Hybrid System across all design requirement metrics in the Randomly Generated Environments for the Sphere.

Appendix H

Experimental Data Results from Chapter 8, Section 8.3: Performance of Hybrid System with Objects of Different Size and Shape

H.1 Task Completion

H.1.1 Size

Table H.1: Percentage Task Completion for the Hybrid System Manipulating Different Sized Objects in Line Following Environments

Object	Weighting	Line Following Paths		
		1	2	3
Medium	**Explicit**	**100.00%**	**100.00%**	**100.00%**
	Original Explicit	100.00%	100.00%	100.00%
	w = 0.25	**100.00%**	**100.00%**	**22.00%**
	Original w = 0.25	91.00%	76.00%	62.00%
	w = 0.5	**100.00%**	**100.00%**	**27.00%**
	Original w = 0.5	98.00%	92.00%	57.00%
	w = 0.75	**100.00%**	**100.00%**	**34.00%**
	Original w = 0.75	100.00%	100.00%	79.00%
	Implicit	**100.00%**	**100.00%**	**99.00%**
	Original Implicit	100.00%	100.00%	99.00%
Large	**Explicit**	**100.00%**	**100.00%**	**100.00%**
	Original Explicit	100.00%	100.00%	100.00%
	w = 0.25	**100.00%**	**99.00%**	**67.00%**
	Original w = 0.25	91.00%	76.00%	62.00%
	w = 0.5	**100.00%**	**91.00%**	**60.00%**
	Original w = 0.5	98.00%	92.00%	57.00%
	w = 0.75	**100.00%**	**100.00%**	**31.00%**
	Original w = 0.75	100.00%	100.00%	79.00%
	Implicit	**100.00%**	**100.00%**	**92.00%**
	Original Implicit	100.00%	100.00%	99.00%

Table H.2: Percentage Task Completion for the Hybrid System Manipulating Different Sized Objects in Simple and Cluttered Environments

Object	Weighting	Cluttered Environments		
		1	2	3
Medium	**Explicit**	**100.00%**	**72.00%**	**100.00%**
	Original Explicit	100.00%	60.00%	100.00%
	w = 0.25	**100.00%**	**73.00%**	**100.00%**
	Original w = 0.25	100.00%	100.00%	100.00%
	w = 0.5	**100.00%**	**82.00%**	**100.00%**
	Original w = 0.5	100.00%	100.00%	100.00%
	w = 0.75	**100.00%**	**83.00%**	**100.00%**
	Original w = 0.75	100.00%	100.00%	100.00%
	Implicit	**100.00%**	**84.00%**	**100.00%**
	Original Implicit	100.00%	100.00%	100.00%
Large	**Explicit**	**97.00%**	**44.00%**	**100.00%**
	Original Explicit	100.00%	60.00%	100.00%
	w = 0.25	**100.00%**	**30.00%**	**100.00%**
	Original w = 0.25	100.00%	100.00%	100.00%
	w = 0.5	**100.00%**	**17.00%**	**100.00%**
	Original w = 0.5	100.00%	100.00%	100.00%
	w = 0.75	**100.00%**	**20.00%**	**100.00%**
	Original w = 0.75	100.00%	100.00%	100.00%
	Implicit	**100.00%**	**16.00%**	**100.00%**
	Original Implicit	100.00%	100.00%	100.00%

H.1.2 Shape

Table H.3: Percentage Task Completion for the Hybrid System Manipulating Different Shaped Objects in Line Following Environments

Object	Weighting	Line Following Paths		
		1	2	3
Cuboid	**Explicit**	**100.00%**	**100.00%**	**100.00%**
	Original Explicit	100.00%	100.00%	100.00%
	w = 0.25	**100.00%**	**100.00%**	**45.00%**
	w = 0.25	91.00%	76.00%	62.00%
	w = 0.5	**100.00%**	**100.00%**	**55.00%**
	Original w = 0.5	98.00%	92.00%	57.00%
	w = 0.75	**100.00%**	**97.00%**	**61.00%**
	Original w = 0.75	100.00%	100.00%	79.00%
	Implicit	**100.00%**	**100.00%**	**89.00%**
	Original Implicit	100.00%	100.00%	99.00%
Cylinder	**Explicit**	**100.00%**	**100.00%**	**100.00%**
	Original Explicit	100.00%	100.00%	100.00%
	w = 0.25	**100.00%**	**100.00%**	**100.00%**
	Original w = 0.25	91.00%	76.00%	62.00%
	w = 0.5	**100.00%**	**100.00%**	**71.00%**
	Original w = 0.5	98.00%	92.00%	57.00%
	w = 0.75	**100.00%**	**100.00%**	**54.00%**
	Original w = 0.75	100.00%	100.00%	79.00%
	Implicit	**100.00%**	**100.00%**	**53.00%**
	Original Implicit	100.00%	100.00%	99.00%
Sphere	**Explicit**	**100.00%**	**100.00%**	**100.00%**
	Original Explicit	100.00%	100.00%	100.00%
	w = 0.25	**100.00%**	**100.00%**	**98.00%**
	Original w = 0.25	91.00%	76.00%	62.00%
	w = 0.5	**100.00%**	**100.00%**	**100.00%**
	Original w = 0.5	98.00%	92.00%	57.00%
	w = 0.75	**100.00%**	**100.00%**	**100.00%**
	Original w = 0.75	100.00%	100.00%	79.00%
	Implicit	**100.00%**	**100.00%**	**100.00%**
	Original Implicit	100.00%	100.00%	99.00%

Table H.4: Percentage Task Completion for the Hybrid System Manipulating Different Shaped Objects in Simple and Cluttered Environments

Object	Weighting	Cluttered Environments		
		1	2	3
Cuboid	**Explicit**	**82.00%**	**7.00%**	**99.00%**
	Original Explicit	100.00%	60.00%	100.00%
	w = 0.25	**99.00%**	**1.00%**	**100.00%**
	Original w = 0.25	100.00%	100.00%	100.00%
	w = 0.5	**100.00%**	**8.00%**	**100.00%**
	Original w = 0.5	100.00%	100.00%	100.00%
	w = 0.75	**100.00%**	**7.00%**	**100.00%**
	Original w = 0.75	100.00%	100.00%	100.00%
	Implicit	**100.00%**	**6.00%**	**100.00%**
	Original Implicit	100.00%	100.00%	100.00%
Cylinder	**Explicit**	**71.00%**	**4.00%**	**92.00%**
	Original Explicit	100.00%	60.00%	100.00%
	w = 0.25	**100.00%**	**0.00%**	**100.00%**
	Original w = 0.25	100.00%	100.00%	100.00%
	w = 0.5	**100.00%**	**0.00%**	**100.00%**
	Original w = 0.5	100.00%	100.00%	100.00%
	w = 0.75	**97.00%**	**0.00%**	**100.00%**
	Original w = 0.75	100.00%	100.00%	100.00%
	Implicit	**88.00%**	**0.00%**	**100.00%**
	Original Implicit	100.00%	100.00%	100.00%
Sphere	**Explicit**	**98.00%**	**73.00%**	**99.00%**
	Original Explicit	100.00%	60.00%	100.00%
	w = 0.25	**100.00%**	**100.00%**	**100.00%**
	Original w = 0.25	100.00%	100.00%	100.00%
	w = 0.5	**100.00%**	**78.00%**	**100.00%**
	Original w = 0.5	100.00%	100.00%	100.00%
	w = 0.75	**100.00%**	**79.00%**	**100.00%**
	Original w = 0.75	100.00%	100.00%	100.00%
	Implicit	**100.00%**	**70.00%**	**100.00%**
	Original Implicit	100.00%	100.00%	100.00%

Table H.5: Percentage Task Completion for the Hybrid System Manipulating Different Shaped Objects in Randomly Generated Environments

Object	Weighting	Randomly Generated Environments		
		1	2	3
Cuboid	**Explicit**	**100.00%**	**100.00%**	**100.00%**
	Original Explicit	100.00%	100.00%	93.00%
	w = 0.25	**100.00%**	**100.00%**	**100.00%**
	Original w = 0.25	100.00%	100.00%	100.00%
	w = 0.5	**100.00%**	**100.00%**	**93.00%**
	Original w = 0.5	100.00%	100.00%	100.00%
	w = 0.75	**100.00%**	**100.00%**	**94.00%**
	Original w = 0.75	100.00%	100.00%	100.00%
	Implicit	**100.00%**	**100.00%**	**98.00%**
	Original Implicit	100.00%	100.00%	100.00%
Cylinder	**Explicit**	**100.00%**	**100.00%**	**100.00%**
	Original Explicit	100.00%	100.00%	93.00%
	w = 0.25	**100.00%**	**100.00%**	**100.00%**
	Original w = 0.25	100.00%	100.00%	100.00%
	w = 0.5	**100.00%**	**100.00%**	**97.00%**
	Original w = 0.5	100.00%	100.00%	100.00%
	w = 0.75	**100.00%**	**100.00%**	**93.00%**
	Original w = 0.75	100.00%	100.00%	100.00%
	Implicit	**100.00%**	**100.00%**	**80.00%**
	Original Implicit	100.00%	100.00%	100.00%
Sphere	**Explicit**	**100.00%**	**100.00%**	**100.00%**
	Original Explicit	100.00%	100.00%	93.00%
	w = 0.25	**100.00%**	**100.00%**	**100.00%**
	Original w = 0.25	100.00%	100.00%	100.00%
	w = 0.5	**100.00%**	**100.00%**	**100.00%**
	Original w = 0.5	100.00%	100.00%	100.00%
	w = 0.75	**100.00%**	**100.00%**	**100.00%**
	Original w = 0.75	100.00%	100.00%	100.00%
	Implicit	**100.00%**	**100.00%**	**100.00%**
	Original Implicit	100.00%	100.00%	100.00%

H.2 Time Taken

H.2.1 Size

Table H.6: Mean Time Taken in Seconds and Standard Deviation to Complete Task for the Hybrid System Manipulating the Medium Object in the Line Following Environmental Setup

Weighting	Line Following Paths		
	1	2	3
Explicit	**110.15 (36.34)**	**103.20 (29.99)**	**114.58 (29.99)**
Original Explicit	121.81 (46.49)	119.22 (40.55)	121.15 (35.70)
Sig. Diff	0.140	0.006	0.301
w = 0.25	**98.19 (24.80)**	**97.15 (25.37)**	**126.52 (24.33)**
Original w = 0.25	134.35 (103.35)	206.05 (214.39)	118.71 (32.50)
Sig. Diff	p <0.001	p <0.001	0.265
w = 0.5	**92.52 (21.73)**	**85.13 (19.85)**	**118.53 (18.42)**
Original w = 0.5	131.89 (147.99)	118.76 (101.62)	107.65 (19.52)
Sig. Diff	0.092	p <0.001	0.015
w = 0.75	**81.40 (16.95)**	**84.10 (20.02)**	**111.10 (13.43)**
Original w = 0.75	90.46 (21.63)	77.43 (17.20)	94.37 (21.03)
Sig. Diff	0.010	0.028	p <0.001
Implicit	**80.51 (20.25)**	**76.32 (17.90)**	**86.05 (19.00)**
Original Implicit	80.25 (18.25)	79.18 (18.89)	81.45 (19.03)
Sig. Diff	0.561	0.142	0.060

Table H.7: Mean Time Taken in Seconds and Standard Deviation to Complete Task for the Hybrid System Manipulating the Large Object in the Line Following Environmental Setup

Weighting	Line Following Paths		
	1	2	3
Explicit	**98.95 (31.63)**	**102.55 (30.90)**	**109.30 (33.62)**
Original Explicit	121.81 (46.49)	119.22 (40.55)	121.15 (35.70)
Sig. Diff	p <0.001	0.003	0.007
w = 0.25	**94.35 (27.13)**	**97.79 (22.56)**	**113.51 (17.84)**
Original w = 0.25	134.35 (103.35)	206.05 (214.39)	118.71 (32.50)
Sig. Diff	p <0.001	p <0.001	0.202
w = 0.5	**81.43 (18.73)**	**88.16 (18.27)**	**107.86 (18.08)**
Original w = 0.5	131.89 (147.99)	118.76 (101.62)	107.65 (19.52)
Sig. Diff	p <0.001	0.001	0.948
w = 0.75	**81.43 (16.40)**	**85.58 (17.54)**	**105.49 (25.67)**
Original w = 0.75	90.46 (21.63)	77.43 (17.20)	94.37 (21.03)
Sig. Diff	0.015	p <0.001	0.014
Implicit	**81.49 (18.46)**	**80.91 (17.85)**	**87.94 (17.17)**
Original Implicit	80.25 (18.25)	79.18 (18.89)	81.45 (19.03)
Sig. Diff	0.803	0.614	0.002

Table H.8: Mean Time Taken in Seconds and Standard Deviation to Complete Task for the Hybrid System Manipulating the Medium Object in the Simple (SE) and Cluttered (CE) Environments

Weighting	Paths			
	1		2	3
	SE	CE	CE	CE
Explicit	**153.61 (53.24)**	**367.45 (117.37)**	**411.77 (96.83)**	**357.12 (104.05)**
Original Explicit	170.98 (62.64)	414.36 (127.10)	445.31 (113.61)	431.18 (120.53)
Sig. Diff	0.028	p <0.001	p <0.001	p <0.001
w = 0.25	**128.87 (28.87)**	**279.52 (67.02)**	**304.94 (56.40)**	**268.73 (62.15)**
Original w = 0.25	124.66 (29.48)	270.09 (67.01)	263.68 (60.60)	273.22 (65.83)
Sig. Diff	0.322	0.424	0.003	0.356
w = 0.5	**125.59 (27.42)**	**271.13 (59.49)**	**281.79 (46.63)**	**271.25 (57.01)**
Original w = 0.5	129.72 (50.93)	283.73 (66.40)	270.75 (58.86)	257.41 (61.12)
Sig. Diff	0.072	0.369	0.023	0.804
w = 0.75	**117.25 (28.45)**	**266.49 (58.32)**	**266.94 (45.42)**	**264.72 (57.67)**
Original w = 0.75	116.27 (27.92)	281.52 (68.64)	263.25 (63.95)	264.54 (59.27)
Sig. Diff	0.530	0.530	0.789	0.193
Implicit	**114.57 (26.20)**	**264.56 (57.86)**	**269.61 (49.02)**	**254.58 (52.23)**
Original Implicit	118.84 (26.18)	271.44 (67.54)	257.93 (58.21)	263.55 (65.87)
Sig. Diff	0.709	0.201	0.051	0.424

Table H.9: Mean Time Taken in Seconds and Standard Deviation to Complete Task for the Hybrid System Manipulating the Large Object in the Simple (SE) and Cluttered (CE) Environments

Weighting	Paths			
	1		2	3
	SE	CE	CE	CE
Explicit	**154.24 (48.96)**	**397.76 (86.10)**	**453.23 (64.87)**	**374.15 (84.30)**
Original Explicit	170.98 (62.64)	414.36 (127.10)	445.31 (113.61)	431.18 (120.53)
Sig. Diff	0.088	0.167	0.341	0.001
w = 0.25	**118.91 (26.23)**	**280.05 (64.86)**	**348.33 (34.48)**	**262.70 (60.22)**
Original w = 0.25	124.66 (29.48)	270.09 (67.01)	263.68 (60.60)	273.22 (65.83)
Sig. Diff	0.083	0.357	p <0.001	0.103
w = 0.5	**120.04 (25.94)**	**267.74 (58.38)**	**349.31 (18.59)**	**252.55 (55.72)**
Original w = 0.5	129.72 (50.93)	283.73 (66.40)	270.75 (58.86)	257.41 (61.12)
Sig. Diff	0.599	0.168	p <0.001	0.047
w = 0.75	**117.67 (27.69)**	**257.95 (57.27)**	**375.90 (28.49)**	**258.07 (53.31)**
Original w = 0.75	116.27 (27.92)	281.52 (68.64)	263.25 (63.95)	264.54 (59.27)
Sig. Diff	0.401	0.082	p <0.001	0.488
Implicit	**117.74 (28.22)**	**259.35 (58.22)**	**396.06 (24.93)**	**250.73 (49.66)**
Original Implicit	118.84 (26.18)	271.44 (67.54)	257.93 (58.21)	263.55 (65.87)
Sig. Diff	0.891	0.035	p <0.001	0.232

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H.2.2 Shape

Table H.10: Mean Time Taken in Seconds and Standard Deviation to Complete Task for the Hybrid System Manipulating the Medium Object in the Randomly Generated Environments

Weighting	Randomly Generated Environments		
	1	2	3
Explicit	**172.27 (54.74)**	**221.42 (66.42)**	**99.31 (22.88)**
Original Explicit	189.45 (57.78)	266.01 (80.07)	181.78 (94.63)
Sig. Diff	p <0.001	p <0.001	p <0.001
w = 0.25	**137.57 (31.97)**	**183.16 (42.69)**	**100.75 (23.30)**
Original w = 0.25	138.24 (29.51)	172.47 (40.02)	104.11 (24.81)
Sig. Diff	0.133	0.968	0.007
w = 0.5	**131.84 (29.69)**	**177.37 (38.53)**	**102.00 (22.98)**
Original w = 0.5	140.64 (30.78)	173.53 (38.21)	105.65 (22.36)
Sig. Diff	0.086	0.271	0.779
w = 0.75	**133.29 (31.45)**	**176.68 (40.07)**	**102.38 (22.89)**
Original w = 0.75	137.31 (31.90)	174.68 (42.70)	100.78 (24.22)
Sig. Diff	0.573	0.165	0.207
Implicit	**130.83 (27.55)**	**169.64 (39.01)**	**99.31 (22.88)**
Original Implicit	137.92 (34.28)	168.28 (41.27)	95.06 (20.45)
Sig. Diff	0.234	0.875	0.397

Table H.11: Mean Time Taken in Seconds and Standard Deviation to Complete Task for the Hybrid System Manipulating the Large Object in the Randomly Generated Environments

Weighting	Randomly Generated Environments		
	1	2	3
Explicit	**187.93 (45.48)**	**320.92 (26.08)**	**143.73 (36.33)**
Original Explicit	189.45 (57.78)	266.01 (80.07)	181.78 (94.63)
Sig. Diff	0.014	p <0.001	p <0.001
w = 0.25	**136.96 (29.80)**	**182.14 (41.92)**	**102.98 (23.46)**
Original w = 0.25	138.24 (29.51)	172.47 (40.02)	104.11 (24.81)
Sig. Diff	0.139	0.789	0.023
w = 0.5	**132.60 (28.20)**	**173.51 (40.29)**	**100.02 (22.62)**
Original w = 0.5	140.64 (30.78)	173.53 (38.21)	105.65 (22.36)
Sig. Diff	0.219	0.878	0.356
w = 0.75	**129.85 (29.74)**	**168.44 (38.48)**	**100.73 (25.42)**
Original w = 0.75	137.31 (31.90)	174.68 (42.70)	100.78 (24.22)
Sig. Diff	0.195	0.913	0.662
Implicit	**127.13 (27.15)**	**169.84 (38.40)**	**98.00 (22.14)**
Original Implicit	137.92 (34.28)	168.28 (41.27)	95.06 (20.45)
Sig. Diff	0.034	0.888	0.166

Table H.12: Mean Time Taken in Seconds and Standard Deviation to Complete Task for the Hybrid System Manipulating the Cuboid in the Line Following Environmental Setup

Weighting	Line Following Paths		
	1	2	3
Explicit	**107.70 (37.31)**	**102.67 (34.21)**	**107.54 (34.70)**
Original Explicit	121.81 (46.49)	119.22 (40.55)	121.15 (35.70)
Sig. Diff	0.025	p <0.001	0.005
w = 0.25	**103.11 (28.33)**	**96.30 (26.99)**	**116.86 (23.16)**
Original w = 0.25	134.35 (103.35)	206.05 (214.39)	118.71 (32.50)
Sig. Diff	0.003	p <0.001	0.498
w = 0.5	**96.30 (26.99)**	**90.17 (20.25)**	**116.42 (64.36)**
Original w = 0.5	131.89 (147.99)	118.76 (101.62)	107.65 (19.52)
Sig. Diff	0.015	0.005	0.605
w = 0.75	**84.84 (19.14)**	**84.86 (18.35)**	**99.88 (19.74)**
Original w = 0.75	90.46 (21.63)	77.43 (17.20)	94.37 (21.03)
Sig. Diff	0.064	0.002	0.103
Implicit	**80.49 (17.28)**	**82.24 (18.80)**	**84.59 (17.91)**
Original Implicit	80.25 (18.25)	79.18 (18.89)	81.45 (19.03)
Sig. Diff	0.025	p <0.001	0.005

Table H.13: Mean Time Taken in Seconds and Standard Deviation to Complete Task for the Hybrid System Manipulating the Cylinder in the Line Following Environmental Setup

Weighting	Line Following Paths		
	1	2	3
Explicit	**109.33 (37.13)**	**106.12 (34.81)**	**108.91 (33.18)**
Original Explicit	121.81 (46.49)	119.22 (40.55)	121.15 (35.70)
Sig. Diff	0.097	0.013	0.007
w = 0.25	**97.36 (23.90)**	**93.70 (24.63)**	**91.44 (23.05)**
Original w = 0.25	134.35 (103.35)	206.05 (214.39)	118.71 (32.50)
Sig. Diff	p <0.001	p <0.001	p <0.001
w = 0.5	**90.01 (20.23)**	**87.12 (19.33)**	**89.04 (21.71)**
Original w = 0.5	131.89 (147.99)	118.76 (101.62)	107.65 (19.52)
Sig. Diff	0.015	p <0.001	p <0.001
w = 0.75	**87.66 (19.82)**	**81.95 (19.50)**	**77.76 (18.92)**
Original w = 0.75	90.46 (21.63)	77.43 (17.20)	94.37 (21.03)
Sig. Diff	0.375	0.166	p <0.001
Implicit	**81.16 (19.30)**	**77.71 (17.77)**	**71.24 (10.43)**
Original Implicit	80.25 (18.25)	79.18 (18.89)	81.45 (19.03)
Sig. Diff	0.097	0.013	0.007

Table H.14: Mean Time Taken in Seconds and Standard Deviation to Complete Task for the Hybrid System Manipulating the Sphere in the Line Following Environmental Setup

Weighting	Line Following Paths		
	1	2	3
Explicit	**110.92 (35.90)**	**109.25 (34.70)**	**119.43 (34.93)**
Original Explicit	121.81 (46.49)	119.22 (40.55)	121.15 (35.70)
Sig. Diff	0.199	0.098	0.700
w = 0.25	**97.95 (23.82)**	**94.97 (21.25)**	**97.41 (22.86)**
Original w = 0.25	134.35 (103.35)	206.05 (214.39)	118.71 (32.50)
Sig. Diff	p <0.001	p <0.001	p <0.001
w = 0.5	**89.29 (18.43)**	**83.37 (15.83)**	**87.70 (17.64)**
Original w = 0.5	131.89 (147.99)	118.76 (101.62)	107.65 (19.52)
Sig. Diff	0.013	p <0.001	p <0.001
w = 0.75	**78.88 (14.42)**	**78.34 (16.13)**	**89.47 (20.72)**
Original w = 0.75	90.46 (21.63)	77.43 (17.20)	94.37 (21.03)
Sig. Diff	p <0.001	p <0.001	0.130
Implicit	**69.73 (12.71)**	**80.68 (16.70)**	**81.12 (18.45)**
Original Implicit	80.25 (18.25)	79.18 (18.89)	81.45 (19.03)
Sig. Diff	0.199	0.098	0.700

Table H.15: Mean Time Taken in Seconds and Standard Deviation to Complete Task for the Hybrid System Manipulating the Cuboid in the Simple (SE) and Cluttered (CE) Environments

Weighting	Paths			
	1		2	3
	SE	CE	CE	CE
Explicit	**165.22 (56.84)**	**368.87 (97.27)**	**556.18 (26.47)**	**348.40 (106.28)**
Original Explicit	170.98 (62.64)	414.36 (127.10)	445.31 (113.61)	431.18 (120.53)
Sig. Diff	0.551	0.005	0.006	p <0.001
w = 0.25	**120.28 (27.60)**	**277.41 (62.66)**	**484.05 (N/A)**	**251.92 (54.43)**
Original w = 0.25	124.66 (29.48)	270.09 (67.01)	263.68 (60.60)	273.22 (65.83)
Sig. Diff	0.3013	0.226	0.090	0.020
w = 0.5	**118.23 (26.81)**	**263.72 (51.34)**	**448.45 (17.57)**	**253.85 (59.66)**
Original w = 0.5	129.72 (50.93)	283.73 (66.40)	270.75 (58.86)	257.41 (61.12)
Sig. Diff	0.009	0.062	p <0.001	0.627
w = 0.75	**117.63 (25.06)**	**262.56 (58.48)**	**440.33 (22.57)**	**254.37 (57.28)**
Original w = 0.75	116.27 (27.92)	281.52 (68.64)	263.25 (63.95)	264.54 (59.27)
Sig. Diff	0.4931	0.060	p <0.001	0.201
Implicit	**117.49 (29.44)**	**255.63 (54.45)**	**449.97 (11.20)**	**263.37 (56.13)**
Original Implicit	118.84 (26.18)	271.44 (67.54)	257.93 (58.21)	263.55 (65.87)
Sig. Diff	0.497	0.158	p <0.001	0.703

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Table H.16: Mean Time Taken in Seconds and Standard Deviation to Complete Task for the Hybrid System Manipulating the Cylinder in the Simple (SE) and Cluttered (CE) Environments

Weighting	Paths			
	1		2	3
	SE	CE	CE	CE
Explicit	**165.36 (57.02)**	**408.31 (95.60)**	**579.09 (14.09)**	**371.34 (98.62)**
Original Explicit	170.98 (62.64)	414.36 (127.10)	445.31 (113.61)	431.18 (120.53)
Sig. Diff	0.577	0.648	0.019	p <0.001
w = 0.25	**123.26 (29.18)**	**268.11 (51.34)**	**N/A**	**253.70 (54.79)**
Original w = 0.25	124.66 (29.48)	270.09 (67.01)	263.68 (60.60)	273.22 (65.83)
Sig. Diff	0.599	0.506	N/A	0.035
w = 0.5	**119.88 (29.23)**	**259.86 (54.90)**	**N/A**	**257.31 (61.14)**
Original w = 0.5	129.72 (50.93)	283.73 (66.40)	270.75 (58.86)	257.41 (61.12)
Sig. Diff	0.020	0.012	N/A	0.872
w = 0.75	**117.71 (26.81)**	**262.83 (57.33)**	**N/A**	**254.69 (55.74)**
Original w = 0.75	116.27 (27.92)	281.52 (68.64)	263.25 (63.95)	264.54 (59.27)
Sig. Diff	0.609	0.081	N/A	0.245
Implicit	**114.47 (25.48)**	**267.02 (56.41)**	**N/A**	**245.92 (57.82)**
Original Implicit	118.84 (26.18)	271.44 (67.54)	257.93 (58.21)	263.55 (65.87)
Sig. Diff	0.239	0.948	N/A	0.054

Table H.17: Mean Time Taken in Seconds and Standard Deviation to Complete Task for the Hybrid System Manipulating the Sphere in the Simple (SE) and Cluttered (CE) Environments

Weighting	Paths			
	1		2	3
	SE	CE	CE	CE
Explicit	**154.38 (47.36)**	**348.72 (92.62)**	**401.87 (92.39)**	**351.91 (102.14)**
Original Explicit	170.98 (62.64)	414.36 (127.10)	445.31 (113.61)	431.18 (120.53)
Sig. Diff	0.115	p <0.001	0.022	p <0.001
w = 0.25	**122.27 (23.22)**	**244.91 (44.48)**	**245.38 (50.68)**	**237.60 (44.70)**
Original w = 0.25	124.66 (29.48)	270.09 (67.01)	263.68 (60.60)	273.22 (65.83)
Sig. Diff	0.997	0.025	0.023	7.00E-05
w = 0.5	**111.01 (19.87)**	**239.66 (44.87)**	**250.75 (35.72)**	**229.52 (43.85)**
Original w = 0.5	129.72 (50.93)	283.73 (66.40)	270.75 (58.86)	257.41 (61.12)
Sig. Diff	p <0.001	p <0.001	0.110	p <0.001
w = 0.75	**107.67 (19.00)**	**233.27 (42.33)**	**244.63 (36.51)**	**221.06 (38.48)**
Original w = 0.75	116.27 (27.92)	281.52 (68.64)	263.25 (63.95)	264.54 (59.27)
Sig. Diff	0.093	p <0.001	0.208	p <0.001
Implicit	**103.99 (16.98)**	**221.68 (40.92)**	**246.10 (35.61)**	**217.40 (34.26)**
Original Implicit	118.84 (26.18)	271.44 (67.54)	257.93 (58.21)	263.55 (65.87)
Sig. Diff	0.008	p <0.001	0.643	p <0.001

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H.3 Total Distance

H.3.1 Size

Table H.18: Mean Time Taken in Seconds and Standard Deviation to Complete Task for the Hybrid System Manipulating the Cuboid in the Randomly Generated Environments

Weighting	Randomly Generated Environments		
	1	2	3
Explicit	**176.15 (58.07)**	**244.54 (79.93)**	**144.61 (41.27)**
Original Explicit	189.45 (57.78)	266.01 (80.07)	181.78 (94.63)
Sig. Diff	0.021	0.019	0.010
w = 0.25	**133.59 (28.95)**	**181.49 (41.01)**	**99.39 (23.62)**
Original w = 0.25	138.24 (29.51)	172.47 (40.02)	104.11 (24.81)
Sig. Diff	0.245	0.084	0.116
w = 0.5	**129.85 (29.26)**	**170.88 (41.18)**	**143.20 (79.76)**
Original w = 0.5	140.64 (30.78)	173.53 (38.21)	105.65 (22.36)
Sig. Diff	0.007	0.344	0.002
w = 0.75	**133.16 (28.56)**	**176.43 (40.83)**	**110.63 (40.96)**
Original w = 0.75	137.31 (31.90)	174.68 (42.70)	100.78 (24.22)
Sig. Diff	0.400	0.722	0.051
Implicit	**130.21 (27.91)**	**169.01 (39.19)**	**105.31 (42.19)**
Original Implicit	137.92 (34.28)	168.28 (41.27)	95.06 (20.45)
Sig. Diff	0.170	0.781	0.046

Table H.19: Mean Time Taken in Seconds and Standard Deviation to Complete Task for the Hybrid System Manipulating the Cylinder in the Randomly Generated Environments

Weighting	Randomly Generated Environments		
	1	2	3
Explicit	**179.52 (60.75)**	**237.12 (73.45)**	**141.67 (38.09)**
Original Explicit	189.45 (57.78)	266.01 (80.07)	181.78 (94.63)
Sig. Diff	0.028	0.002	0.002
w = 0.25	**142.91 (32.50)**	**179.08 (41.41)**	**105.56 (24.28)**
Original w = 0.25	138.24 (29.51)	172.47 (40.02)	104.11 (24.81)
Sig. Diff	0.423	0.311	0.731
w = 0.5	**133.39 (28.14)**	**169.12 (39.89)**	**97.91 (21.54)**
Original w = 0.5	140.64 (30.78)	173.53 (38.21)	105.65 (22.36)
Sig. Diff	0.106	0.265	0.014
w = 0.75	**134.27 (33.65)**	**170.38 (39.57)**	**97.38 (21.49)**
Original w = 0.75	137.31 (31.90)	174.68 (42.70)	100.78 (24.22)
Sig. Diff	0.273	0.518	0.377
Implicit	**126.94 (31.18)**	**160.42 (37.01)**	**101.55 (19.64)**
Original Implicit	137.92 (34.28)	168.28 (41.27)	95.06 (20.45)
Sig. Diff	0.013	0.172	0.023

Table H.20: Mean Time Taken in Seconds and Standard Deviation to Complete Task for the Hybrid System Manipulating the Sphere in the Randomly Generated Environments

Weighting	Randomly Generated Environments		
	1	2	3
Explicit	**183.60 (57.17)**	**236.66 (65.54)**	**139.24 (44.57)**
Original Explicit	189.45 (57.78)	266.01 (80.07)	181.78 (94.63)
Sig. Diff	0.262	0.007	p <0.001
w = 0.25	**135.85 (28.53)**	**172.46 (37.84)**	**100.03 (21.30)**
Original w = 0.25	138.24 (29.51)	172.47 (40.02)	104.11 (24.81)
Sig. Diff	0.532	0.981	0.309
w = 0.5	**123.38 (20.27)**	**157.35 (27.43)**	**96.33 (18.44)**
Original w = 0.5	140.64 (30.78)	173.53 (38.21)	105.65 (22.36)
Sig. Diff	p <0.001	0.007	0.003
w = 0.75	**122.62 (21.80)**	**152.19 (25.77)**	**90.59 (17.23)**
Original w = 0.75	137.31 (31.90)	174.68 (42.70)	100.78 (24.22)
Sig. Diff	0.002	p <0.001	0.005
Implicit	**118.54 (20.87)**	**144.78 (27.25)**	**86.70 (17.23)**
Original Implicit	137.92 (34.28)	168.28 (41.27)	95.06 (20.45)
Sig. Diff	p <0.001	p <0.001	0.002

Table H.21: Mean and Standard Deviation Total Distance Travelled by Object in Metres for the Hybrid System Manipulating the Medium Object in the Line Following Environmental Setup

Weighting	Line Following Paths		
	1	2	3
Explicit	**3.50 (0.06)**	**3.32 (0.05)**	**3.44 (0.05)**
Original Explicit	3.51 (0.06)	3.33 (0.06)	3.42 (0.05)
Sig. Diff	0.364	0.053	0.009
w = 0.25	**3.49 (0.05)**	**3.33 (0.06)**	**3.69 (0.07)**
Original w = 0.25	3.80 (0.99)	4.32 (1.83)	3.51 (0.08)
Sig. Diff	p <0.001	p <0.001	p <0.001
w = 0.5	**3.50 (0.06)**	**3.32 (0.07)**	**3.66 (0.10)**
Original w = 0.5	3.89 (1.46)	3.63 (0.91)	3.52 (0.07)
Sig. Diff	0.008	p <0.001	p <0.001
w = 0.75	**3.49 (0.05)**	**3.35 (0.08)**	**3.66 (0.08)**
Original w = 0.75	3.52 (0.06)	3.32 (0.06)	3.49 (0.07)
Sig. Diff	0.001	0.004	p <0.001
Implicit	**3.50 (0.06)**	**3.34 (0.06)**	**3.48 (0.06)**
Original Implicit	3.50 (0.05)	3.36 (0.07)	3.45 (0.06)
Sig. Diff	0.371	0.030	0.001

Table H.22: Mean and Standard Deviation Total Distance Travelled by Object in Metres for the Hybrid System Manipulating the Large Object in the Line Following Environmental Setup

Weighting	Line Following Paths		
	1	2	3
Explicit	**3.52 (0.05)**	**3.44 (0.02)**	**3.55 (0.04)**
Original Explicit	3.51 (0.06)	3.33 (0.06)	3.42 (0.05)
Sig. Diff	0.253	p <0.001	p <0.001
w = 0.25	**3.52 (0.05)**	**3.52 (0.05)**	**3.87 (0.10)**
Original w = 0.25	3.80 (0.99)	4.32 (1.83)	3.51 (0.08)
Sig. Diff	0.006	0.392	p <0.001
w = 0.5	**3.52 (0.05)**	**3.48 (0.03)**	**3.75 (0.06)**
Original w = 0.5	3.89 (1.46)	3.63 (0.91)	3.52 (0.07)
Sig. Diff	0.974	p <0.001	p <0.001
w = 0.75	**3.53 (0.05)**	**3.51 (0.05)**	**3.77 (0.07)**
Original w = 0.75	3.52 (0.06)	3.32 (0.06)	3.49 (0.07)
Sig. Diff	0.151	p <0.001	p <0.001
Implicit	**3.62 (0.09)**	**3.57 (0.07)**	**3.69 (0.05)**
Original Implicit	3.50 (0.05)	3.36 (0.07)	3.45 (0.06)
Sig. Diff	p <0.001	p <0.001	p <0.001

Table H.23: Mean and Standard Deviation Total Distance Travelled by Object in Metres for the Hybrid System Manipulating the Medium Object in the Simple (SE) and Cluttered (CE) Environments

Weighting	Paths			
	1		2	3
	SE	CE	CE	CE
Explicit	**5.25 (0.06)**	**12.81 (0.07)**	**12.50 (0.02)**	**12.38 (0.05)**
Original Explicit	5.27 (0.05)	12.82 (0.20)	12.51 (0.06)	12.40 (0.14)
Sig. Diff	0.092	0.010	0.973	0.816
w = 0.25	**5.27 (0.05)**	**12.82 (0.05)**	**12.52 (0.02)**	**12.42 (0.04)**
Original w = 0.25	5.27 (0.05)	12.64 (0.08)	12.43 (0.01)	12.27 (0.02)
Sig. Diff	0.109	p <0.001	p <0.001	p <0.001
w = 0.5	**5.27 (0.05)**	**12.82 (0.04)**	**12.56 (0.05)**	**12.43 (0.05)**
Original w = 0.5	5.28 (0.05)	12.69 (0.05)	12.45 (0.04)	12.28 (0.04)
Sig. Diff	0.367	p <0.001	p <0.001	p <0.001
w = 0.75	**5.26 (0.06)**	**12.87 (0.08)**	**12.61 (0.08)**	**12.49 (0.10)**
Original w = 0.75	5.27 (0.06)	12.76 (0.14)	12.53 (0.12)	12.36 (0.10)
Sig. Diff	0.660	p <0.001	p <0.001	p <0.001
Implicit	**5.26 (0.06)**	**12.92 (0.11)**	**12.09 (1.50)**	**12.53 (0.12)**
Original Implicit	5.28 (0.06)	12.85 (0.25)	12.63 (0.21)	12.52 (0.24)
Sig. Diff	0.257	p <0.001	0.041	p <0.001

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Table H.24: Mean and Standard Deviation Total Distance Travelled by Object in Metres for the Hybrid System Manipulating the Large Object in the Simple (SE) and Cluttered (CE) Environments

Weighting	Paths			
	1		2	3
	SE	CE	CE	CE
Explicit	**5.27 (0.07)**	**12.92 (0.06)**	**12.62 (0.06)**	**12.54 (0.06)**
Original Explicit	5.27 (0.05)	12.82 (0.20)	12.51 (0.06)	12.40 (0.14)
Sig. Diff	0.508	0.833	p <0.001	p <0.001
w = 0.25	**5.25 (0.05)**	**12.83 (0.03)**	**12.57 (0.03)**	**12.42 (0.02)**
Original w = 0.25	5.27 (0.05)	12.64 (0.08)	12.43 (0.01)	12.27 (0.02)
Sig. Diff	0.016	p <0.001	p <0.001	p <0.001
w = 0.5	**5.26 (0.05)**	**12.86 (0.04)**	**12.66 (0.04)**	**12.44 (0.04)**
Original w = 0.5	5.28 (0.05)	12.69 (0.05)	12.45 (0.04)	12.28 (0.04)
Sig. Diff	0.530	p <0.001	p <0.001	p <0.001
w = 0.75	**5.26 (0.06)**	**12.93 (0.10)**	**12.85 (0.09)**	**12.52 (0.10)**
Original w = 0.75	5.27 (0.06)	12.76 (0.14)	12.53 (0.12)	12.36 (0.10)
Sig. Diff	0.891	p <0.001	p <0.001	p <0.001
Implicit	**5.27 (0.07)**	**13.06 (0.19)**	**13.05 (0.13)**	**12.61 (0.15)**
Original Implicit	5.28 (0.06)	12.85 (0.25)	12.63 (0.21)	12.52 (0.24)
Sig. Diff	0.875	p <0.001	p <0.001	p <0.001

H.3.2 Shape

Table H.25: Mean and Standard Deviation Total Distance Travelled by Object in Metres for the Hybrid System Manipulating the Medium Object in the Randomly Generated Environments

Weighting	Randomly Generated Environments		
	1	2	3
Explicit	**6.11 (0.01)**	**7.99 (0.02)**	**4.43 (0.03)**
Original Explicit	6.18 (0.03)	8.00 (0.09)	4.42 (0.04)
Sig. Diff	$p < 0.001$	0.055	$p < 0.001$
w = 0.25	**6.12 (0.02)**	**8.01 (0.01)**	**4.43 (0.04)**
Original w = 0.25	6.14 (0.01)	7.90 (0.03)	4.38 (0.04)
Sig. Diff	$p < 0.001$	$p < 0.001$	$p < 0.001$
w = 0.5	**6.12 (0.02)**	**8.01 (0.01)**	**4.44 (0.03)**
Original w = 0.5	6.14 (0.01)	7.90 (0.04)	4.39 (0.04)
Sig. Diff	$p < 0.001$	$p < 0.001$	$p < 0.001$
w = 0.75	**6.12 (0.03)**	**8.04 (0.04)**	**4.44 (0.03)**
Original w = 0.75	6.14 (0.02)	7.92 (0.05)	4.39 (0.05)
Sig. Diff	$p < 0.001$	$p < 0.001$	$p < 0.001$
Implicit	**6.13 (0.04)**	**8.05 (0.06)**	**4.44 (0.04)**
Original Implicit	6.16 (0.04)	7.97 (0.09)	4.39 (0.05)
Sig. Diff	$p < 0.001$	$p < 0.001$	$p < 0.001$

Table H.26: Mean and Standard Deviation Total Distance Travelled by Object in Metres for the Hybrid System Manipulating the Large Object in the Randomly Generated Environments

Weighting	Randomly Generated Environments		
	1	2	3
Explicit	**6.18 (0.05)**	**8.21 (0.05)**	**4.47 (0.08)**
Original Explicit	6.18 (0.03)	8.00 (0.09)	4.42 (0.04)
Sig. Diff	0.007	$p < 0.001$	$p < 0.001$
w = 0.25	**6.13 (0.02)**	**8.04 (0.03)**	**4.46 (0.04)**
Original w = 0.25	6.14 (0.01)	7.90 (0.03)	4.38 (0.04)
Sig. Diff	0.016	$p < 0.001$	$p < 0.001$
w = 0.5	**6.14 (0.03)**	**8.04 (0.03)**	**4.46 (0.04)**
Original w = 0.5	6.14 (0.01)	7.90 (0.04)	4.39 (0.04)
Sig. Diff	0.955	$p < 0.001$	$p < 0.001$
w = 0.75	**6.15 (0.04)**	**8.06 (0.04)**	**4.47 (0.07)**
Original w = 0.75	6.14 (0.02)	7.92 (0.05)	4.39 (0.05)
Sig. Diff	0.264	$p < 0.001$	$p < 0.001$
Implicit	**6.17 (0.05)**	**8.11 (0.06)**	**4.50 (0.08)**
Original Implicit	6.16 (0.04)	7.97 (0.09)	4.39 (0.05)
Sig. Diff	0.201	$p < 0.001$	$p < 0.001$

Table H.27: Mean and Standard Deviation Total Distance Travelled by Object in Metres for the Hybrid System Manipulating the Cuboid in the Line Following Environmental Setup

Weighting	Line Following Paths		
	1	2	3
Explicit	**3.50 (0.06)**	**3.36 (0.06)**	**3.47 (0.09)**
Original Explicit	3.51 (0.06)	3.33 (0.06)	3.42 (0.05)
Sig. Diff	0.226	0.003	p <0.001
w = 0.25	**3.50 (0.06)**	**3.37 (0.06)**	**3.69 (0.09)**
Original w = 0.25	3.80 (0.99)	4.32 (1.83)	3.51 (0.08)
Sig. Diff	p <0.001	p <0.001	p <0.001
w = 0.5	**3.50 (0.06)**	**3.39 (0.06)**	**5.26 (11.85)**
Original w = 0.5	3.89 (1.46)	3.63 (0.91)	3.52 (0.07)
Sig. Diff	0.002	0.182	p <0.001
w = 0.75	**3.50 (0.06)**	**3.43 (0.06)**	**3.65 (0.08)**
Original w = 0.75	3.52 (0.06)	3.32 (0.06)	3.49 (0.07)
Sig. Diff	0.117	p <0.001	p <0.001
Implicit	**3.53 (0.07)**	**3.49 (0.09)**	**3.54 (0.08)**
Original Implicit	3.50 (0.05)	3.36 (0.07)	3.45 (0.06)
Sig. Diff	0.002	p <0.001	p <0.001

Table H.28: Mean and Standard Deviation Total Distance Travelled by Object in Metres for the Hybrid System Manipulating the Cylinder in the Line Following Environmental Setup

Weighting	Line Following Paths		
	1	2	3
Explicit	**3.50 (0.06)**	**3.35 (0.06)**	**3.48 (0.08)**
Original Explicit	5.27 (0.06)	5.27 (0.06)	5.27 (0.06)
Sig. Diff	0.336	0.108	p <0.001
w = 0.25	**3.49 (0.05)**	**3.34 (0.06)**	**3.53 (0.11)**
Original w = 0.25	3.80 (0.99)	4.32 (1.83)	3.51 (0.08)
Sig. Diff	p <0.001	p <0.001	0.469
w = 0.5	**3.50 (0.06)**	**3.35 (0.06)**	**3.60 (0.24)**
Original w = 0.5	5.26 (0.05)	5.26 (0.05)	5.26 (0.05)
Sig. Diff	0.002	p <0.001	0.533
w = 0.75	**3.52 (0.06)**	**3.38 (0.08)**	**3.59 (0.25)**
Original w = 0.75	3.52 (0.06)	3.32 (0.06)	3.49 (0.07)
Sig. Diff	0.775	p <0.001	0.493
Implicit	**3.56 (0.09)**	**3.39 (0.08)**	**3.49 (0.11)**
Original Implicit	3.50 (0.05)	3.36 (0.07)	3.45 (0.06)
Sig. Diff	p <0.001	0.002	0.007

Table H.29: Mean and Standard Deviation Total Distance Travelled by Object in Metres for the Hybrid System Manipulating the Sphere in the Line Following Environmental Setup

Weighting	Line Following Paths		
	1	2	3
Explicit	**3.50 (0.05)**	**3.38 (0.04)**	**3.41 (0.05)**
Original Explicit	3.51 (0.06)	3.33 (0.06)	3.42 (0.05)
Sig. Diff	0.517	p <0.001	0.588
w = 0.25	**3.50 (0.05)**	**3.39 (0.04)**	**3.43 (0.05)**
Original w = 0.25	3.80 (0.99)	4.32 (1.83)	3.51 (0.08)
Sig. Diff	p <0.001	p <0.001	p <0.001
w = 0.5	**3.50 (0.05)**	**3.41 (0.05)**	**3.42 (0.05)**
Original w = 0.5	3.89 (1.46)	3.63 (0.91)	3.52 (0.07)
Sig. Diff	0.016	0.511	p <0.001
w = 0.75	**3.51 (0.05)**	**3.49 (0.08)**	**3.44 (0.06)**
Original w = 0.75	3.52 (0.06)	3.32 (0.06)	3.49 (0.07)
Sig. Diff	0.097	p <0.001	p <0.001
Implicit	**3.49 (0.05)**	**3.51 (0.11)**	**3.43 (0.06)**
Original Implicit	3.50 (0.05)	3.36 (0.07)	3.45 (0.06)
Sig. Diff	0.083	p <0.001	0.038

Table H.30: Mean and Standard Deviation Total Distance Travelled by Object in Metres for the Hybrid System Manipulating the Cuboid in the Simple (SE) and Cluttered (CE) Environments

Weighting	Paths			
	1		2	3
	SE	CE	CE	CE
Explicit	**5.30 (0.09)**	**12.92 (0.04)**	12.67 (0.01)	**12.53 (0.04)**
Original Explicit	5.27 (0.05)	12.82 (0.20)	12.51 (0.06)	12.40 (0.14)
Sig. Diff	0.036	p <0.001	p <0.001	p <0.001
w = 0.25	**5.26 (0.05)**	**12.87 (0.08)**	12.68 (N/A)	**12.47 (0.04)**
Original w = 0.25	5.27 (0.05)	12.64 (0.08)	12.43 (0.01)	12.27 (0.02)
Sig. Diff	0.130	p <0.001	0.089	p <0.001
w = 0.5	**5.26 (0.05)**	**12.89 (0.04)**	**12.83 (0.08)**	**12.48 (0.05)**
Original w = 0.5	5.28 (0.05)	12.69 (0.05)	12.45 (0.04)	12.28 (0.04)
Sig. Diff	0.003	p <0.001	p <0.001	p <0.001
w = 0.75	**5.27 (0.06)**	**12.96 (0.09)**	**12.95 (0.07)**	**12.55 (0.09)**
Original w = 0.75	5.27 (0.06)	12.76 (0.14)	12.53 (0.12)	12.36 (0.10)
Sig. Diff	0.476	p <0.001	p <0.001	p <0.001
Implicit	**5.27 (0.07)**	**13.03 (0.13)**	**13.03 (0.07)**	**12.65 (0.14)**
Original Implicit	5.28 (0.06)	12.85 (0.25)	12.63 (0.21)	12.52 (0.24)
Sig. Diff	0.533	p <0.001	p <0.001	p <0.001

Table H.31: Mean and Standard Deviation Total Distance Travelled by Object in Metres for the Hybrid System Manipulating the Cylinder in the Simple (SE) and Cluttered (CE) Environments

Weighting	Paths			
	1		2	3
	SE	CE	CE	CE
Explicit	**5.27 (0.05)**	**12.89 (0.06)**	**12.54 (0.01)**	**12.50 (0.08)**
Original Explicit	5.27 (0.06)	5.27 (0.06)	5.27 (0.06)	5.27 (0.06)
Sig. Diff	0.994	0.013	0.332	p <0.001
w = 0.25	**5.26 (0.06)**	**12.86 (0.03)**	N/A	**12.43 (0.03)**
Original w = 0.25	5.27 (0.05)	12.64 (0.08)	12.43 (0.01)	12.27 (0.02)
Sig. Diff	0.145	p <0.001	N/A	p <0.001
w = 0.5	**5.27 (0.06)**	**12.92 (0.04)**	**N/A**	**12.49 (0.04)**
Original w = 0.5	5.26 (0.05)	5.26 (0.05)	5.26 (0.05)	5.26 (0.05)
Sig. Diff	0.062	p <0.001	N/A	p <0.001
w = 0.75	**5.28 (0.08)**	**13.06 (0.11)**	**N/A**	**12.57 (0.10)**
Original w = 0.75	5.27 (0.06)	12.76 (0.14)	12.53 (0.12)	12.36 (0.10)
Sig. Diff	0.282	p <0.001	N/A	p <0.001
Implicit	**5.28 (0.07)**	**13.28 (0.23)**	**N/A**	**12.66 (0.16)**
Original Implicit	5.28 (0.06)	12.85 (0.25)	12.63 (0.21)	12.52 (0.24)
Sig. Diff	0.891	p <0.001	N/A	p <0.001

Table H.32: Mean and Standard Deviation Total Distance Travelled by Object in Metres for the Hybrid System Manipulating the Sphere in the Simple (SE) and Cluttered (CE) Environments

Weighting	Paths			
	1		2	3
	SE	CE	CE	CE
Explicit	**5.26 (0.05)**	**12.83 (0.10)**	**12.51 (0.04)**	**12.42 (0.08)**
Original Explicit	5.27 (0.05)	12.82 (0.20)	12.51 (0.06)	12.40 (0.14)
Sig. Diff	0.233	0.429	0.238	0.158
w = 0.25	**5.27 (0.04)**	**12.82 (0.02)**	**12.55 (0.03)**	**12.40 (0.02)**
Original w = 0.25	5.27 (0.05)	12.64 (0.08)	12.43 (0.01)	12.27 (0.02)
Sig. Diff	0.810	p <0.001	p <0.001	p <0.001
w = 0.5	**5.27 (0.06)**	**12.87 (0.03)**	**12.60 (0.03)**	**12.45 (0.003)**
Original w = 0.5	5.28 (0.05)	12.69 (0.05)	12.45 (0.04)	12.28 (0.04)
Sig. Diff	0.021	p <0.001	p <0.001	p <0.001
w = 0.75	**5.28 (0.06)**	**12.91 (0.04)**	**12.63 (0.04)**	**12.48 (0.04)**
Original w = 0.75	5.27 (0.06)	12.76 (0.14)	12.53 (0.12)	12.36 (0.10)
Sig. Diff	0.317	p <0.001	p <0.001	p <0.001
Implicit	**5.28 (0.05)**	**12.94 (0.06)**	**12.69 (0.08)**	**12.50 (0.04)**
Original Implicit	5.28 (0.06)	12.85 (0.25)	12.63 (0.21)	12.52 (0.24)
Sig. Diff	0.981	p <0.001	p <0.001	0.004

H.4 Maximum Displacement

H.4.1 Size

Table H.33: Mean and Standard Deviation Total Distance Travelled by Object in Metres for the Hybrid System Manipulating the Cuboid in the Randomly Generated Environments

Weighting	Randomly Generated Environments		
	1	2	3
Explicit	**6.13 (0.05)**	**8.06 (0.03)**	**4.45 (0.05)**
Original Explicit	6.18 (0.03)	8.00 (0.09)	4.42 (0.04)
Sig. Diff	p <0.001	p <0.001	p <0.001
w = 0.25	**6.12 (0.02)**	**8.05 (0.02)**	**4.46 (0.03)**
Original w = 0.25	6.14 (0.01)	7.90 (0.03)	4.38 (0.04)
Sig. Diff	p <0.001	p <0.001	p <0.001
w = 0.5	**6.11 (0.04)**	**8.05 (0.03)**	**4.62 (0.35)**
Original w = 0.5	6.14 (0.01)	7.90 (0.04)	4.39 (0.04)
Sig. Diff	p <0.001	p <0.001	p <0.001
w = 0.75	**6.14 (0.04)**	**8.11 (0.05)**	**4.50 (0.17)**
Original w = 0.75	6.14 (0.02)	7.92 (0.05)	4.39 (0.05)
Sig. Diff	0.103	p <0.001	p <0.001
Implicit	**6.16 (0.05)**	**8.12 (0.06)**	**4.51 (0.17)**
Original Implicit	6.16 (0.04)	7.97 (0.09)	4.39 (0.05)
Sig. Diff	0.699	p <0.001	p <0.001

Table H.34: Mean and Standard Deviation Total Distance Travelled by Object in Metres for the Hybrid System Manipulating the Cylinder in the Randomly Generated Environments

Weighting	Randomly Generated Environments		
	1	2	3
Explicit	**6.14 (0.10)**	**8.07 (0.05)**	**4.44 (0.05)**
Original Explicit	5.27 (0.06)	5.27 (0.06)	5.27 (0.06)
Sig. Diff	p <0.001	p <0.001	p <0.001
w = 0.25	**6.14 (0.03)**	**8.02 (0.02)**	**4.44 (0.04)**
Original w = 0.25	6.14 (0.01)	7.90 (0.03)	4.38 (0.04)
Sig. Diff	0.760	p <0.001	p <0.001
w = 0.5	**6.18 (0.06)**	**8.03 (0.03)**	**4.46 (0.05)**
Original w = 0.5	5.26 (0.05)	5.26 (0.05)	5.26 (0.05)
Sig. Diff	p <0.001	p <0.001	p <0.001
w = 0.75	**6.28 (0.11)**	**8.06 (0.05)**	**4.50 (0.05)**
Original w = 0.75	6.14 (0.02)	7.92 (0.05)	4.39 (0.05)
Sig. Diff	p <0.001	p <0.001	p <0.001
Implicit	**6.30 (0.12)**	**8.07 (0.06)**	**4.44 (0.05)**
Original Implicit	6.16 (0.04)	7.97 (0.09)	4.39 (0.05)
Sig. Diff	p <0.001	p <0.001	p <0.001

Table H.35: Mean and Standard Deviation Total Distance Travelled by Object in Metres for the Hybrid System Manipulating the Sphere in the Randomly Generated Environments

Weighting	Randomly Generated Environments		
	1	2	3
Explicit	**6.13 (0.01)**	**7.99 (0.03)**	**4.44 (0.03)**
Original Explicit	6.18 (0.03)	8.00 (0.09)	4.42 (0.04)
Sig. Diff	p <0.001	0.371	p <0.001
w = 0.25	**6.13 (0.02)**	**7.97 (0.02)**	**4.42 (0.04)**
Original w = 0.25	6.14 (0.01)	7.90 (0.03)	4.38 (0.04)
Sig. Diff	p <0.001	p <0.001	p <0.001
w = 0.5	**6.14 (0.02)**	**8.00 (0.02)**	**4.44 (0.04)**
Original w = 0.5	6.14 (0.01)	7.90 (0.04)	4.39 (0.04)
Sig. Diff	0.473	p <0.001	p <0.001
w = 0.75	**6.17 (0.04)**	**8.02 (0.03)**	**4.44 (0.04)**
Original w = 0.75	6.14 (0.02)	7.92 (0.05)	4.39 (0.05)
Sig. Diff	p <0.001	p <0.001	p <0.001
Implicit	**6.19 (0.04)**	**8.03 (0.04)**	**4.44 (0.05)**
Original Implicit	6.16 (0.04)	7.97 (0.09)	4.39 (0.05)
Sig. Diff	p <0.001	p <0.001	p <0.001

Table H.36: Mean Maximum Displacement and Standard Deviation of Object in Metres for the Hybrid System Manipulating the Medium Object in the Line Following Environmental Setup

Weighting	Line Following Paths		
	1	2	3
Explicit	**0.019 (0.006)**	**0.020 (0.005)**	**0.020 (0.005)**
Original Explicit	0.018 (0.006)	0.018 (0.006)	0.019 (0.005)
Sig. Diff	0.157	0.005	0.218
w = 0.25	**0.024 (0.004)**	**0.024 (0.003)**	**0.027 (0.004)**
Original w = 0.25	0.027 (0.008)	0.034 (0.009)	0.031 (0.009)
Sig. Diff	0.016	p <0.001	0.883
w = 0.5	**0.026 (0.005)**	**0.030 (0.003)**	**0.028 (0.004)**
Original w = 0.5	0.028 (0.007)	0.031 (0.006)	0.031 (0.006)
Sig. Diff	0.185	0.213	0.005
w = 0.75	**0.028 (0.005)**	**0.031 (0.004)**	**0.028 (0.003)**
Original w = 0.75	0.028 (0.006)	0.032 (0.004)	0.032 (0.006)
Sig. Diff	0.305	0.043	p <0.001
Implicit	**0.029 (0.006)**	**0.031 (0.005)**	**0.031 (0.004)**
Original Implicit	0.029 (0.005)	0.031 (0.005)	0.033 (0.006)
Sig. Diff	0.531	0.783	0.135

Table H.37: Mean Maximum Displacement and Standard Deviation of Object in Metres for the Hybrid System Manipulating the Large Object in the Line Following Environmental Setup

Weighting	Line Following Paths		
	1	2	3
Explicit	**0.022 (0.006)**	**0.021 (0.006)**	**0.022 (0.006)**
Original Explicit	0.018 (0.006)	0.018 (0.006)	0.019 (0.005)
Sig. Diff	p <0.001	p <0.001	p <0.001
w = 0.25	**0.024 (0.005)**	**0.025 (0.004)**	**0.027 (0.003)**
Original w = 0.25	0.027 (0.008)	0.034 (0.009)	0.031 (0.009)
Sig. Diff	0.008	p <0.001	0.301
w = 0.5	**0.027 (0.004)**	**0.030 (0.003)**	**0.029 (0.005)**
Original w = 0.5	0.028 (0.007)	0.031 (0.006)	0.031 (0.006)
Sig. Diff	0.780	0.060	0.130
w = 0.75	**0.030 (0.004)**	**0.034 (0.004)**	**0.031 (0.006)**
Original w = 0.75	0.028 (0.006)	0.032 (0.004)	0.032 (0.006)
Sig. Diff	p <0.001	0.162	0.082
Implicit	**0.037 (0.001)**	**0.037 (0.002)**	**0.032 (0.004)**
Original Implicit	0.029 (0.005)	0.031 (0.005)	0.033 (0.006)
Sig. Diff	p <0.001	p <0.001	0.525

Table H.38: Mean Maximum Displacement and Standard Deviation of Object in Metres for the Hybrid System Manipulating the Medium Object in the Simple (SE) and Cluttered (CE) Environments

Weighting	Paths			
	1		2	3
	SE	CE	CE	CE
Explicit	**0.020 (0.005)**	**0.020 (0.005)**	**0.017 (0.003)**	**0.020 (0.005)**
Original Explicit	0.018 (0.006)	0.019 (0.005)	0.016 (0.004)	0.017 (0.005)
Sig. Diff	0.023	0.013	p <0.001	0.002
w = 0.25	**0.026 (0.006)**	**0.030 (0.006)**	**0.025 (0.004)**	**0.029 (0.006)**
Original w = 0.25	0.025 (0.005)	0.029 (0.006)	0.028 (0.005)	0.028 (0.005)
Sig. Diff	p <0.001	0.485	0.037	0.019
w = 0.5	**0.027 (0.005)**	**0.032 (0.004)**	**0.029 (0.002)**	**0.030 (0.004)**
Original w = 0.5	0.024 (0.005)	0.030 (0.004)	0.029 (0.004)	0.030 (0.004)
Sig. Diff	0.031	p <0.001	0.523	0.026
w = 0.75	**0.029 (0.003)**	**0.035 (0.004)**	**0.033 (0.002)**	**0.034 (0.003)**
Original w = 0.75	0.029 (0.004)	0.034 (0.003)	0.034 (0.003)	0.034 (0.003)
Sig. Diff	0.536	0.590	0.156	0.509
Implicit	**0.034 (0.004)**	**0.037 (0.004)**	**0.035 (0.003)**	**0.036 (0.003)**
Original Implicit	0.031 (0.004)	0.037 (0.003)	0.038 (0.002)	0.038 (0.003)
Sig. Diff	p <0.001	0.295	p <0.001	p <0.001

Table H.39: Mean Maximum Displacement and Standard Deviation of Object in Metres for the Hybrid System Manipulating the Large Object in the Simple (SE) and Cluttered (CE) Environments

Weighting	Paths			
	1		2	3
	SE	CE	CE	CE
Explicit	**0.019 (0.006)**	**0.020 (0.004)**	**0.016 (0.002)**	**0.020 (0.004)**
Original Explicit	0.018 (0.006)	0.019 (0.005)	0.016 (0.004)	0.017 (0.005)
Sig. Diff	0.026	0.251	0.023	p <0.001
w = 0.25	**0.026 (0.006)**	**0.032 (0.005)**	**0.024 (0.002)**	**0.032 (0.006)**
Original w = 0.25	0.025 (0.005)	0.029 (0.006)	0.028 (0.005)	0.028 (0.005)
Sig. Diff	0.135	p <0.001	0.031	p <0.001
w = 0.5	**0.027 (0.005)**	**0.034 (0.005)**	**0.025 (0.003)**	**0.033 (0.006)**
Original w = 0.5	0.024 (0.005)	0.030 (0.004)	0.029 (0.004)	0.030 (0.004)
Sig. Diff	0.419	p <0.001	p <0.001	p <0.001
w = 0.75	**0.031 (0.002)**	**0.036 (0.005)**	**0.033 (0.005)**	**0.034 (0.004)**
Original w = 0.75	0.029 (0.004)	0.034 (0.003)	0.034 (0.003)	0.034 (0.003)
Sig. Diff	0.083	0.067	0.014	0.227
Implicit	**0.036 (0.002)**	**0.039 (0.003)**	**0.038 (0.002)**	**0.039 (0.002)**
Original Implicit	0.031 (0.004)	0.037 (0.003)	0.038 (0.002)	0.038 (0.003)
Sig. Diff	p <0.001	0.001	0.698	0.741

H.4.2 Shape

Table H.40: Mean Maximum Displacement and Standard Deviation of Object in Metres for the Hybrid System Manipulating the Medium Object in the Randomly Generated Environments

Weighting	Randomly Generated Environments		
	1	2	3
Explicit	**0.021 (0.005)**	**0.021 (0.005)**	**0.020 (0.005)**
Original Explicit	0.019 (0.005)	0.018 (0.006)	0.017 (0.005)
Sig. Diff	p <0.001	0.001	p <0.001
w = 0.25	**0.027 (0.005)**	**0.026 (0.006)**	**0.026 (0.006)**
Original w = 0.25	0.027 (0.005)	0.027 (0.006)	0.025 (0.006)
Sig. Diff	0.089	0.329	0.002
w = 0.5	**0.028 (0.006)**	**0.028 (0.005)**	**0.026 (0.005)**
Original w = 0.5	0.026 (0.005)	0.027 (0.005)	0.025 (0.005)
Sig. Diff	0.012	0.470	0.186
w = 0.75	**0.032 (0.002)**	**0.031 (0.004)**	**0.030 (0.003)**
Original w = 0.75	0.030 (0.003)	0.030 (0.003)	0.029 (0.004)
Sig. Diff	p <0.001	0.851	0.345
Implicit	**0.039 (0.003)**	**0.036 (0.004)**	**0.034 (0.004)**
Original Implicit	0.034 (0.004)	0.034 (0.003)	0.033 (0.004)
Sig. Diff	p <0.001	0.001	p <0.001

Table H.41: Mean Maximum Displacement and Standard Deviation of Object in Metres for the Hybrid System Manipulating the Large Object in the Randomly Generated Environments

Weighting	Randomly Generated Environments		
	1	2	3
Explicit	**0.020 (0.005)**	**0.018 (0.003)**	**0.019 (0.004)**
Original Explicit	0.019 (0.005)	0.018 (0.006)	0.017 (0.005)
Sig. Diff	0.001	0.405	p <0.001
w = 0.25	**0.028 (0.005)**	**0.029 (0.006)**	**0.027 (0.006)**
Original w = 0.25	0.027 (0.005)	0.027 (0.006)	0.025 (0.006)
Sig. Diff	0.004	p <0.001	p <0.001
w = 0.5	**0.029 (0.005)**	**0.030 (0.006)**	**0.028 (0.005)**
Original w = 0.5	0.026 (0.005)	0.027 (0.005)	0.025 (0.005)
Sig. Diff	p <0.001	0.002	0.004
w = 0.75	**0.034 (0.002)**	**0.031 (0.004)**	**0.033 (0.002)**
Original w = 0.75	0.030 (0.003)	0.030 (0.003)	0.029 (0.004)
Sig. Diff	p <0.001	0.265	p <0.001
Implicit	**0.037 (0.003)**	**0.034 (0.004)**	**0.040 (0.001)**
Original Implicit	0.034 (0.004)	0.034 (0.003)	0.033 (0.004)
Sig. Diff	p <0.001	0.942	p <0.001

Table H.42: Mean Maximum Displacement and Standard Deviation of Object in Metres for the Hybrid System Manipulating the Cuboid in the Line Following Environmental Setup

Weighting	Line Following Paths		
	1	2	3
Explicit	**0.020 (0.006)**	**0.021 (0.006)**	**0.021 (0.006)**
Original Explicit	0.018 (0.006)	0.018 (0.006)	0.019 (0.005)
Sig. Diff	0.035	p <0.001	0.036
w = 0.25	**0.023 (0.004)**	**0.025 (0.004)**	**0.026 (0.003)**
Original w = 0.25	0.027 (0.008)	0.034 (0.009)	0.031 (0.009)
Sig. Diff	p <0.001	p <0.001	0.051
w = 0.5	**0.027 (0.005)**	**0.028 (0.004)**	**0.033 (0.041)**
Original w = 0.5	0.028 (0.007)	0.031 (0.006)	0.031 (0.006)
Sig. Diff	0.367	p <0.001	0.002
w = 0.75	**0.028 (0.005)**	**0.032 (0.005)**	**0.029 (0.004)**
Original w = 0.75	0.028 (0.006)	0.032 (0.004)	0.032 (0.006)
Sig. Diff	0.287	0.490	p <0.001
Implicit	**0.039 (0.002)**	**0.040 (0.002)**	**0.031 (0.005)**
Original Implicit	0.029 (0.005)	0.031 (0.005)	0.033 (0.006)
Sig. Diff	p <0.001	p <0.001	0.011

Table H.43: Mean Maximum Displacement and Standard Deviation of Object in Metres for the Hybrid System Manipulating the Cylinder in the Line Following Environmental Setup

Weighting	Line Following Paths		
	1	2	3
Explicit	**0.020 (0.006)**	**0.020 (0.006)**	**0.021 (0.006)**
Original Explicit	0.018 (0.006)	0.018 (0.006)	0.019 (0.005)
Sig. Diff	0.112	0.009	0.008
w = 0.25	**0.023 (0.004)**	**0.024 (0.004)**	**0.026 (0.003)**
Original w = 0.25	0.027 (0.008)	0.034 (0.009)	0.031 (0.009)
Sig. Diff	0.001	p <0.001	0.055
w = 0.5	**0.026 (0.005)**	**0.028 (0.003)**	**0.033 (0.003)**
Original w = 0.5	0.028 (0.007)	0.031 (0.006)	0.031 (0.006)
Sig. Diff	0.133	p <0.001	p <0.001
w = 0.75	**0.027 (0.005)**	**0.033 (0.005)**	**0.038 (0.004)**
Original w = 0.75	0.028 (0.006)	0.032 (0.004)	0.032 (0.006)
Sig. Diff	0.939	0.842	p <0.001
Implicit	**0.038 (0.004)**	**0.037 (0.006)**	**0.036 (0.004)**
Original Implicit	0.029 (0.005)	0.031 (0.005)	0.033 (0.006)
Sig. Diff	p <0.001	p <0.001	p <0.001

Table H.44: Mean Maximum Displacement and Standard Deviation of Object in Metres for the Hybrid System Manipulating the Sphere in the Line Following Environmental Setup

Weighting	Line Following Paths		
	1	2	3
Explicit	**0.020 (0.006)**	**0.020 (0.006)**	**0.019 (0.005)**
Original Explicit	0.018 (0.006)	0.018 (0.006)	0.019 (0.005)
Sig. Diff	0.022	0.006	0.508
w = 0.25	**0.025 (0.004)**	**0.024 (0.003)**	**0.026 (0.003)**
Original w = 0.25	0.027 (0.008)	0.034 (0.009)	0.031 (0.009)
Sig. Diff	0.293	p <0.001	0.130
w = 0.5	**0.029 (0.004)**	**0.032 (0.003)**	**0.032 (0.004)**
Original w = 0.5	0.028 (0.007)	0.031 (0.006)	0.031 (0.006)
Sig. Diff	0.002	0.321	0.041
w = 0.75	**0.032 (0.004)**	**0.034 (0.005)**	**0.032 (0.005)**
Original w = 0.75	0.028 (0.006)	0.032 (0.004)	0.032 (0.006)
Sig. Diff	p <0.001	0.130	0.449
Implicit	**0.035 (0.005)**	**0.037 (0.005)**	**0.032 (0.005)**
Original Implicit	0.029 (0.005)	0.031 (0.005)	0.033 (0.006)
Sig. Diff	p <0.001	p <0.001	0.194

Table H.45: Mean Maximum Displacement and Standard Deviation of Object in Metres for the Hybrid System Manipulating the Cuboid in the Simple (SE) and Cluttered (CE) Environments

Weighting	Paths			
	1		2	3
	SE	CE	CE	CE
Explicit	**0.019 (0.005)**	**0.022 (0.004)**	**0.014 (0.001)**	**0.023 (0.005)**
Original Explicit	0.018 (0.006)	0.019 (0.005)	0.016 (0.004)	0.017 (0.005)
Sig. Diff	0.179	p <0.001	0.580	p <0.001
w = 0.25	**0.026 (0.005)**	**0.033 (0.005)**	**0.029 (N/A)**	**0.033 (0.006)**
Original w = 0.25	0.025 (0.005)	0.029 (0.006)	0.028 (0.005)	0.028 (0.005)
Sig. Diff	0.367	p <0.001	0.959	1.16E-09
w = 0.5	**0.026 (0.005)**	**0.035 (0.004)**	**0.034 (0.003)**	**0.034 (0.005)**
Original w = 0.5	0.024 (0.005)	0.030 (0.004)	0.029 (0.004)	0.030 (0.004)
Sig. Diff	0.008	p <0.001	0.002	p <0.001
w = 0.75	**0.031 (0.002)**	**0.036 (0.005)**	**0.039 (0.003)**	**0.035 (0.004)**
Original w = 0.75	0.029 (0.004)	0.034 (0.003)	0.034 (0.003)	0.034 (0.003)
Sig. Diff	0.017	p <0.001	p <0.001	0.013
Implicit	**0.035 (0.002)**	**0.039 (0.003)**	**0.040 (0.003)**	**0.038 (0.003)**
Original Implicit	0.031 (0.004)	0.037 (0.003)	0.038 (0.002)	0.038 (0.003)
Sig. Diff	p <0.001	p <0.001	0.226	0.316

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Table H.46: Mean Maximum Displacement and Standard Deviation of Object in Metres for the Hybrid System Manipulating the Cylinder in the Simple (SE) and Cluttered (CE) Environments

Weighting	Paths			
	1		2	3
	SE	CE	CE	CE
Explicit	**0.019 (0.006)**	**0.019 (0.004)**	**0.0136 (~0.000)**	**0.020 (0.005)**
Original Explicit	0.018 (0.006)	0.019 (0.005)	0.016 (0.004)	0.017 (0.005)
Sig. Diff	0.439	0.699	0.117	$p < 0.001$
w = 0.25	**0.026 (0.005)**	**0.034 (0.005)**	**N/A**	**0.033 (0.005)**
Original w = 0.25	0.025 (0.005)	0.029 (0.006)	0.028 (0.005)	0.028 (0.005)
Sig. Diff	0.555	$p < 0.001$	N/A	$p < 0.001$
w = 0.5	**0.026 (0.005)**	**0.035 (0.005)**	**N/A**	**0.034 (0.006)**
Original w = 0.5	0.024 (0.005)	0.030 (0.004)	0.029 (0.004)	0.030 (0.004)
Sig. Diff	0.006	$p < 0.001$	N/A	$p < 0.001$
w = 0.75	**0.028 (0.005)**	**0.037 (0.005)**	**N/A**	**0.035 (0.005)**
Original w = 0.75	0.029 (0.004)	0.034 (0.003)	0.034 (0.003)	0.034 (0.003)
Sig. Diff	0.091	$p < 0.001$	N/A	0.119
Implicit	**0.030 (0.005)**	**0.040 (0.005)**	**N/A**	**0.037 (0.005)**
Original Implicit	0.031 (0.004)	0.037 (0.003)	0.038 (0.002)	0.038 (0.003)
Sig. Diff	0.028	$p < 0.001$	N/A	0.390

Table H.47: Mean Maximum Displacement and Standard Deviation of Object in Metres for the Hybrid System Manipulating the Sphere in the Simple (SE) and Cluttered (CE) Environments

Weighting	Paths			
	1		2	3
	SE	CE	CE	CE
Explicit	**0.020 (0.005)**	**0.026 (0.005)**	**0.019 (0.004)**	**0.023 (0.006)**
Original Explicit	0.018 (0.006)	0.019 (0.005)	0.016 (0.004)	0.017 (0.005)
Sig. Diff	0.043	p <0.001	0.008	p <0.001
w = 0.25	**0.027 (0.003)**	**0.035 (0.005)**	**0.034 (0.005)**	**0.034 (0.005)**
Original w = 0.25	0.025 (0.005)	0.029 (0.006)	0.028 (0.005)	0.028 (0.005)
Sig. Diff	0.025	p <0.001	p <0.001	p <0.001
w = 0.5	**0.032 (0.003)**	**0.036 (0.005)**	**0.033 (0.004)**	**0.035 (0.005)**
Original w = 0.5	0.024 (0.005)	0.030 (0.004)	0.029 (0.004)	0.030 (0.004)
Sig. Diff	p <0.001	p <0.001	p <0.001	p <0.001
w = 0.75	**0.035 (0.005)**	**0.038 (0.005)**	**0.035 (0.004)**	**0.037 (0.004)**
Original w = 0.75	0.029 (0.004)	0.034 (0.003)	0.034 (0.003)	0.034 (0.003)
Sig. Diff	p <0.001	p <0.001	0.308	p <0.001
Implicit	**0.036 (0.005)**	**0.040 (0.005)**	**0.036 (0.003)**	**0.038 (0.004)**
Original Implicit	0.031 (0.004)	0.037 (0.003)	0.038 (0.002)	0.038 (0.003)
Sig. Diff	p <0.001	0.002	p <0.001	0.784

H.5 Path Fidelity

H.5.1 Size

Table H.48: Mean Maximum Displacement and Standard Deviation of Object in Metres for the Hybrid System Manipulating the Cuboid in the Randomly Generated Environments

Weighting	Randomly Generated Environments		
	1	2	3
Explicit	**0.022 (0.006)**	**0.022 (0.005)**	**0.020 (0.006)**
Original Explicit	0.019 (0.005)	0.018 (0.006)	0.017 (0.005)
Sig. Diff	0.002	p <0.001	0.002
w = 0.25	**0.029 (0.005)**	**0.028 (0.006)**	**0.028 (0.006)**
Original w = 0.25	0.027 (0.005)	0.027 (0.006)	0.025 (0.006)
Sig. Diff	0.017	0.174	0.001
w = 0.5	**0.030 (0.005)**	**0.030 (0.006)**	**0.028 (0.009)**
Original w = 0.5	0.026 (0.005)	0.027 (0.005)	0.025 (0.005)
Sig. Diff	p <0.001	p <0.001	0.011
w = 0.75	**0.035 (0.001)**	**0.032 (0.004)**	**0.032 (0.003)**
Original w = 0.75	0.030 (0.003)	0.030 (0.003)	0.029 (0.004)
Sig. Diff	p <0.001	p <0.001	p <0.001
Implicit	**0.041 (0.003)**	**0.035 (0.003)**	**0.040 (0.002)**
Original Implicit	0.034 (0.004)	0.034 (0.003)	0.033 (0.004)
Sig. Diff	p <0.001	0.400	p <0.001

Table H.49: Mean Maximum Displacement and Standard Deviation of Object in Metres for the Hybrid System Manipulating the Cylinder in the Randomly Generated Environments

Weighting	Randomly Generated Environments		
	1	2	3
Explicit	**0.021 (0.006)**	**0.021 (0.005)**	**0.021 (0.006)**
Original Explicit	0.019 (0.005)	0.018 (0.006)	0.017 (0.005)
Sig. Diff	0.043	0.001	p <0.001
w = 0.25	**0.027 (0.005)**	**0.029 (0.006)**	**0.026 (0.006)**
Original w = 0.25	0.027 (0.005)	0.027 (0.006)	0.025 (0.006)
Sig. Diff	0.641	0.066	0.359
w = 0.5	**0.030 (0.004)**	**0.030 (0.006)**	**0.028 (0.005)**
Original w = 0.	0.026 (0.005)	0.027 (0.005)	0.025 (0.005)
Sig. Diff	p <0.001	p <0.001	p <0.001
w = 0.75	**0.037 (0.001)**	**0.031 (0.005)**	**0.034 (0.002)**
Original w = 0.75	0.030 (0.003)	0.030 (0.003)	0.029 (0.004)
Sig. Diff	p <0.001	0.107	p <0.001
Implicit	**0.043 (0.003)**	**0.034 (0.005)**	**0.041 (0.002)**
Original Implicit	0.034 (0.004)	0.034 (0.003)	0.033 (0.004)
Sig. Diff	p <0.001	0.555	p <0.001

Table H.50: Mean Maximum Displacement and Standard Deviation of Object in Metres for the Hybrid System Manipulating the Sphere in the Randomly Generated Environments

Weighting	Randomly Generated Environments		
	1	2	3
Explicit	**0.022 (0.007)**	**0.023 (0.006)**	**0.021 (0.007)**
Original Explicit	0.019 (0.005)	0.018 (0.006)	0.017 (0.005)
Sig. Diff	0.002	p <0.001	0.003
w = 0.25	**0.031 (0.005)**	**0.031 (0.005)**	**0.029 (0.005)**
Original w = 0.25	0.027 (0.005)	0.027 (0.006)	0.025 (0.006)
Sig. Diff	p <0.001	p <0.001	p <0.001
w = 0.5	**0.033 (0.004)**	**0.033 (0.005)**	**0.031 (0.005)**
Original w = 0.	0.026 (0.005)	0.027 (0.005)	0.025 (0.005)
Sig. Diff	p <0.001	p <0.001	p <0.001
w = 0.75	**0.035 (0.004)**	**0.035 (0.005)**	**0.033 (0.005)**
Original w = 0.75	0.030 (0.003)	0.030 (0.003)	0.029 (0.004)
Sig. Diff	p <0.001	p <0.001	p <0.001
Implicit	**0.040 (0.002)**	**0.037 (0.005)**	**0.035 (0.005)**
Original Implicit	0.034 (0.004)	0.034 (0.003)	0.033 (0.004)
Sig. Diff	p <0.001	p <0.001	p <0.001

Table H.51: Percentage Mean and Standard Deviation Path Fidelity for the Hybrid System Manipulating the Medium Object in the Line Following Environmental Setup

Weighting	Line Following Paths		
	1	2	3
Explicit	**91.75% (13.79%)**	**100% (0%)**	**94.80% (8.82%)**
Original Explicit	90.75% (14.93%)	100% (∼0%)	99.40% (3.43%)
Sig. Diff	0.704	1	p <0.001
w = 0.25	**86.25% (16.04%)**	**93.00% (8.60%)**	**79.09% (17.97%)**
Original w = 0.25	78.02 (27.09%)	56.58% (25.54%)	79.35% (19.15%)
Sig. Diff	0.137	p <0.001	0.889
w = 0.5	**92.75% (12.96%)**	**98.50% (5.35%)**	**79.26% (21.11%)**
Original w = 0.5	86.48% (22.47%)	71.56% (25.02%)	90.18% (15.64%)
Sig. Diff	0.118	p <0.001	0.011
w = 0.75	**94.25% (13.23%)**	**98.17% (5.75%)**	**80.00% (17.75%)**
Original w = 0.75	93.25% (13.23%)	99.50% (2.86%)	91.65% (14.18%)
Sig. Diff	0.425	0.045	p <0.001
Implicit	**96.50% (9.41%)**	**94.67% (9.73%)**	**92.53% (10.91%)**
Original Implicit	93.00 (12.35%)	89.67% (14.17%)	96.57% (9.49%)
Sig. Diff	0.021	0.011	0.001

Table H.52: Percentage Mean and Standard Deviation Path Fidelity for the Hybrid System Manipulating the Large Object in the Line Following Environmental Setup

Weighting	Line Following Paths		
	1	2	3
Explicit	**88.00% (17.94%)**	**80.33% (11.21%)**	**96.60% (7.55%)**
Original Explicit	90.75% (14.93%)	100% (∼0%)	99.40% (3.43%)
Sig. Diff	0.327	p <0.001	0.001
w = 0.25	**90.75% (13.13%)**	**94.44% (11.66%)**	**66.57% (22.93%)**
Original w = 0.25	78.02 (27.09%)	56.58% (25.54%)	79.35% (19.15%)
Sig. Diff	0.002	p <0.001	0.001
w = 0.5	**90.75% (13.60%)**	**89.74% (14.65%)**	**82.00% (17.93%)**
Original w = 0.5	86.48% (22.47%)	71.56% (25.02%)	90.18% (15.64%)
Sig. Diff	0.622	p <0.001	0.004
w = 0.75	**83.75% (15.23%)**	**86.67% (14.79%)**	**80.00% (20.00%)**
Original w = 0.75	93.25% (13.23%)	99.50% (2.86%)	91.65% (14.18%)
Sig. Diff	p <0.001	p <0.001	0.001
Implicit	**83.25% (19.15%)**	**74.33% (21.51%)**	**83.26% (18.10%)**
Original Implicit	93.00 (12.35%)	89.67% (14.17%)	96.57% (9.49%)
Sig. Diff	p <0.001	p <0.001	p <0.001

Table H.53: Percentage Mean and Standard Deviation Path Fidelity for the Hybrid System Manipulating the Medium Object in the Simple (SE) and Cluttered (CE) Environments

Weighting	Paths			
	1		2	3
	SE	CE	CE	CE
Explicit	**90.89% (1.60%)**	**73.07% (9.82%)**	**77.67% (4.52%)**	**75.20% (10.06%)**
Original Explicit	91.00% (2.12%)	64.09% (15.65%)	72.96% (8.33%)	69.04 (15.25%)
Sig. Diff	0.392	p <0.001	p <0.001	p <0.001
w = 0.25	**91.46% (1.37%)**	**74.42% (8.37%)**	**77.23% (4.62%)**	**75.18% (9.04%)**
Original w = 0.25	91.24% (1.87%)	75.61% (7.70%)	75.69% (5.67%)	78.94% (5.27%)
Sig. Diff	0.294	0.137	0.413	0.017
w = 0.5	**91.45% (1.42%)**	**74.92% (6.89%)**	**76.19% (3.6%)**	**78.32% (5.71%)**
Original w = 0.5	91.72% (1.71%)	76.90% (6.14%)	75.59% (4.38%)	76.78% (5.26%)
Sig. Diff	0.227	0.154	0.038	0.239
w = 0.75	**91.21% (1.70%)**	**74.07% (5.62%)**	**74.23% (3.30%)**	**76.46% (5.82%)**
Original w = 0.75	91.33% (1.88%)	75.09% (5.39%)	73.03% (4.04%)	75.83% (4.32%)
Sig. Diff	0.878	0.672	0.158	0.018
Implicit	**91.56% (1.14%)**	**73.03% (5.38%)**	**70.90% (6.79%)**	**74.34% (5.52%)**
Original Implicit	91.79% (1.60%)	70.78% (3.55%)	69.44% (2.80%)	70.56% (3.35%)
Sig. Diff	0.277	0.015	p <0.001	p <0.001

Table H.54: Percentage Mean and Standard Deviation Path Fidelity for the Hybrid System Manipulating the Large Object in the Simple (SE) and Cluttered (CE) Environments

Weighting	Paths			
	1		2	3
	SE	CE	CE	CE
Explicit	**92.10% (1.11%)**	**84.34% (6.74%)**	**87.90% (2.59%)**	**82.39% (7.33%)**
Original Explicit	91.00% (2.12%)	64.09% (15.65%)	72.96% (8.33%)	69.04 (15.25%)
Sig. Diff	p <0.001	p <0.001	p <0.001	v
w = 0.25	**92.20% (1.11%)**	**73.59% (6.36%)**	**78.31% (1.51%)**	**75.81% (7.26%)**
Original w = 0.25	91.24% (1.87%)	75.61% (7.70%)	75.69% (5.67%)	78.94% (5.27%)
Sig. Diff	p <0.001	0.022	0.033	0.010
w = 0.5	**92.31% (1.20%)**	**71.94% (6.28%)**	**77.79% (1.56%)**	**73.08% (8.33%)**
Original w = 0.5	91.72% (1.71%)	76.90% (6.14%)	75.59% (4.38%)	76.78% (5.26%)
Sig. Diff	p <0.001	p <0.001	0.005	p <0.001
w = 0.75	**91.92% (0.98%)**	**70.39% (6.42%)**	**76.91% (1.44%)**	**73.93% (7.81%)**
Original w = 0.75	91.33% (1.88%)	75.09% (5.39%)	73.03% (4.04%)	75.83% (4.32%)
Sig. Diff	0.007	p <0.001	p <0.001	0.946
Implicit	**91.05% (1.13%)**	**69.14% (6.01%)**	**75.13% (2.18%)**	**71.43% (8.13%)**
Original Implicit	91.79% (1.60%)	70.78% (3.55%)	69.44% (2.80%)	70.56% (3.35%)
Sig. Diff	p <0.001	0.001	p <0.001	0.040

H.5.2 Shape

Table H.55: Percentage Mean and Standard Deviation Path Fidelity for the Hybrid System Manipulating the Medium Object in the Randomly Generated Environments

Weighting	Randomly Generated Environments		
	1	2	3
Explicit	**68.88% (12.96%)**	**69.43% (9.93%)**	**61.06% (14.64%)**
Original Explicit	54.36% (23.85%)	56.36% (21.46%)	49.84% (23.26%)
Sig. Diff	p <0.001	p <0.001	p <0.001
w = 0.25	**68.87% (10.92%)**	**70.83% (8.39%)**	**58.62% (8.90%)**
Original w = 0.25	74.08% (8.48%)	71.04% (7.16%)	63.48% (14.71%)
Sig. Diff	p <0.001	0.418	p <0.001
w = 0.5	**69.95% (11.92%)**	**72.16% (7.97%)**	**61.80% (13.85%)**
Original w = 0.5	76.73% (8.01%)	71.77% (6.66%)	66.30% (15.08%)
Sig. Diff	0.002	0.104	0.734
w = 0.75	**73.29% (9.98%)**	**73.20% (7.34%)**	**66.20% (12.51%)**
Original w = 0.75	75.83% (8.16%)	71.61% (7.05%)	64.37% (17.10%)
Sig. Diff	0.262	0.007	0.040
Implicit	**75.61% (7.52%)**	**71.93% (6.13%)**	**65.89% (10.41%)**
Original Implicit	75.31% (9.04%)	68.40% (5.61%)	61.80% (14.57%)
Sig. Diff	0.928	p <0.001	0.390

Table H.56: Percentage Mean and Standard Deviation Path Fidelity for the Hybrid System Manipulating the Large Object in the Randomly Generated Environments

Weighting	Randomly Generated Environments		
	1	2	3
Explicit	**85.95% (6.79%)**	**86.83% (5.13%)**	**81.35% (12.28%)**
Original Explicit	54.36% (23.85%)	56.36% (21.46%)	49.84% (23.26%)
Sig. Diff	p <0.001	p <0.001	p <0.001
w = 0.25	**73.98% (7.89%)**	**73.98% (5.49%)**	**59.30% (10.32%)**
Original w = 0.25	74.08% (8.48%)	71.04% (7.16%)	63.48% (14.71%)
Sig. Diff	0.322	0.041	0.001
w = 0.5	**72.83% (8.26%)**	**73.53% (5.13%)**	**58.66% (10.20%)**
Original w = 0.5	76.73% (8.01%)	71.77% (6.66%)	66.30% (15.08%)
Sig. Diff	0.023	0.005	0.060
w = 0.75	**71.41% (8.85%)**	**72.72% (4.97%)**	**59.86% (11.56%)**
Original w = 0.75	75.83% (8.16%)	71.61% (7.05%)	64.37% (17.10%)
Sig. Diff	0.009	0.013	0.481
Implicit	**70.33% (8.93%)**	**71.74% (5.13%)**	**59.65% (8.86%)**
Original Implicit	75.31% (9.04%)	68.40% (5.61%)	61.80% (14.57%)
Sig. Diff	p <0.001	p <0.001	0.117

Table H.57: Percentage Mean and Standard Deviation Path Fidelity for the Hybrid System Manipulating the Cuboid in the Line Following Environmental Setup

Weighting	Line Following Paths		
	1	2	3
Explicit	**95.00% (11.24%)**	**69.67% (19.73%)**	**94.40% (10.67%)**
Original Explicit	90.75% (14.93%)	100% (∼0%)	99.40% (3.43%)
Sig. Diff	0.028	p <0.001	p <0.001
w = 0.25	**98.75% (5.48%)**	**78.33% (16.67%)**	**86.22% (15.85%)**
Original w = 0.25	78.02 (27.09%)	56.58% (25.54%)	79.35% (19.15%)
Sig. Diff	p <0.001	p <0.001	0.066
w = 0.5	**98.50% (5.97%)**	**83.67% (14.98%)**	**83.27% (19.15%)**
Original w = 0.5	86.48% (22.47%)	71.56% (25.02%)	90.18% (15.64%)
Sig. Diff	p <0.001	0.001	0.026
w = 0.75	**96.00% (9.21%)**	**84.88% (15.97%)**	**88.20% (13.85%)**
Original w = 0.75	93.25% (13.23%)	99.50% (2.86%)	91.65% (14.18%)
Sig. Diff	0.143	p <0.001	0.065
Implicit	**84.50% (16.20%)**	**82.33% (16.21%)**	**86.29% (16.40%)**
Original Implicit	93.00 (12.35%)	89.67% (14.17%)	96.57% (9.49%)
Sig. Diff	0.028	p <0.001	p <0.001

Table H.58: Percentage Mean and Standard Deviation Path Fidelity for the Hybrid System Manipulating the Cylinder in the Line Following Environmental Setup

Weighting	Line Following Paths		
	1	2	3
Explicit	**97.00% (8.16%)**	**80.17% (15.30%)**	**93.80% (11.62%)**
Original Explicit	90.75% (14.93%)	100% (∼0%)	99.40% (3.43%)
Sig. Diff	p <0.001	p <0.001	p <0.001
w = 0.25	**95.25% (10.48%)**	**80.33% (13.48%)**	**82.40% (19.34%)**
Original w = 0.25	78.02 (27.09%)	56.58% (25.54%)	79.35% (19.15%)
Sig. Diff	p <0.001	p <0.001	0.262
w = 0.5	**98.25% (6.41%)**	**87.50% (12.62%)**	**75.77% (17.21%)**
Original w = 0.5	86.48% (22.47%)	71.56% (25.02%)	90.18% (15.64%)
Sig. Diff	p <0.001	p <0.001	3.27E-13
w = 0.75	**97.50% (7.54%)**	**89.50% (12.68%)**	**86.30% (16.40%)**
Original w = 0.75	93.25% (13.23%)	99.50% (2.86%)	91.65% (14.18%)
Sig. Diff	0.008	3.27E-13	0.036
Implicit	**87.00% (16.85%)**	**91.17% (12.64%)**	**83.02% (19.37%)**
Original Implicit	93.00 (12.35%)	89.67% (14.17%)	96.57% (9.49%)
Sig. Diff	p <0.001	p <0.001	3.27E-13

Table H.59: Percentage Mean and Standard Deviation Path Fidelity for the Hybrid System Manipulating the Sphere in the Line Following Environmental Setup

Weighting	Line Following Paths		
	1	2	3
Explicit	**95.75% (10.08%)**	**91.50% (10.19%)**	**99.80% (20.00%)**
Original Explicit	90.75% (14.93%)	100% (∼0%)	99.40% (3.43%)
Sig. Diff	0.010	p <0.001	0.316
w = 0.25	**96.50% (9.41%)**	**86.17% (12.32%)**	**94.08% (11.56%)**
Original w = 0.25	78.02 (27.09%)	56.58% (25.54%)	79.35% (19.15%)
Sig. Diff	p <0.001	p <0.001	p <0.001
w = 0.5	**98.00% (6.82%)**	**87.33% (14.63%)**	**95.00% (11.50%)**
Original w = 0.5	86.48% (22.47%)	71.56% (25.02%)	90.18% (15.64%)
Sig. Diff	p <0.001	p <0.001	0.024
w = 0.75	**98.00% (7.69%)**	**98.00% (15.87%)**	**96.20% (9.30%)**
Original w = 0.75	93.25% (13.23%)	99.50% (2.86%)	91.65% (14.18%)
Sig. Diff	0.001	p <0.001	0.017
Implicit	**93.50% (12.62%)**	**80.17% (21.67%)**	**97.00% (8.23%)**
Original Implicit	93.00 (12.35%)	89.67% (14.17%)	96.57% (9.49%)
Sig. Diff	0.010	p <0.001	0.316

Table H.60: Percentage Mean and Standard Deviation Path Fidelity for the Hybrid System Manipulating the Cuboid in the Simple (SE) and Cluttered (CE) Environments

Weighting	Paths			
	1		2	3
	SE	CE	CE	CE
Explicit	**93.00% (1.15%)**	**75.73% (8.16%)**	**86.12% (1.18%)**	**75.12% (10.63%)**
Original Explicit	91.00% (2.12%)	64.09% (15.65%)	72.96% (8.33%)	69.04 (15.25%)
Sig. Diff	p <0.001	p <0.001	p <0.001	0.003
w = 0.25	**92.82% (1.13%)**	**73.10% (6.38%)**	**80.32% (N/A)**	**74.49% (7.49%)**
Original w = 0.25	91.24% (1.87%)	75.61% (7.70%)	75.69% (5.67%)	78.94% (5.27%)
Sig. Diff	p <0.001	0.057	0.257	p <0.001
w = 0.5	**92.89% (1.16%)**	**72.30% (5.25%)**	**78.46% (1.19%)**	**74.28% (8.36%)**
Original w = 0.5	91.72% (1.71%)	76.90% (6.14%)	75.59% (4.38%)	76.78% (5.26%)
Sig. Diff	p <0.001	p <0.001	0.010	0.228
w = 0.75	**92.76% (1.06%)**	**71.07% (5.67%)**	**75.27% (1.55%)**	**73.20% (7.54%)**
Original w = 0.75	91.33% (1.88%)	75.09% (5.39%)	73.03% (4.04%)	75.83% (4.32%)
Sig. Diff	p <0.001	p <0.001	0.057	0.046
Implicit	**92.20% (1.08%)**	**68.57% (5.34%)**	**75.17% (1.79%)**	**72.68% (7.45%)**
Original Implicit	91.79% (1.60%)	70.78% (3.55%)	69.44% (2.80%)	70.56% (3.35%)
Sig. Diff	0.236	0.001	p <0.001	0.003

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Table H.61: Percentage Mean and Standard Deviation Path Fidelity for the Hybrid System Manipulating the Cylinder in the Simple (SE) and Cluttered (CE) Environments

Weighting	Paths			
	1		2	3
	SE	CE	CE	CE
Explicit	**92.74% (1.03%)**	**76.22% (6.42%)**	**82.13% (0.77%)**	**75.68% (9.41%)**
Original Explicit	91.00% (2.12%)	64.09% (15.65%)	72.96% (8.33%)	69.04 (15.25%)
Sig. Diff	p <0.001	p <0.001	0.022	0.007
w = 0.25	**92.55% (1.28%)**	**72.00% (4.78%)**	**N/A**	**74.57% (7.39%)**
Original w = 0.25	91.24% (1.87%)	75.61% (7.70%)	75.69% (5.67%)	78.94% (5.27%)
Sig. Diff	p <0.001	0.008	N/A	p <0.001
w = 0.5	**92.66% (1.12%)**	**70.26% (5.58%)**	**N/A**	**72.20% (9.25%)**
Original w = 0.5	91.72% (1.71%)	76.90% (6.14%)	75.59% (4.38%)	76.78% (5.26%)
Sig. Diff	p <0.001	p <0.001	N/A	0.006
w = 0.75	**92.67% (1.14%)**	**69.04% (6.55%)**	**N/A**	**70.63% (8.76%)**
Original w = 0.75	91.33% (1.88%)	75.09% (5.39%)	73.03% (4.04%)	75.83% (4.32%)
Sig. Diff	0.609	p <0.001	N/A	p <0.001
Implicit	**92.50% (1.19%)**	**67.09% (7.11%)**	**N/A**	**67.09% (9.45%)**
Original Implicit	91.79% (1.60%)	70.78% (3.55%)	69.44% (2.80%)	70.56% (3.35%)
Sig. Diff	0.004	p <0.001	N/A	0.002

Table H.62: Percentage Mean and Standard Deviation Path Fidelity for the Hybrid System Manipulating the Sphere in the Simple (SE) and Cluttered (CE) Environments

Weighting	Paths			
	1		2	3
	SE	CE	CE	CE
Explicit	**90.68% (2.01%)**	**70.25% (9.78%)**	**76.14% (5.91%)**	**71.38% (11.63%)**
Original Explicit	91.00% (2.12%)	64.09% (15.65%)	72.96% (8.33%)	69.04 (15.25%)
Sig. Diff	0.266	0.003	0.008	0.437
w = 0.25	**91.16% (1.56%)**	**65.64% (5.92%)**	**68.28% (5.48%)**	**64.69% (8.53%)**
Original w = 0.25	91.24% (1.87%)	75.61% (7.70%)	75.69% (5.67%)	78.94% (5.27%)
Sig. Diff	0.775	p <0.001	p <0.001	p <0.001
w = 0.5	**91.14% (1.79%)**	**67.12% (5.71%)**	**69.70% (4.72%)**	**66.86% (9.01%)**
Original w = 0.5	91.72% (1.71%)	76.90% (6.14%)	75.59% (4.38%)	76.78% (5.26%)
Sig. Diff	0.018	p <0.001	p <0.001	p <0.001
w = 0.75	**91.62% (1.78%)**	**65.64% (5.92%)**	**68.28% (5.48%)**	**64.69% (8.53%)**
Original w = 0.75	91.33% (1.88%)	75.09% (5.39%)	73.03% (4.04%)	75.83% (4.32%)
Sig. Diff	0.317	p <0.001	p <0.001	p <0.001
Implicit	**91.77% (1.38%)**	**63.60% (6.18%)**	**67.87% (5.93%)**	**63.58% (7.38%)**
Original Implicit	91.79% (1.60%)	70.78% (3.55%)	69.44% (2.80%)	70.56% (3.35%)
Sig. Diff	p <0.001	p <0.001	0.353	p <0.001

Table H.63: Percentage Mean and Standard Deviation Path Fidelity for the Hybrid System Manipulating the Cuboid in the Randomly Generated Environments

Weighting	Randomly Generate Environments		
	1	2	3
Explicit	**74.97% (10.54%)**	**75.40% (8.64%)**	**65.87% (17.54%)**
Original Explicit	54.36% (23.85%)	56.36% (21.46%)	49.84% (23.26%)
Sig. Diff	p <0.001	p <0.001	p <0.001
w = 0.25	**71.09% (8.10%)**	**72.34% (7.76%)**	**54.44% (10.45%)**
Original w = 0.25	74.08% (8.48%)	71.04% (7.16%)	63.48% (14.71%)
Sig. Diff	0.036	0.012	p <0.001
w = 0.5	**70.78% (8.52%)**	**71.22% (6.94%)**	**58.46% (11.95%)**
Original w = 0.5	76.73% (8.01%)	71.77% (6.66%)	66.30% (15.08%)
Sig. Diff	p <	0.756	0.001
w = 0.75	**73.67% (8.71%)**	**71.78% (6.68%)**	**61.55% (9.54%)**
Original w = 0.75	75.83% (8.16%)	71.61% (7.05%)	64.37% (17.10%)
Sig. Diff	0.235	0.787	0.774
Implicit	**73.07% (7.93%)**	**69.73% (6.57%)**	**57.92% (8.35%)**
Original Implicit	75.31% (9.04%)	68.40% (5.61%)	61.80% (14.57%)
Sig. Diff	0.036	0.064	0.330

Table H.64: Percentage Mean and Standard Deviation Path Fidelity for the Hybrid System Manipulating the Cylinder in the Randomly Generated Environments

Weighting	Randomly Generated Environments		
	1	2	3
Explicit	**71.11% (11.37%)**	**70.55% (9.48%)**	**56.24% (15.13%)**
Original Explicit	54.36% (23.85%)	56.36% (21.46%)	49.84% (23.26%)
Sig. Diff	p <0.001	p <0.001	0.006
w = 0.25	**74.27% (7.98%)**	**73.00% (5.46%)**	**62.31% (8.58%)**
Original w = 0.25	74.08% (8.48%)	71.04% (7.16%)	63.48% (14.71%)
Sig. Diff	0.650	0.003	0.494
w = 0.5	**71.61% (7.70%)**	**69.77% (6.76%)**	**59.13% (8.42%)**
Original w = 0.5	76.73% (8.01%)	71.77% (6.66%)	66.30% (15.08%)
Sig. Diff	p <0.001	0.142	0.002
w = 0.75	**67.66% (9.98%)**	**69.28% (6.64%)**	**57.00% (10.09%)**
Original w = 0.75	75.83% (8.16%)	71.61% (7.05%)	64.37% (17.10%)
Sig. Diff	p <0.001	0.064	0.023
Implicit	**63.55% (11.27%)**	**66.19% (6.58%)**	**58.27% (9.52%)**
Original Implicit	75.31% (9.04%)	68.40% (5.61%)	61.80% (14.57%)
Sig. Diff	p <0.001	0.029	0.432

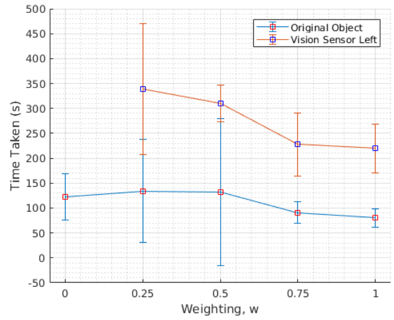
Table H.65: Percentage Mean and Standard Deviation Path Fidelity for the Hybrid System Manipulating the Sphere in the Randomly Generated Environments

Weighting	Randomly Generated Environments		
	1	2	3
Explicit	**68.73% (16.01%)**	**68.70% (12.18%)**	**61.21% (21.32%)**
Original Explicit	54.36% (23.85%)	56.36% (21.46%)	49.84% (23.26%)
Sig. Diff	p <0.001	p <0.001	0.001
w = 0.25	**66.59% (8.74%)**	**65.01% (6.80%)**	**56.06% (9.43%)**
Original w = 0.25	74.08% (8.48%)	71.04% (7.16%)	63.48% (14.71%)
Sig. Diff	0.915	0.369	0.496
w = 0.5	**68.28% (7.84%)**	**66.34% (7.47%)**	**60.38% (8.80%)**
Original w = 0.5	76.73% (8.01%)	71.77% (6.66%)	66.30% (15.08%)
Sig. Diff	p <0.001	p <0.001	0.011
w = 0.75	**66.59% (8.74%)**	**65.01% (6.80%)**	**56.06% (9.43%)**
Original w = 0.75	75.83% (8.16%)	71.61% (7.05%)	64.37% (17.10%)
Sig. Diff	p <0.001	p <0.001	0.006
Implicit	**64.27% (10.10%)**	**61.98% (8.62%)**	**51.58% (10.21%)**
Original Implicit	75.31% (9.04%)	68.40% (5.61%)	61.80% (14.57%)
Sig. Diff	p <0.001	p <0.001	p <0.001

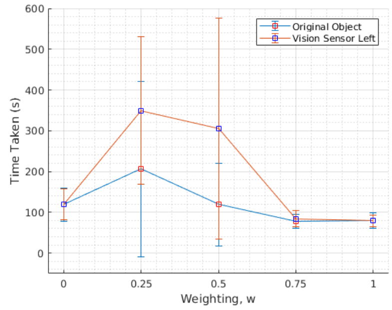
Appendix I

Graphical Results of Performance of Hybrid System with Objects of Different Size and Shape

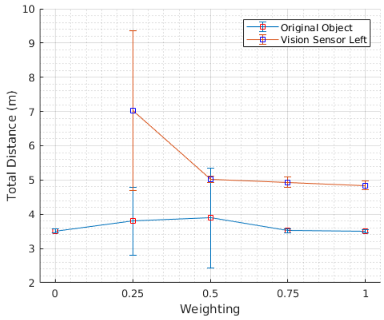
I.1 Vision Sensor Fault



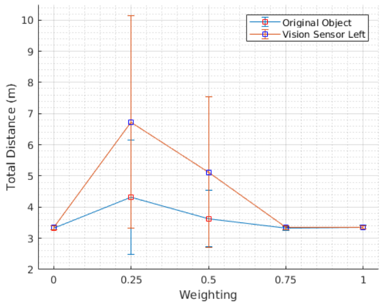
(a) Path 1: Mean Time Taken and Standard Deviation



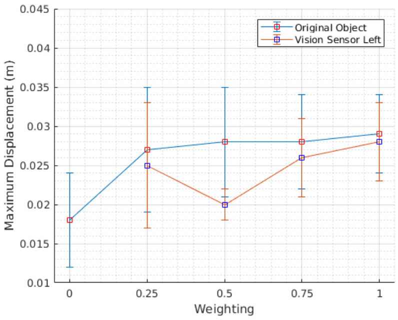
(b) Path 2: Mean Time Taken and Standard Deviation



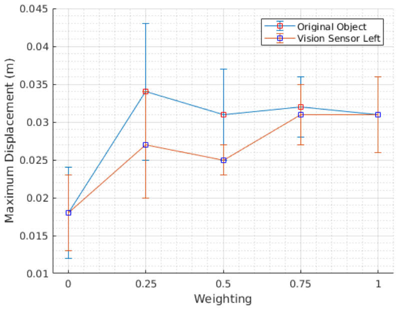
(c) Path 1: Mean Total Distance Travelled and Standard Deviation



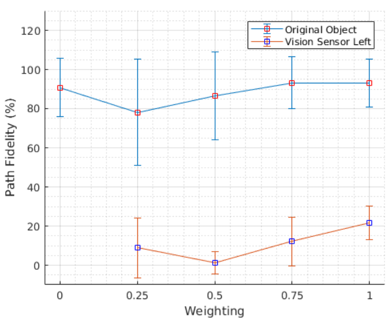
(d) Path 2: Mean Total Distance Travelled and Standard Deviation



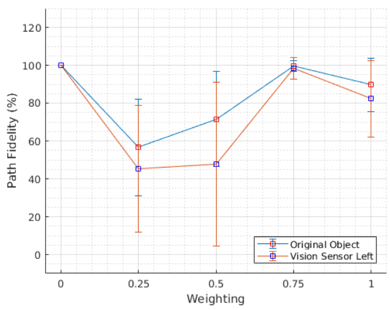
(e) Path 1: Mean Maximum Displacement and Standard Deviation



(f) Path 2: Mean Maximum Displacement and Standard Deviation

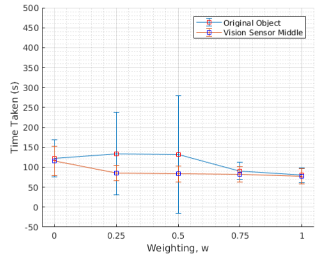


(g) Path 1: Mean Percentage Path Fidelity and Standard Deviation

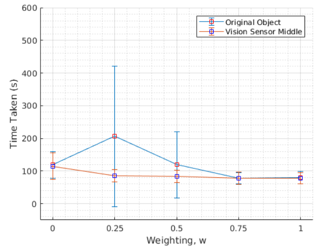


(h) Path 2: Mean Percentage Path Fidelity and Standard Deviation

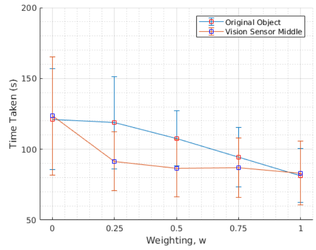
Figure I.1: Performance for the Hybrid System in the Line Following Environmental Setup for a vision sensor fault in the left vision sensor



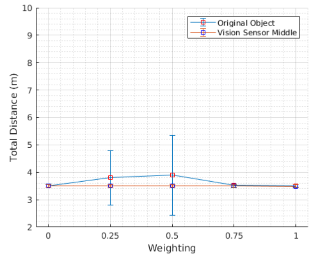
(a) Path 1: Mean Time Taken and Standard Deviation



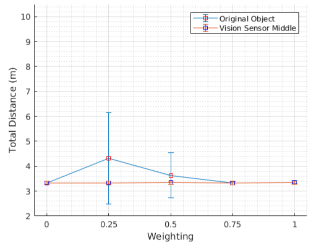
(b) Path 2: Mean Time Taken and Standard Deviation



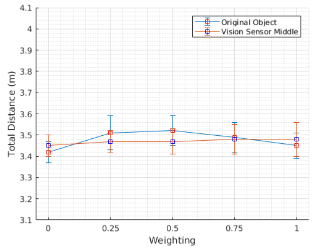
(c) Path 3: Mean Time Taken and Standard Deviation



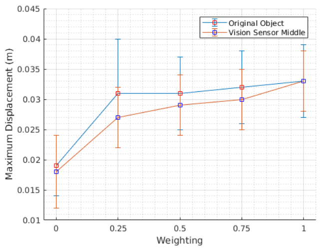
(d) Path 1: Mean Total Distance Travelled and Standard Deviation



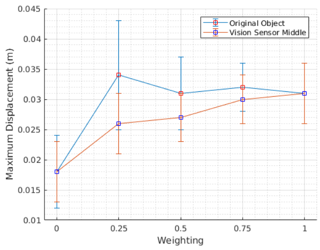
(e) Path 2: Mean Total Distance Travelled and Standard Deviation



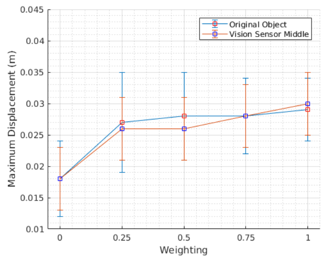
(f) Path 3: Mean Total Distance Travelled and Standard Deviation



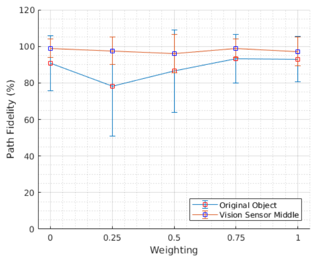
(g) Path 1: Mean Maximum Displacement and Standard Deviation



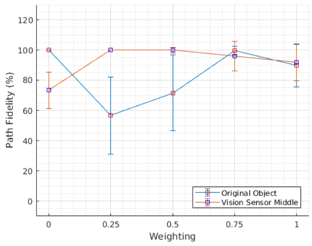
(h) Path 2: Mean Maximum Displacement and Standard Deviation



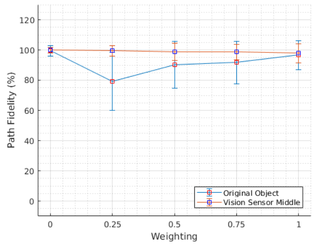
(i) Path 3: Mean Maximum Displacement and Standard Deviation



(j) Path 1: Mean Percentage Path Fidelity and Standard Deviation

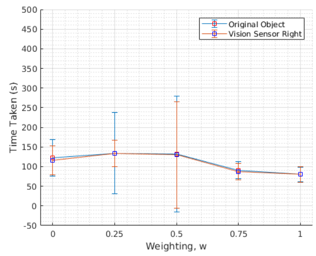


(k) Path 2: Mean Percentage Path Fidelity and Standard Deviation

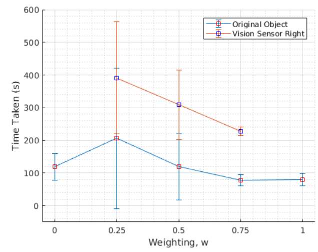


(l) Path 3: Mean Percentage Path Fidelity and Standard Deviation

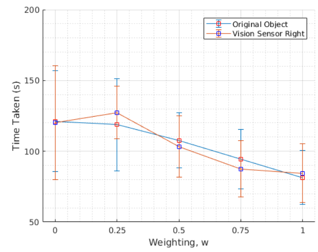
Figure I.2: Performance for the Hybrid System in the Line Following Environmental Setup for a vision sensor fault in the middle vision sensor



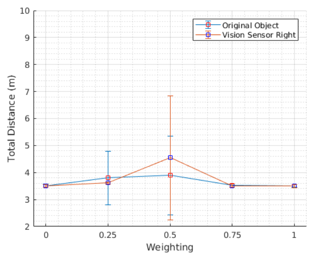
(a) Path 1: Mean Time Taken and Standard Deviation



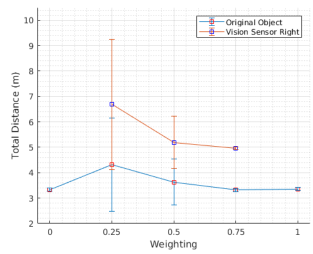
(b) Path 2: Mean Time Taken and Standard Deviation



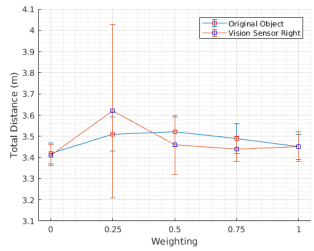
(c) Path 3: Mean Time Taken and Standard Deviation



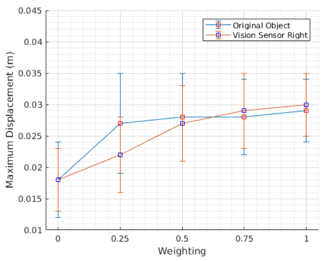
(d) Path 1: Mean Total Distance Travelled and Standard Deviation



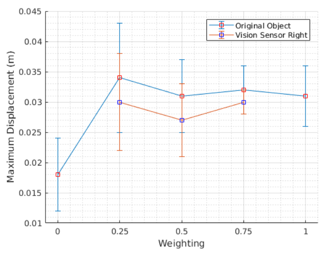
(e) Path 2: Mean Total Distance Travelled and Standard Deviation



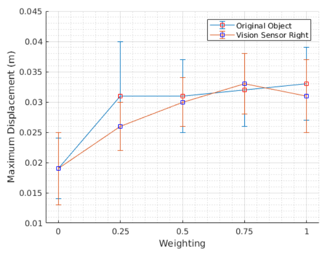
(f) Path 3: Mean Total Distance Travelled and Standard Deviation



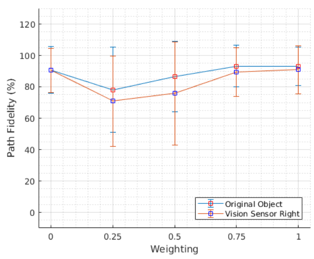
(g) Path 1: Mean Maximum Displacement and Standard Deviation



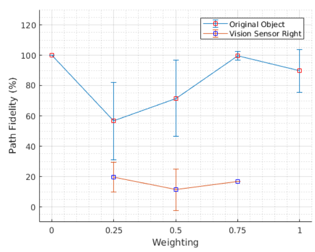
(h) Path 2: Mean Maximum Displacement and Standard Deviation



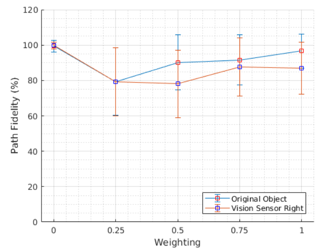
(i) Path 3: Mean Maximum Displacement and Standard Deviation



(j) Path 1: Mean Percentage Path Fidelity and Standard Deviation



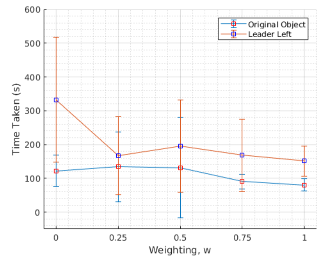
(k) Path 2: Mean Percentage Path Fidelity and Standard Deviation



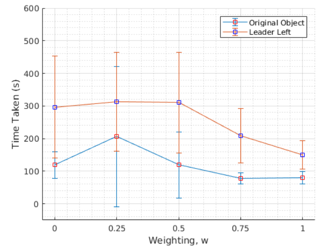
(l) Path 3: Mean Percentage Path Fidelity and Standard Deviation

Figure I.3: Performance for the Hybrid System in the Line Following Environmental Setup for a vision sensor fault in the right vision sensor

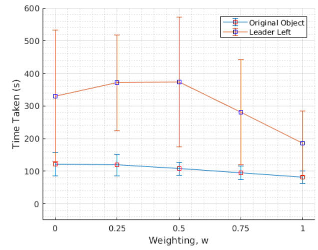
I.2 Partial Motor Fault in Leader Wheels



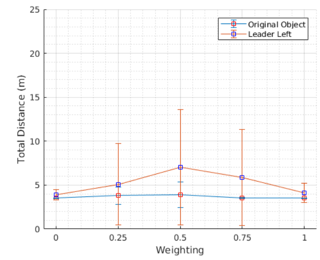
(a) Path 1: Mean Time Taken and Standard Deviation



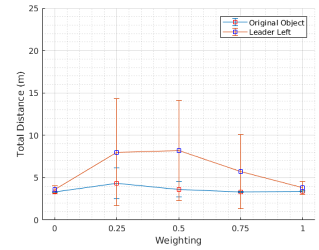
(b) Path 2: Mean Time Taken and Standard Deviation



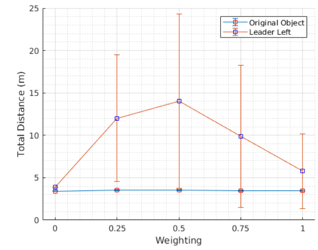
(c) Path 3: Mean Time Taken and Standard Deviation



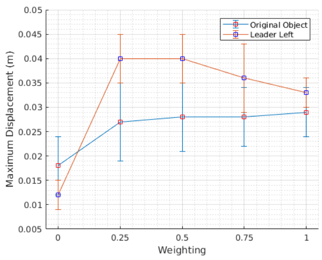
(d) Path 1: Mean Total Distance Travelled and Standard Deviation



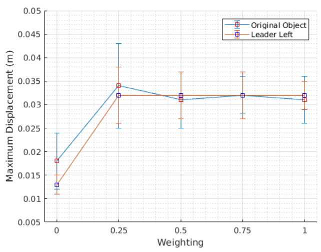
(e) Path 2: Mean Total Distance Travelled and Standard Deviation



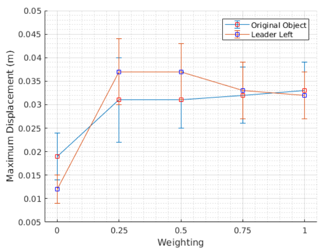
(f) Path 3: Mean Total Distance Travelled and Standard Deviation



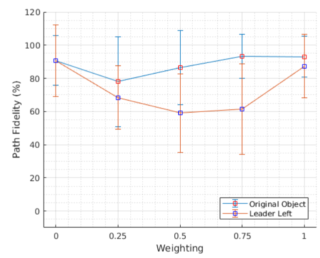
(g) Path 1: Mean Maximum Displacement and Standard Deviation



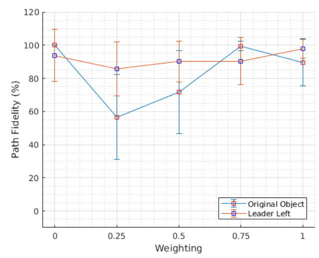
(h) Path 2: Mean Maximum Displacement and Standard Deviation



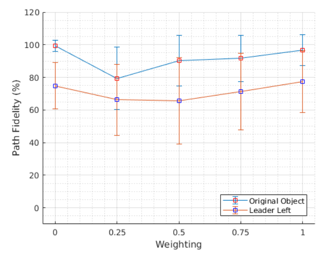
(i) Path 3: Mean Maximum Displacement and Standard Deviation



(j) Path 1: Mean Percentage Path Fidelity and Standard Deviation

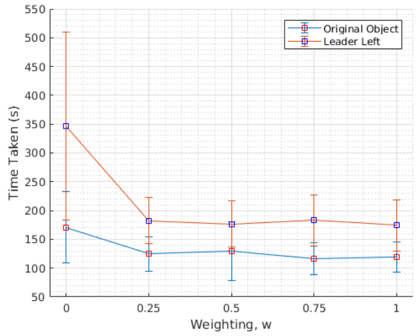


(k) Path 2: Mean Percentage Path Fidelity and Standard Deviation

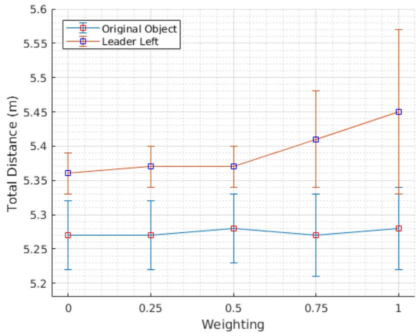


(l) Path 3: Mean Percentage Path Fidelity and Standard Deviation

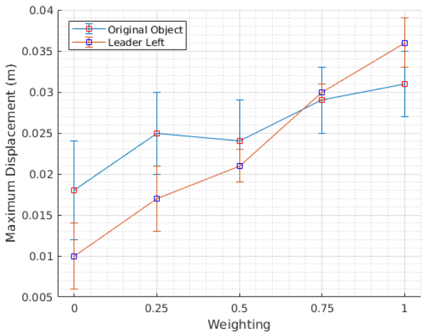
Figure I.4: Performance for the Hybrid System in the Line Following Environmental Setup for a partial motor fault in the leader's left wheel



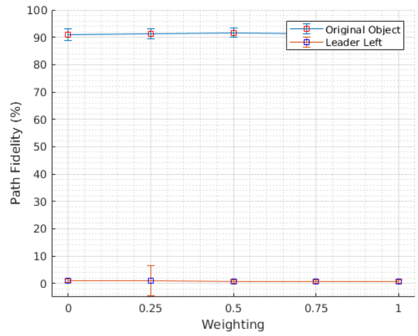
(a) Path 1: Mean Time Taken and Standard Deviation



(b) Path 1: Mean Total Distance Travelled and Standard Deviation

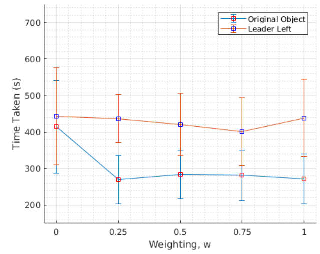


(c) Path 1: Mean Maximum Displacement and Standard Deviation

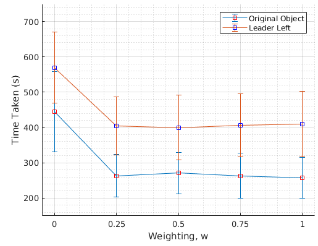


(d) Path 1: Mean Percentage Path Fidelity and Standard Deviation

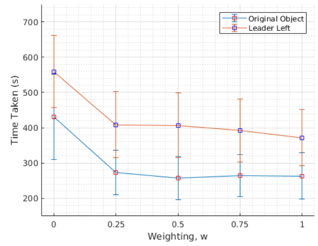
Figure I.5: Performance for the Hybrid System in the Simple Environment for a partial motor fault in the leader's left wheel



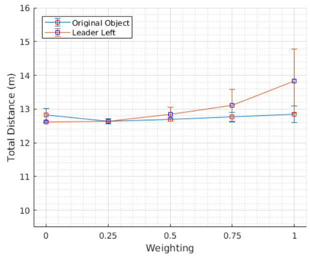
(a) Path 1: Mean Time Taken and Standard Deviation



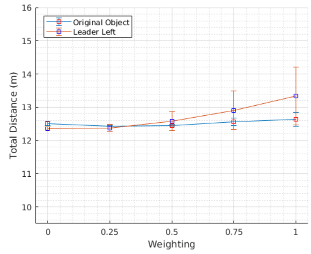
(b) Path 2: Mean Time Taken and Standard Deviation



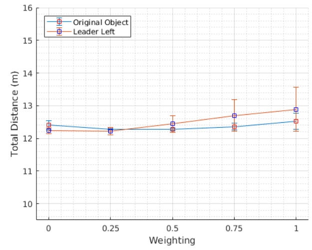
(c) Path 3: Mean Time Taken and Standard Deviation



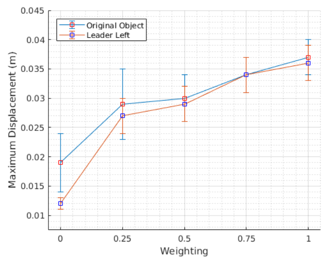
(d) Path 1: Mean Total Distance Travelled and Standard Deviation



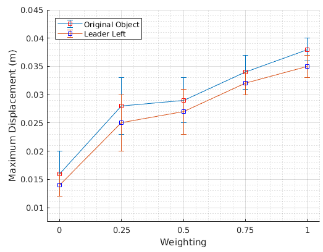
(e) Path 2: Mean Total Distance Travelled and Standard Deviation



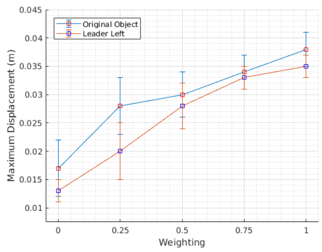
(f) Path 3: Mean Total Distance Travelled and Standard Deviation



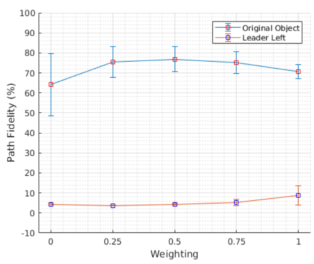
(g) Path 1: Mean Maximum Displacement and Standard Deviation



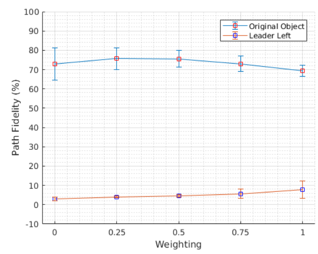
(h) Path 2: Mean Maximum Displacement and Standard Deviation



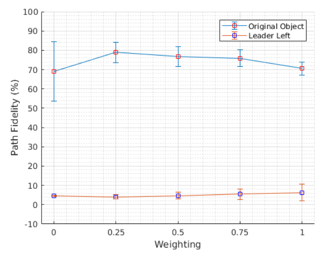
(i) Path 3: Mean Maximum Displacement and Standard Deviation



(j) Path 1: Mean Percentage Path Fidelity and Standard Deviation

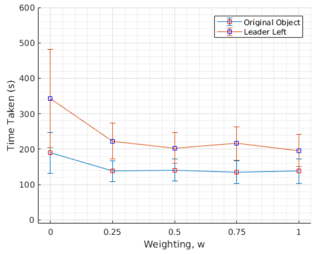


(k) Path 2: Mean Percentage Path Fidelity and Standard Deviation

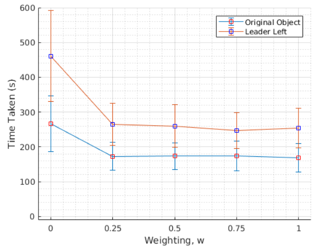


(l) Path 3: Mean Percentage Path Fidelity and Standard Deviation

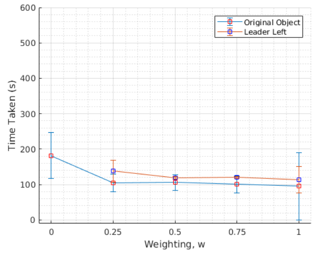
Figure I.6: Performance for the Hybrid System in the Cluttered Environment for a partial motor fault in the leader's left wheel



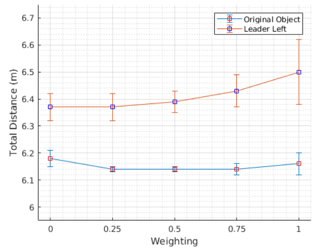
(a) Path 1: Mean Time Taken and Standard Deviation



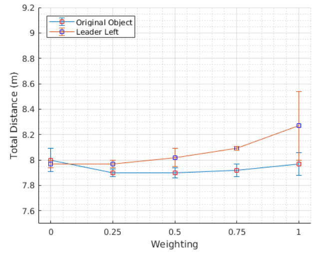
(b) Path 2: Mean Time Taken and Standard Deviation



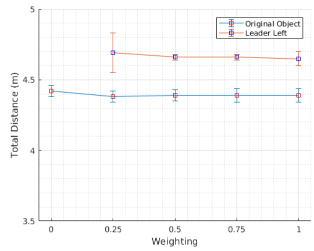
(c) Path 3: Mean Time Taken and Standard Deviation



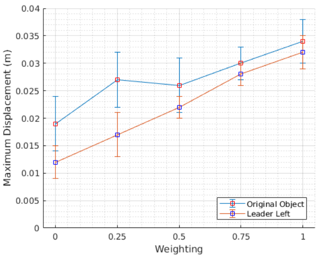
(d) Path 1: Mean Total Distance Travelled and Standard Deviation



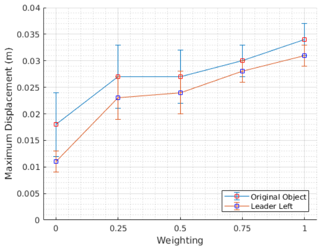
(e) Path 2: Mean Total Distance Travelled and Standard Deviation



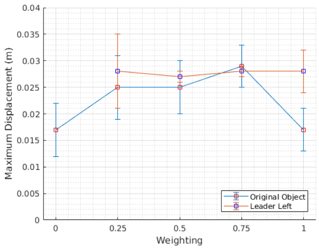
(f) Path 3: Mean Total Distance Travelled and Standard Deviation



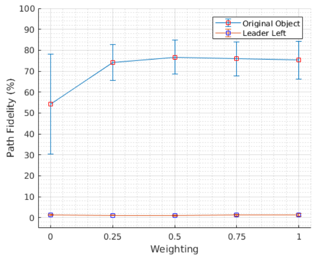
(g) Path 1: Mean Maximum Displacement and Standard Deviation



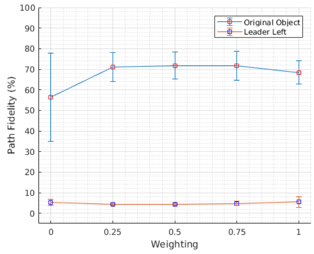
(h) Path 2: Mean Maximum Displacement and Standard Deviation



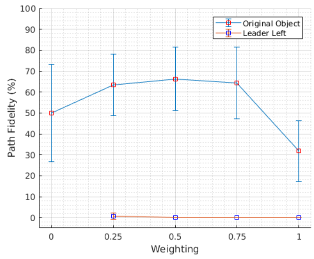
(i) Path 3: Mean Maximum Displacement and Standard Deviation



(j) Path 1: Mean Percentage Path Fidelity and Standard Deviation

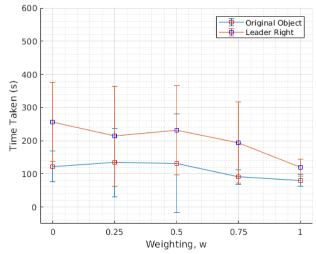


(k) Path 2: Mean Percentage Path Fidelity and Standard Deviation

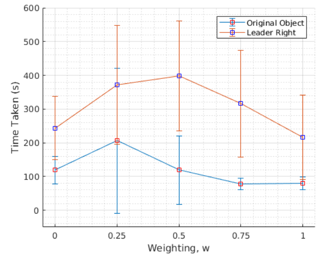


(l) Path 3: Mean Percentage Path Fidelity and Standard Deviation

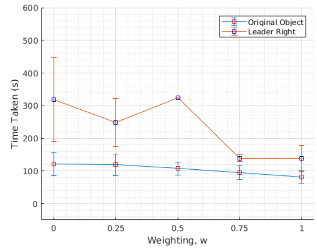
Figure I.7: Performance for the Hybrid System in the Randomly Generated Environments for a partial motor fault in the leader's left wheel



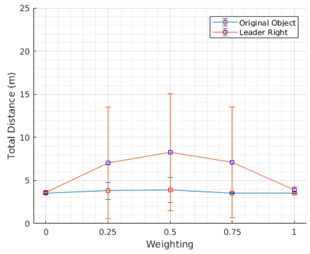
(a) Path 1: Mean Time Taken and Standard Deviation



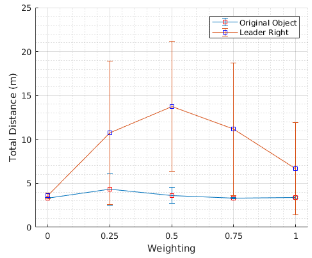
(b) Path 2: Mean Time Taken and Standard Deviation



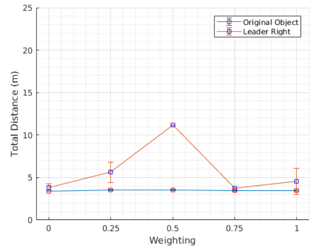
(c) Path 3: Mean Time Taken and Standard Deviation



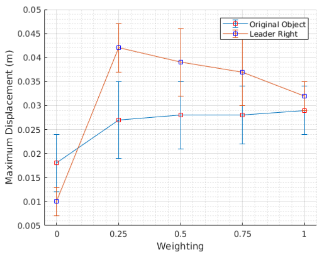
(d) Path 1: Mean Total Distance Travelled and Standard Deviation



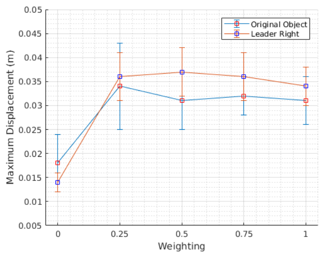
(e) Path 2: Mean Total Distance Travelled and Standard Deviation



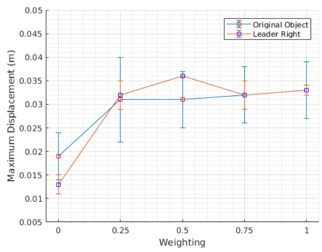
(f) Path 3: Mean Total Distance Travelled and Standard Deviation



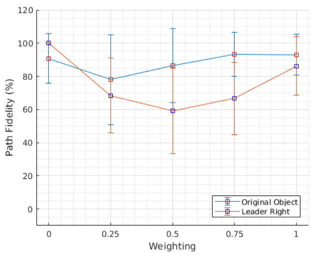
(g) Path 1: Mean Maximum Displacement and Standard Deviation



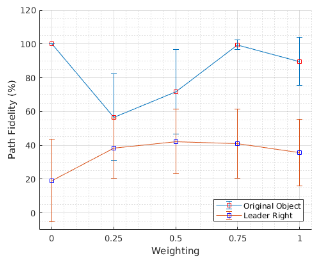
(h) Path 2: Mean Maximum Displacement and Standard Deviation



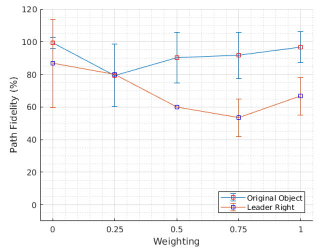
(i) Path 3: Mean Maximum Displacement and Standard Deviation



(j) Path 1: Mean Percentage Path Fidelity and Standard Deviation

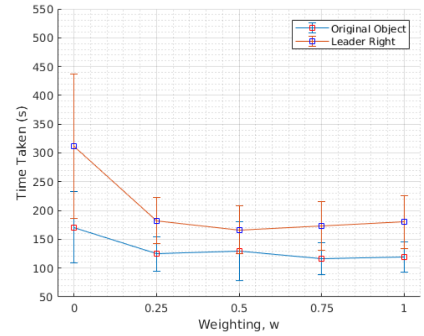


(k) Path 2: Mean Percentage Path Fidelity and Standard Deviation

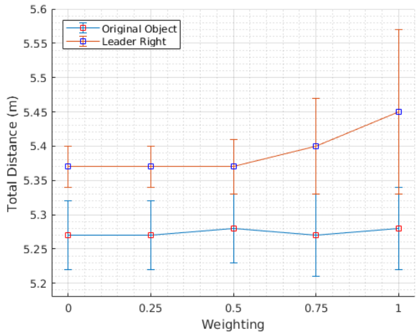


(l) Path 3: Mean Percentage Path Fidelity and Standard Deviation

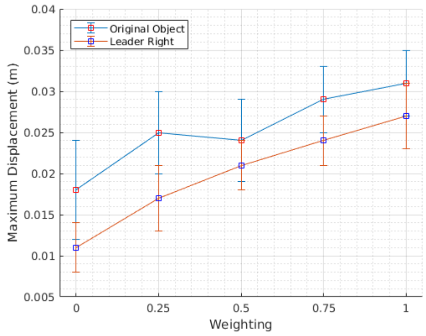
Figure I.8: Performance for the Hybrid System in the Line Following Environmental Setup for a partial motor fault in the leader's right wheel



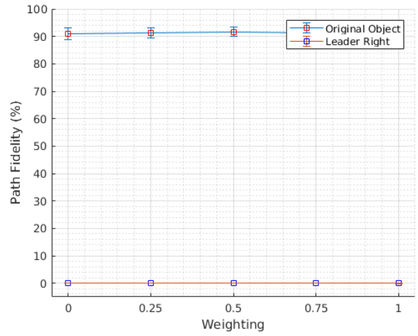
(a) Path 1: Mean Time Taken and Standard Deviation



(b) Path 1: Mean Total Distance Travelled and Standard Deviation

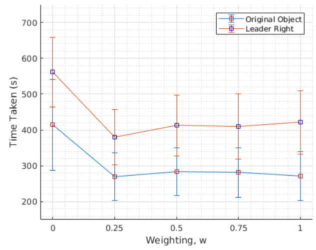


(c) Path 1: Mean Maximum Displacement and Standard Deviation

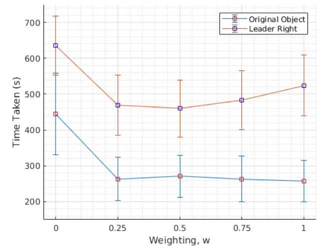


(d) Path 1: Mean Percentage Path Fidelity and Standard Deviation

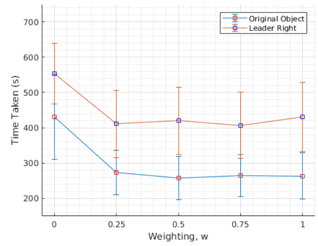
Figure I.9: Performance for the Hybrid System in the Simple Environment for a partial motor fault in the leader's right wheel



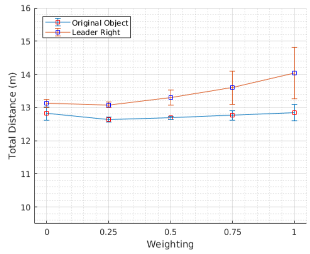
(a) Path 1: Mean Time Taken and Standard Deviation



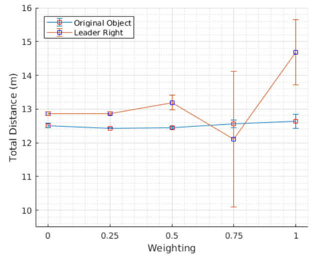
(b) Path 2: Mean Time Taken and Standard Deviation



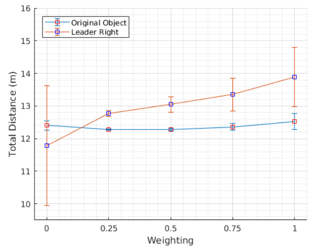
(c) Path 3: Mean Time Taken and Standard Deviation



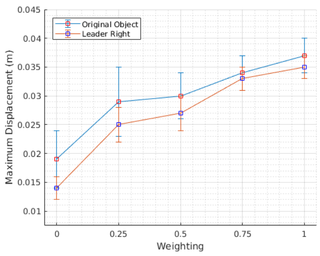
(d) Path 1: Mean Total Distance Travelled and Standard Deviation



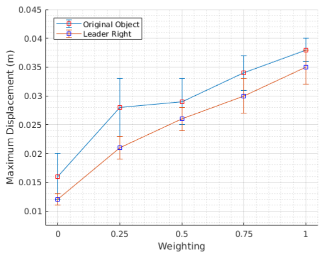
(e) Path 2: Mean Total Distance Travelled and Standard Deviation



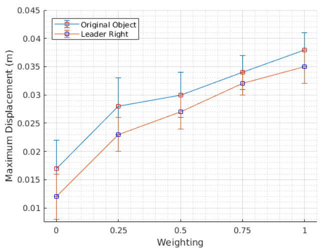
(f) Path 3: Mean Total Distance Travelled and Standard Deviation



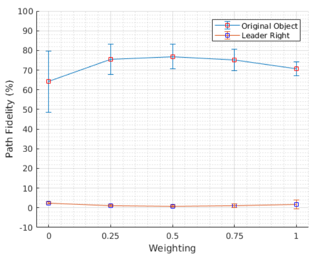
(g) Path 1: Mean Maximum Displacement and Standard Deviation



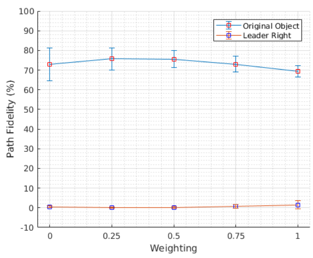
(h) Path 2: Mean Maximum Displacement and Standard Deviation



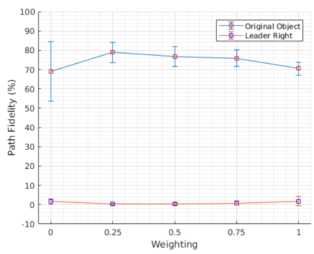
(i) Path 3: Mean Maximum Displacement and Standard Deviation



(j) Path 1: Mean Percentage Path Fidelity and Standard Deviation

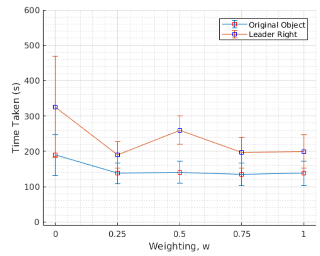


(k) Path 2: Mean Percentage Path Fidelity and Standard Deviation

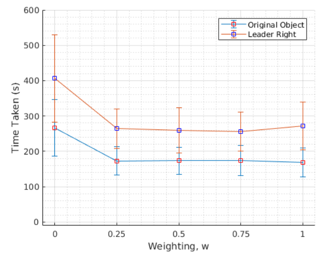


(l) Path 3: Mean Percentage Path Fidelity and Standard Deviation

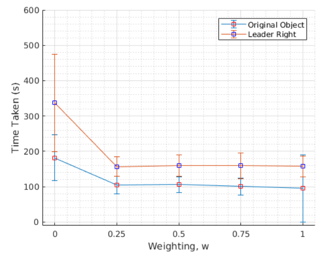
Figure I.10: Performance for the Hybrid System in the Cluttered Environment for a partial motor fault in the leader's right wheel



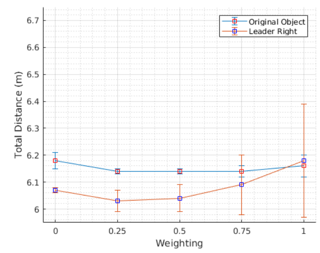
(a) Path 1: Mean Time Taken and Standard Deviation



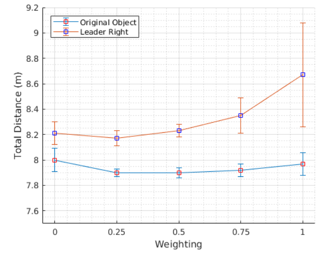
(b) Path 2: Mean Time Taken and Standard Deviation



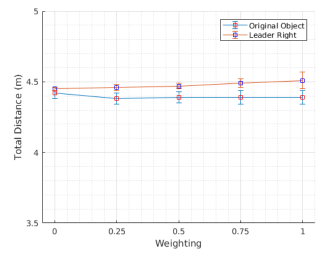
(c) Path 3: Mean Time Taken and Standard Deviation



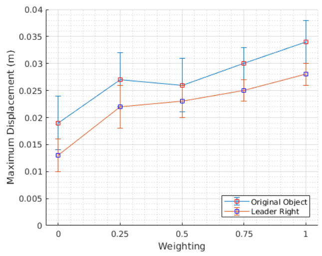
(d) Path 1: Mean Total Distance Travelled and Standard Deviation



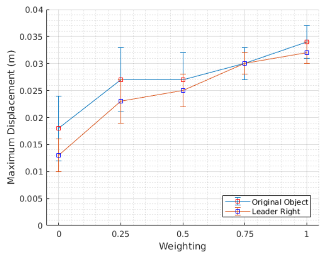
(e) Path 2: Mean Total Distance Travelled and Standard Deviation



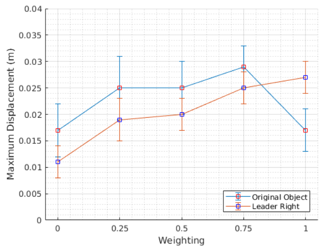
(f) Path 3: Mean Total Distance Travelled and Standard Deviation



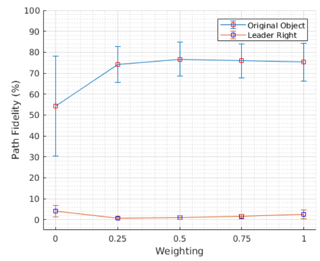
(g) Path 1: Mean Maximum Displacement and Standard Deviation



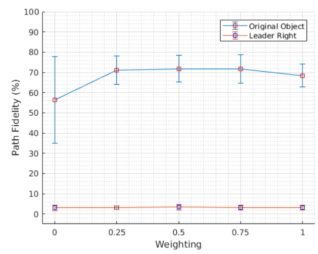
(h) Path 2: Mean Maximum Displacement and Standard Deviation



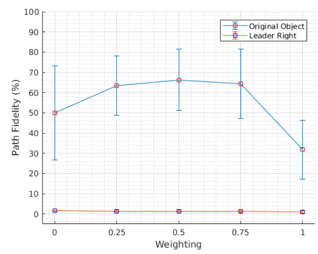
(i) Path 3: Mean Maximum Displacement and Standard Deviation



(j) Path 1: Mean Percentage Path Fidelity and Standard Deviation



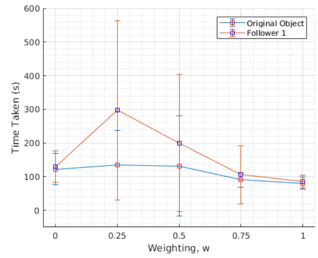
(k) Path 2: Mean Percentage Path Fidelity and Standard Deviation



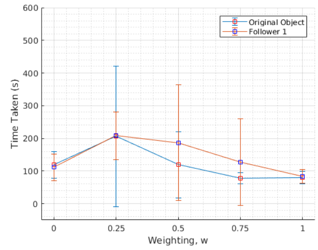
(l) Path 3: Mean Percentage Path Fidelity and Standard Deviation

Figure I.11: Performance for the Hybrid System in the Randomly Generated Environments for a partial motor fault in the leader's right wheel

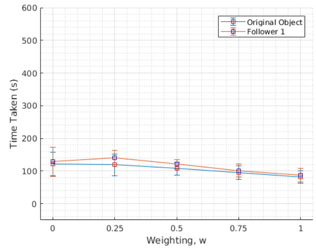
I.3 Partial Motor Fault in Follower Wheels



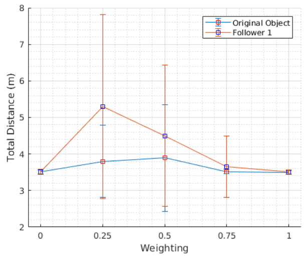
(a) Path 1: Mean Time Taken and Standard Deviation



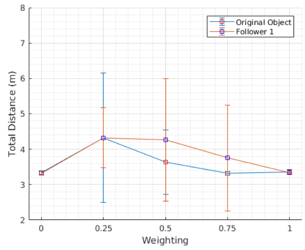
(b) Path 2: Mean Time Taken and Standard Deviation



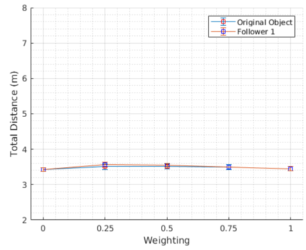
(c) Path 3: Mean Time Taken and Standard Deviation



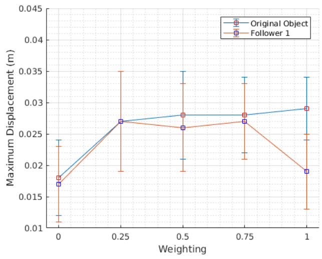
(d) Path 1: Mean Total Distance Travelled and Standard Deviation



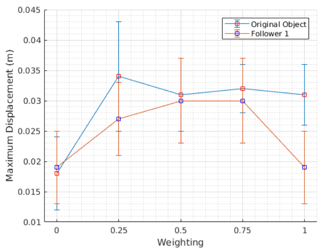
(e) Path 2: Mean Total Distance Travelled and Standard Deviation



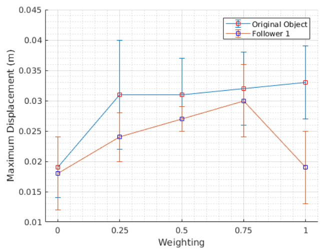
(f) Path 3: Mean Total Distance Travelled and Standard Deviation



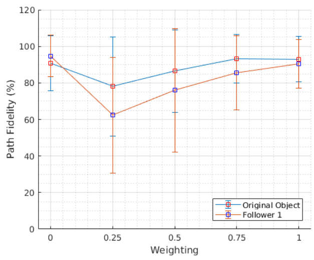
(g) Path 1: Mean Maximum Displacement and Standard Deviation



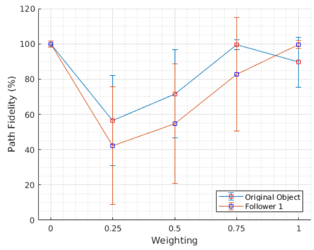
(h) Path 2: Mean Maximum Displacement and Standard Deviation



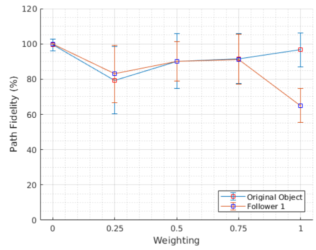
(i) Path 3: Mean Maximum Displacement and Standard Deviation



(j) Path 1: Mean Percentage Path Fidelity and Standard Deviation

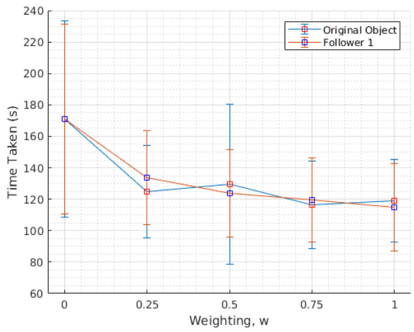


(k) Path 2: Mean Percentage Path Fidelity and Standard Deviation

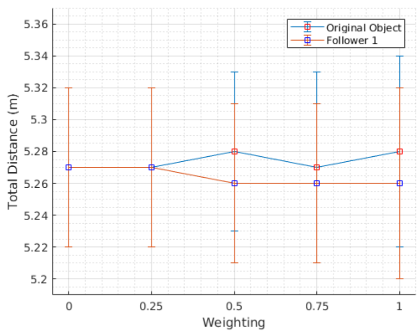


(l) Path 3: Mean Percentage Path Fidelity and Standard Deviation

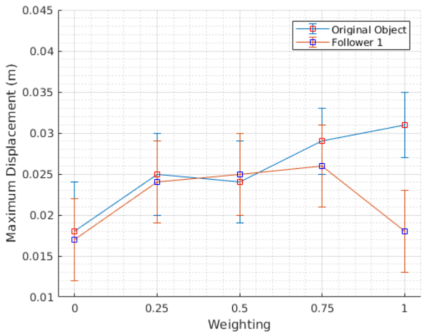
Figure I.12: Performance for the Hybrid System in the Line Following Environmental Setup for a partial motor fault in the follower's wheel 1



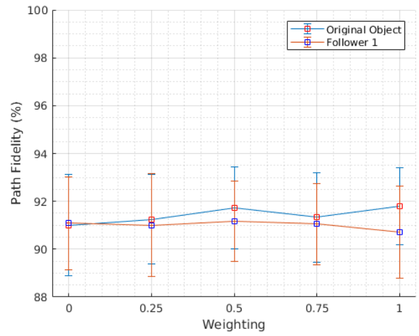
(a) Path 1: Mean Time Taken and Standard Deviation



(b) Path 1: Mean Total Distance Travelled and Standard Deviation

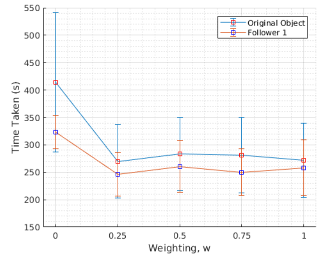


(c) Path 1: Mean Maximum Displacement and Standard Deviation

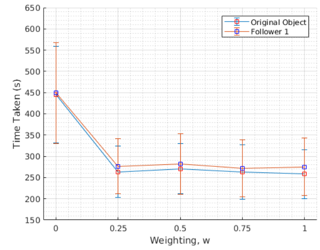


(d) Path 1: Mean Percentage Path Fidelity and Standard Deviation

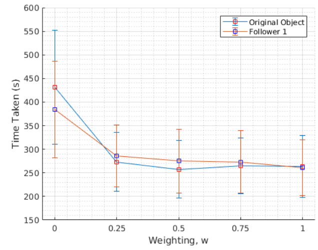
Figure I.13: Performance for the Hybrid System in the Simple Environment for a partial motor fault in the follower's wheel 1



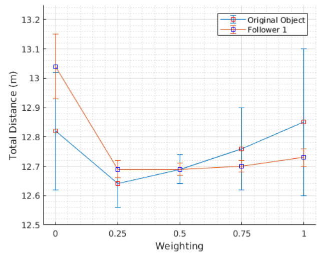
(a) Path 1: Mean Time Taken and Standard Deviation



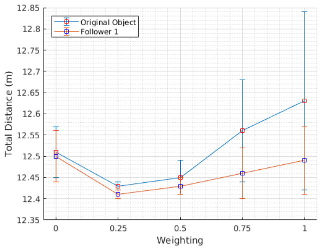
(b) Path 2: Mean Time Taken and Standard Deviation



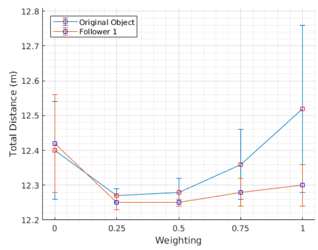
(c) Path 3: Mean Time Taken and Standard Deviation



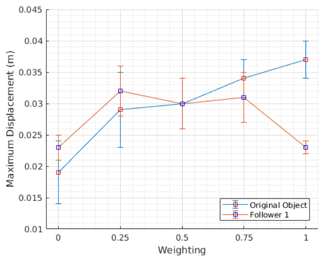
(d) Path 1: Mean Total Distance Travelled and Standard Deviation



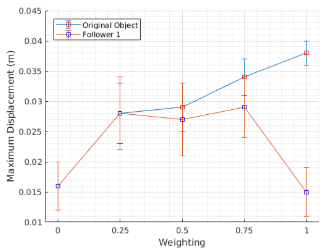
(e) Path 2: Mean Total Distance Travelled and Standard Deviation



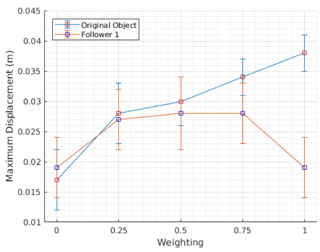
(f) Path 3: Mean Total Distance Travelled and Standard Deviation



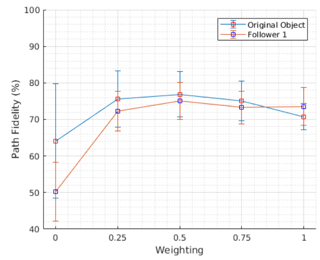
(g) Path 1: Mean Maximum Displacement and Standard Deviation



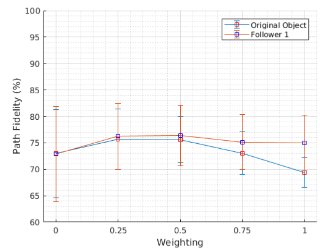
(h) Path 2: Mean Maximum Displacement and Standard Deviation



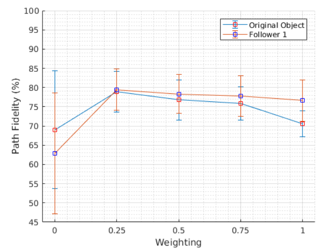
(i) Path 3: Mean Maximum Displacement and Standard Deviation



(j) Path 1: Mean Percentage Path Fidelity and Standard Deviation

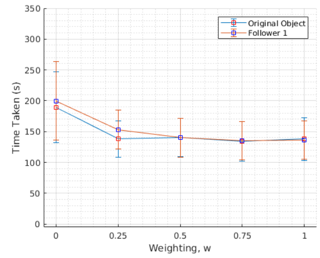


(k) Path 2: Mean Percentage Path Fidelity and Standard Deviation

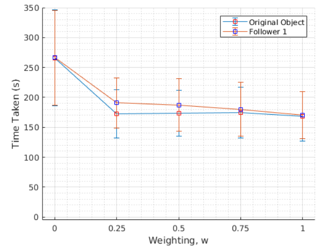


(l) Path 3: Mean Percentage Path Fidelity and Standard Deviation

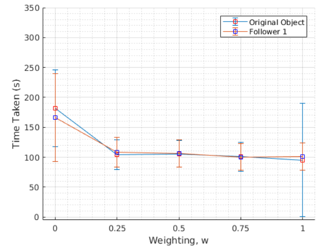
Figure I.14: Performance for the Hybrid System in the Cluttered Environment for a partial motor fault in the follower's wheel 1



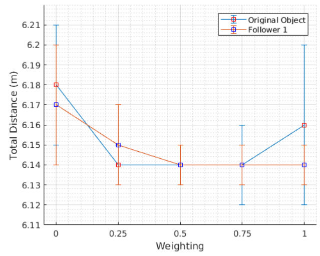
(a) Path 1: Mean Time Taken and Standard Deviation



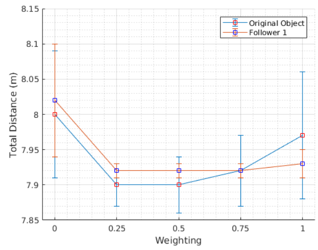
(b) Path 2: Mean Time Taken and Standard Deviation



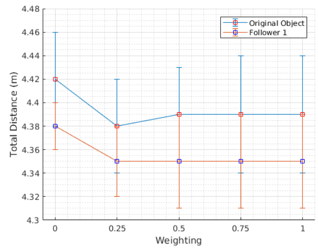
(c) Path 3: Mean Time Taken and Standard Deviation



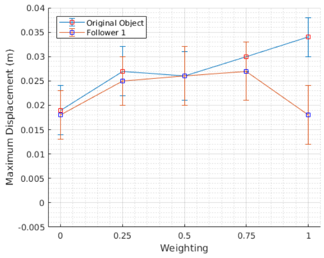
(d) Path 1: Mean Total Distance Travelled and Standard Deviation



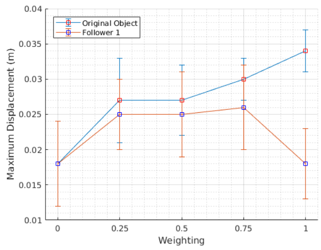
(e) Path 2: Mean Total Distance Travelled and Standard Deviation



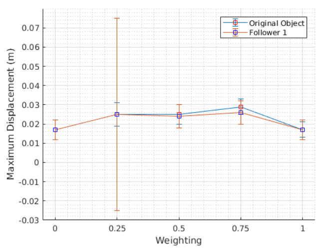
(f) Path 3: Mean Total Distance Travelled and Standard Deviation



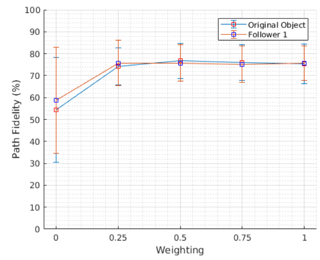
(g) Path 1: Mean Maximum Displacement and Standard Deviation



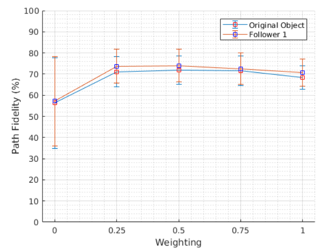
(h) Path 2: Mean Maximum Displacement and Standard Deviation



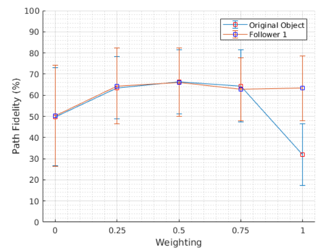
(i) Path 3: Mean Maximum Displacement and Standard Deviation



(j) Path 1: Mean Percentage Path Fidelity and Standard Deviation

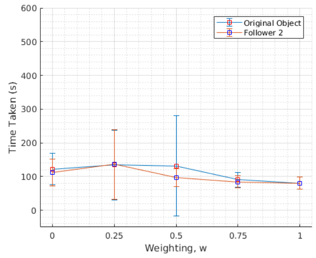


(k) Path 2: Mean Percentage Path Fidelity and Standard Deviation

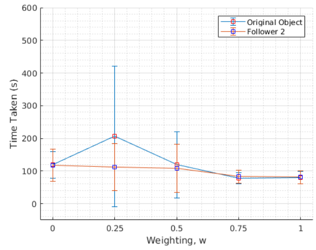


(l) Path 3: Mean Percentage Path Fidelity and Standard Deviation

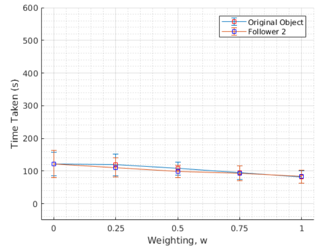
Figure I.15: Performance for the Hybrid System in the Randomly Generated Environments for a partial motor fault in the follower's wheel 1



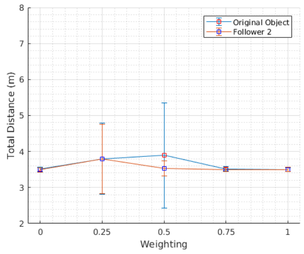
(a) Path 1: Mean Time Taken and Standard Deviation



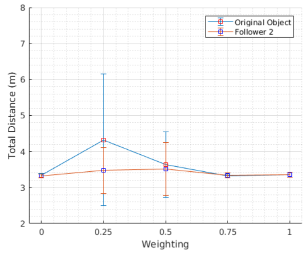
(b) Path 2: Mean Time Taken and Standard Deviation



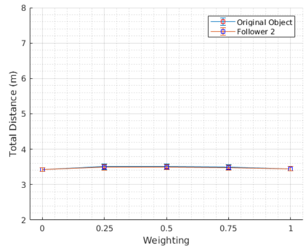
(c) Path 3: Mean Time Taken and Standard Deviation



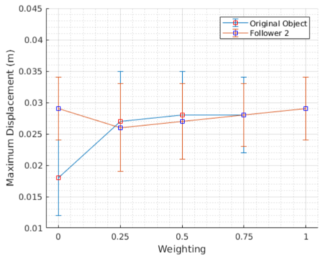
(d) Path 1: Mean Total Distance Travelled and Standard Deviation



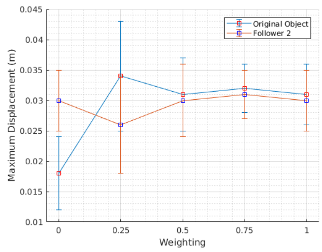
(e) Path 2: Mean Total Distance Travelled and Standard Deviation



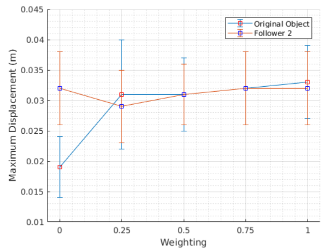
(f) Path 3: Mean Total Distance Travelled and Standard Deviation



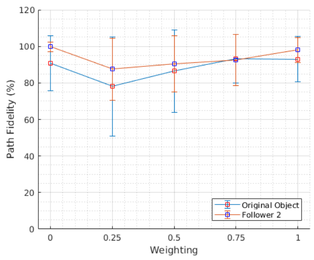
(g) Path 1: Mean Maximum Displacement and Standard Deviation



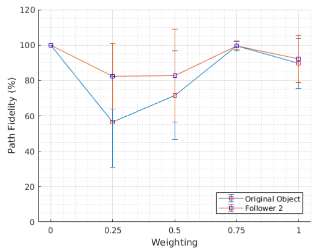
(h) Path 2: Mean Maximum Displacement and Standard Deviation



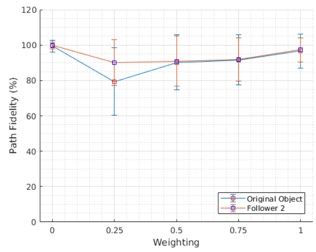
(i) Path 3: Mean Maximum Displacement and Standard Deviation



(j) Path 1: Mean Percentage Path Fidelity and Standard Deviation

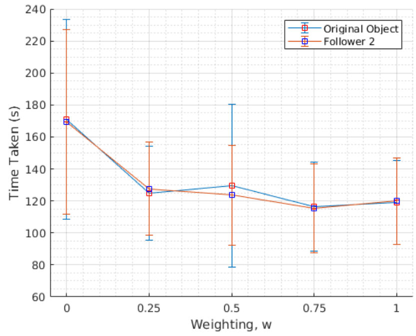


(k) Path 2: Mean Percentage Path Fidelity and Standard Deviation

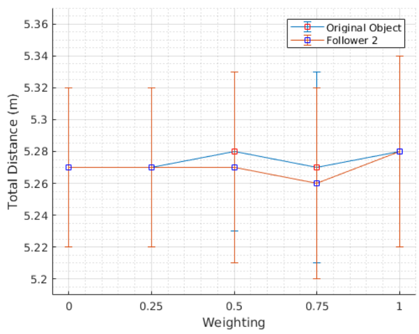


(l) Path 3: Mean Percentage Path Fidelity and Standard Deviation

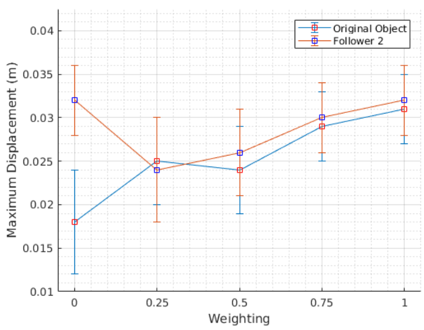
Figure I.16: Performance for the Hybrid System in the Line Following Environmental Setup for a partial motor fault in the follower's wheel 2



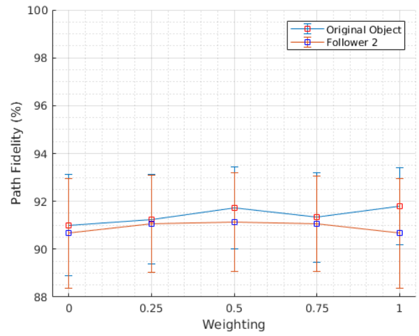
(a) Path 1: Mean Time Taken and Standard Deviation



(b) Path 1: Mean Total Distance Travelled and Standard Deviation

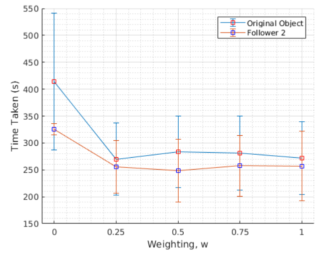


(c) Path 1: Mean Maximum Displacement and Standard Deviation

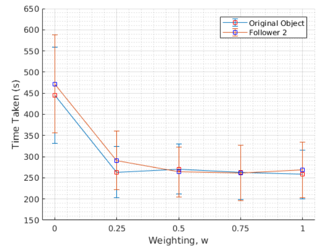


(d) Path 1: Mean Percentage Path Fidelity and Standard Deviation

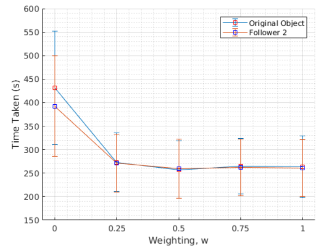
Figure I.17: Performance for the Hybrid System in the Simple Environment for a partial motor fault in the follower's wheel 2



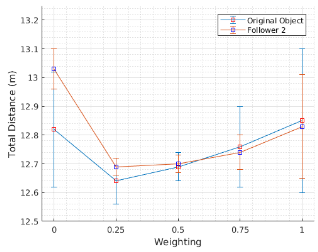
(a) Path 1: Mean Time Taken and Standard Deviation



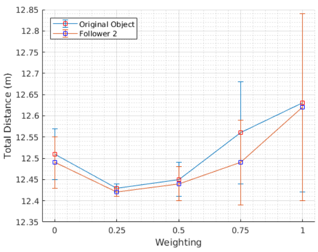
(b) Path 2: Mean Time Taken and Standard Deviation



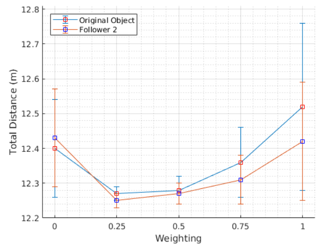
(c) Path 3: Mean Time Taken and Standard Deviation



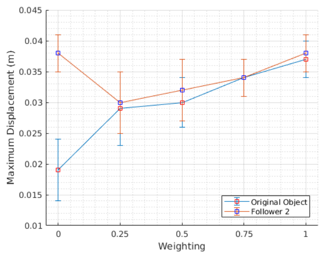
(d) Path 1: Mean Total Distance Travelled and Standard Deviation



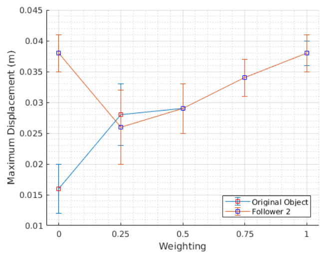
(e) Path 2: Mean Total Distance Travelled and Standard Deviation



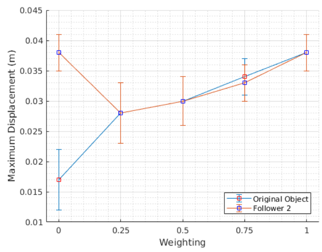
(f) Path 3: Mean Total Distance Travelled and Standard Deviation



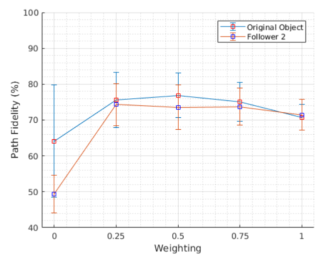
(g) Path 1: Mean Maximum Displacement and Standard Deviation



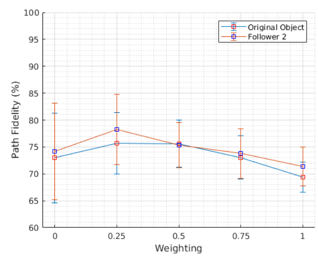
(h) Path 2: Mean Maximum Displacement and Standard Deviation



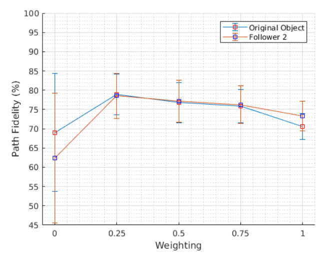
(i) Path 3: Mean Maximum Displacement and Standard Deviation



(j) Path 1: Mean Percentage Path Fidelity and Standard Deviation

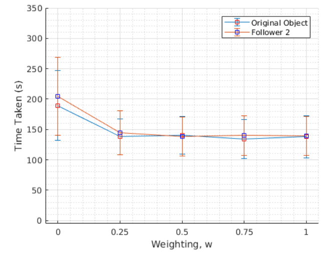


(k) Path 2: Mean Percentage Path Fidelity and Standard Deviation

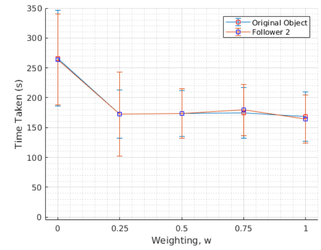


(l) Path 3: Mean Percentage Path Fidelity and Standard Deviation

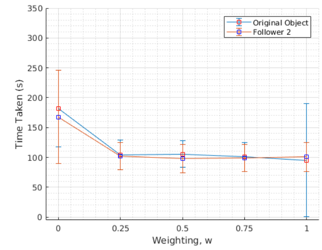
Figure I.18: Performance for the Hybrid System in the Cluttered Environment for a partial motor fault in the follower's wheel 2



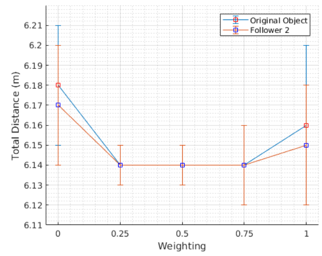
(a) Path 1: Mean Time Taken and Standard Deviation



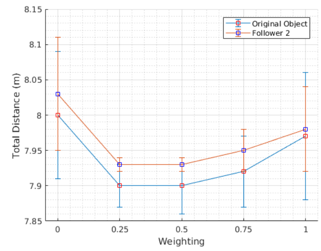
(b) Path 2: Mean Time Taken and Standard Deviation



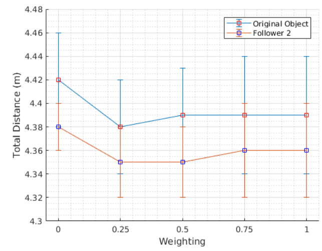
(c) Path 3: Mean Time Taken and Standard Deviation



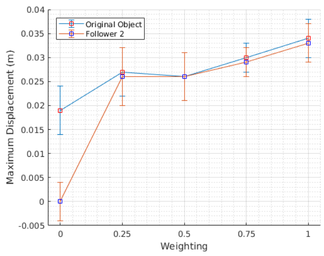
(d) Path 1: Mean Total Distance Travelled and Standard Deviation



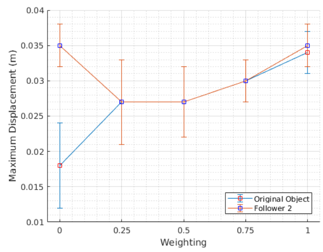
(e) Path 2: Mean Total Distance Travelled and Standard Deviation



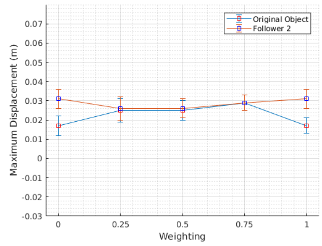
(f) Path 3: Mean Total Distance Travelled and Standard Deviation



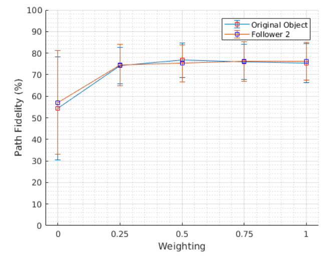
(g) Path 1: Mean Maximum Displacement and Standard Deviation



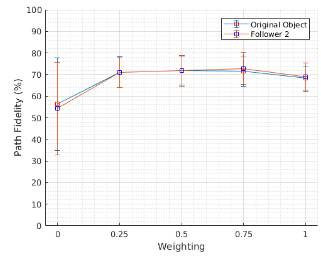
(h) Path 2: Mean Maximum Displacement and Standard Deviation



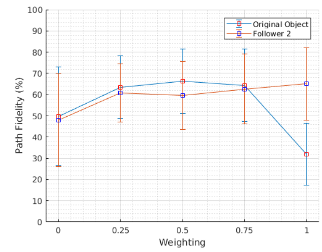
(i) Path 3: Mean Maximum Displacement and Standard Deviation



(j) Path 1: Mean Percentage Path Fidelity and Standard Deviation

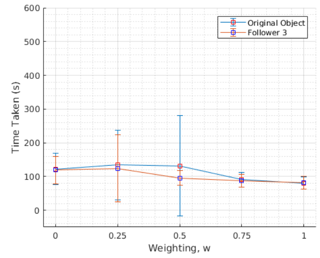


(k) Path 2: Mean Percentage Path Fidelity and Standard Deviation

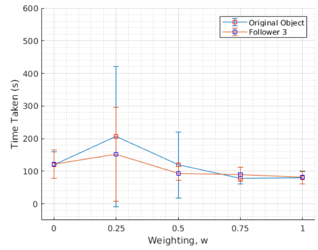


(l) Path 3: Mean Percentage Path Fidelity and Standard Deviation

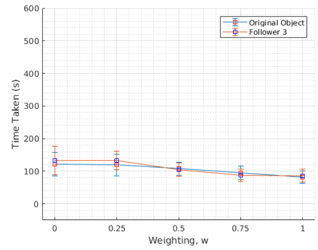
Figure I.19: Performance for the Hybrid System in the Randomly Generated Environments for a partial motor fault in the follower's wheel 2



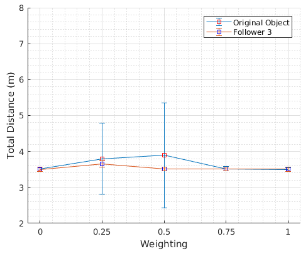
(a) Path 1: Mean Time Taken and Standard Deviation



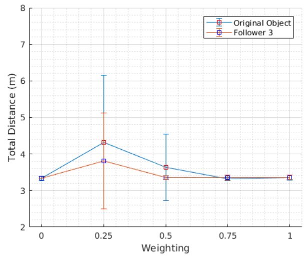
(b) Path 2: Mean Time Taken and Standard Deviation



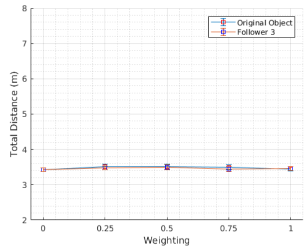
(c) Path 3: Mean Time Taken and Standard Deviation



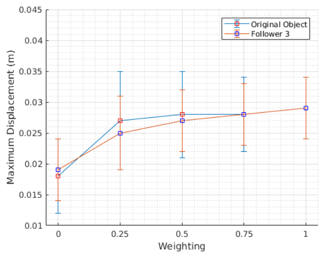
(d) Path 1: Mean Total Distance Travelled and Standard Deviation



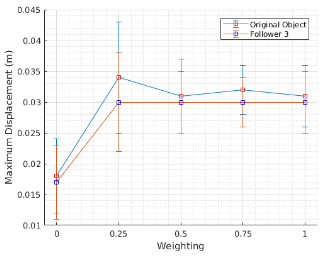
(e) Path 2: Mean Total Distance Travelled and Standard Deviation



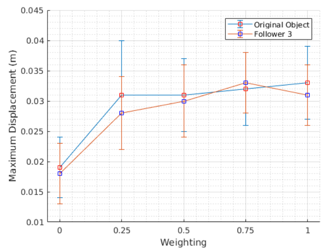
(f) Path 3: Mean Total Distance Travelled and Standard Deviation



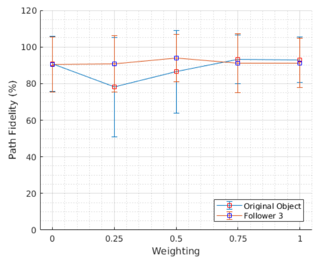
(g) Path 1: Mean Maximum Displacement and Standard Deviation



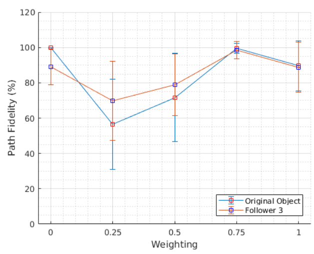
(h) Path 2: Mean Maximum Displacement and Standard Deviation



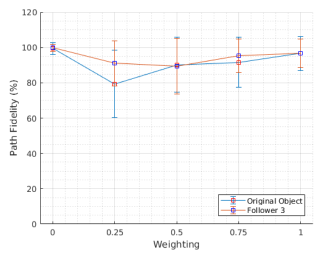
(i) Path 3: Mean Maximum Displacement and Standard Deviation



(j) Path 1: Mean Percentage Path Fidelity and Standard Deviation

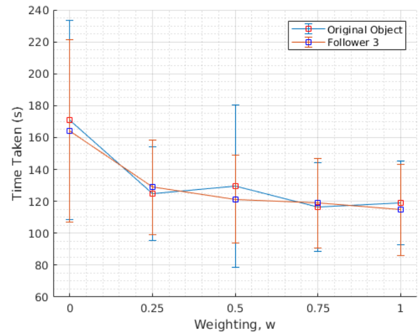


(k) Path 2: Mean Percentage Path Fidelity and Standard Deviation

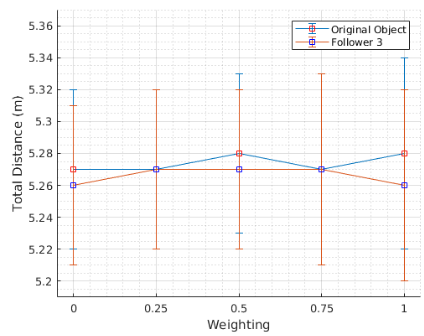


(l) Path 3: Mean Percentage Path Fidelity and Standard Deviation

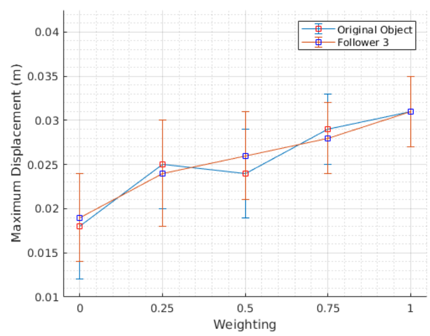
Figure I.20: Performance for the Hybrid System in the Line Following Environmental Setup for a partial motor fault in the follower's wheel 3



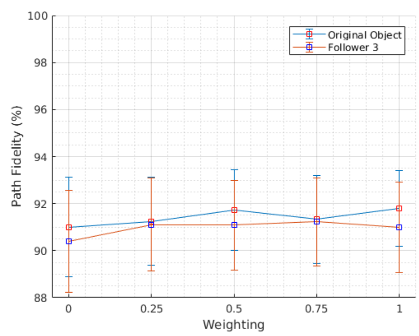
(a) Path 1: Mean Time Taken and Standard Deviation



(b) Path 1: Mean Total Distance Travelled and Standard Deviation

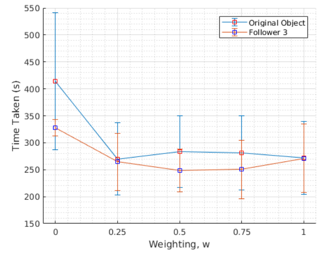


(c) Path 1: Mean Maximum Displacement and Standard Deviation

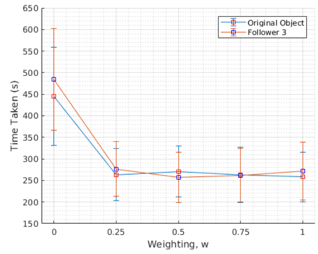


(d) Path 1: Mean Percentage Path Fidelity and Standard Deviation

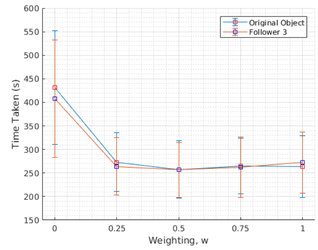
Figure I.21: Performance for the Hybrid System in the Simple Environment for a partial motor fault in the follower's wheel 3



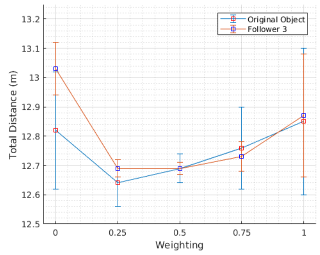
(a) Path 1: Mean Time Taken and Standard Deviation



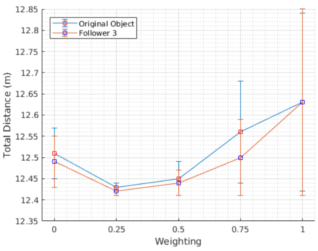
(b) Path 2: Mean Time Taken and Standard Deviation



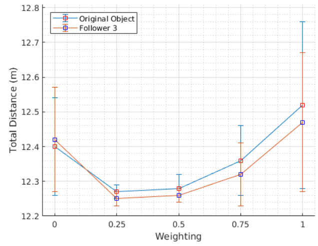
(c) Path 3: Mean Time Taken and Standard Deviation



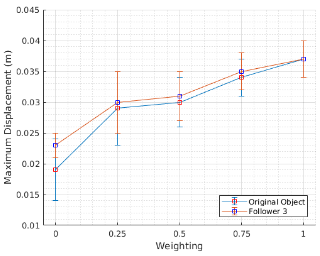
(d) Path 1: Mean Total Distance Travelled and Standard Deviation



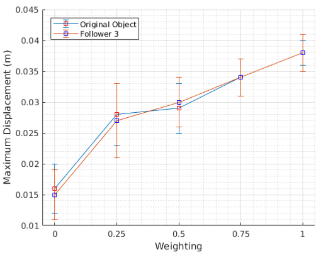
(e) Path 2: Mean Total Distance Travelled and Standard Deviation



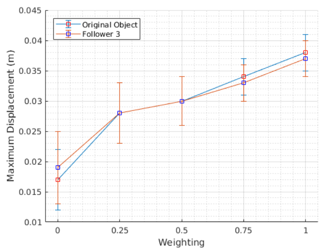
(f) Path 3: Mean Total Distance Travelled and Standard Deviation



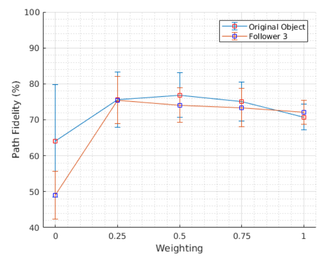
(g) Path 1: Mean Maximum Displacement and Standard Deviation



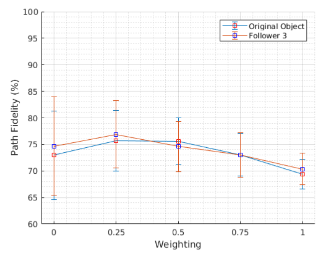
(h) Path 2: Mean Maximum Displacement and Standard Deviation



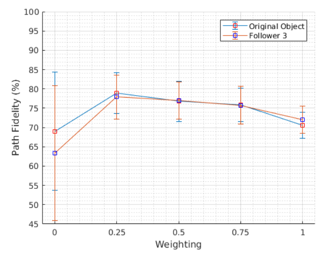
(i) Path 3: Mean Maximum Displacement and Standard Deviation



(j) Path 1: Mean Percentage Path Fidelity and Standard Deviation

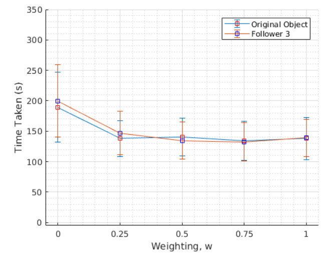


(k) Path 2: Mean Percentage Path Fidelity and Standard Deviation

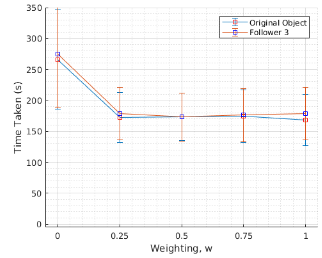


(l) Path 3: Mean Percentage Path Fidelity and Standard Deviation

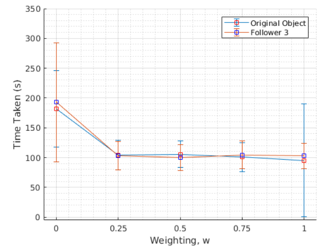
Figure I.22: Performance for the Hybrid System in the Cluttered Environment for a partial motor fault in the follower's wheel 3



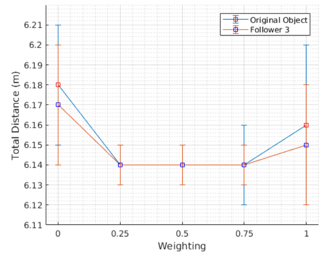
(a) Path 1: Mean Time Taken and Standard Deviation



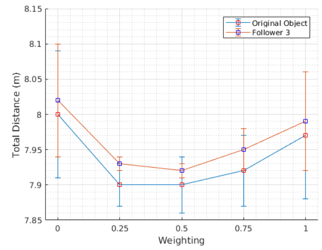
(b) Path 2: Mean Time Taken and Standard Deviation



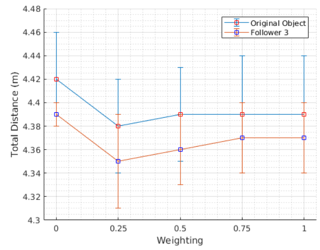
(c) Path 3: Mean Time Taken and Standard Deviation



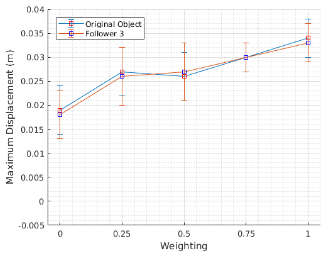
(d) Path 1: Mean Total Distance Travelled and Standard Deviation



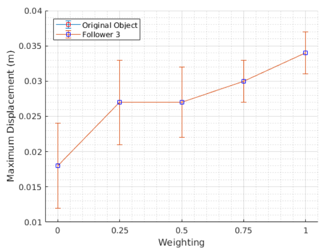
(e) Path 2: Mean Total Distance Travelled and Standard Deviation



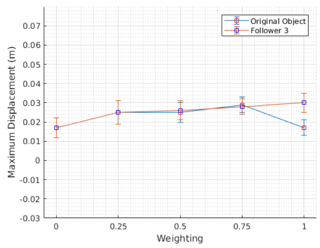
(f) Path 3: Mean Total Distance Travelled and Standard Deviation



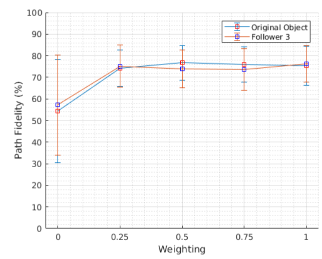
(g) Path 1: Mean Maximum Displacement and Standard Deviation



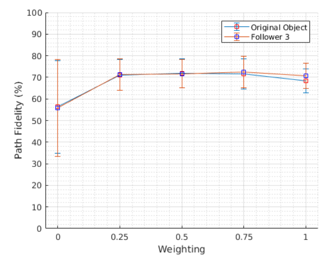
(h) Path 2: Mean Maximum Displacement and Standard Deviation



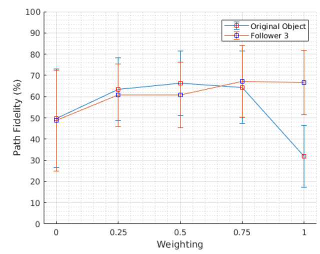
(i) Path 3: Mean Maximum Displacement and Standard Deviation



(j) Path 1: Mean Percentage Path Fidelity and Standard Deviation



(k) Path 2: Mean Percentage Path Fidelity and Standard Deviation



(l) Path 3: Mean Percentage Path Fidelity and Standard Deviation

Figure I.23: Performance for the Hybrid System in the Randomly Generated Environments for a partial motor fault in the follower's wheel 3

Appendix J

Experimental Data from Chapter 9: Fault Tolerance of the Hybrid System in Object Manipulation Tasks

J.1 Vision Sensor Fault

Table J.1: Percentage Task Completion for the Hybrid System in the Line Following Environment in the presence of a Left Vision Sensor Fault

Weighting	Line Following Environment Path		
	1	2	3
Exp	**0.00%**	**100.00%**	**0.00%**
Exp Original	100.00%	100.00%	100.00%
w = 0.25	**17.00%**	**28.00%**	**0.00%**
Original w = 0.25	100.00%	91.00%	76.00%
w = 0.5	**20.00%**	**61.00%**	**0.00%**
Original w = 0.5	100.00%	98.00%	92.00%
w = 0.75	**60.00%**	**100.00%**	**0.00%**
Original w = 0.75	100.00%	100.00%	100.00%
Imp	**52.00%**	**100.00%**	**0.00%**
Imp Original	100.00%	100.00%	99.00%

Table J.2: Percentage Task Completion for the Hybrid System in the Line Following Environment in the presence of a Middle Vision Sensor Fault

Weighting	Line Following Environment Path		
	1	2	3
Exp	**100.00%**	**100.00%**	**100.00%**
Exp Original	100.00%	100.00%	100.00%
w = 0.25	**100.00%**	**100.00%**	**99.00%**
Original w = 0.25	100.00%	91.00%	76.00%
w = 0.5	**100.00%**	**100.00%**	**100.00%**
Original w = 0.5	100.00%	98.00%	92.00%
w = 0.75	**100.00%**	**100.00%**	**100.00%**
Original w = 0.75	100.00%	100.00%	100.00%
Imp	**100.00%**	**100.00%**	**98.00%**
Imp Original	100.00%	100.00%	99.00%

Table J.3: Percentage Task Completion for the Hybrid System in the Line Following Environment in the presence of a Right Vision Sensor Fault

Weighting	Line Following Environment Path		
	1	2	3
Exp	**100.00%**	**0.00%**	**100.00%**
Exp Original	100.00%	100.00%	100.00%
w = 0.25	**43.00%**	**33.00%**	**50.00%**
Original w = 0.25	100.00%	91.00%	76.00%
w = 0.5	**88.00%**	**19.00%**	**71.00%**
Original w = 0.5	100.00%	98.00%	92.00%
w = 0.75	**100.00%**	**31.00%**	**92.00%**
Original w = 0.75	100.00%	100.00%	100.00%
Imp	**100.00%**	**0.00%**	**99.00%**
Imp Original	100.00%	100.00%	99.00%

Table J.4: Mean Time Taken in Seconds and Standard Deviation for the Hybrid System in the Line Following Environment in the presence of a Left Vision Sensor Fault

Weighting	Line Following Environment Path		
	1	2	3
Exp	**N/A**	**119.87 (38.55)**	**N/A**
Exp Original	121.81 (46.49)	119.22 (40.55)	121.15 (35.70)
Sig Diff.	N/A	0.733	N/A
w = 0.25	**338.84 (131.72)**	**349.35 (281.29)**	**N/A**
Original w = 0.25	134.35 (103.35)	206.05 (214.39)	118.71 (32.50)
Sig Diff.	p <0.001	p <0.001	N/A
w = 0.5	**310.25 (37.17)**	**305.94 (271.08)**	**N/A**
Original w = 0.5	131.89 (147.99)	118.76 (101.62)	107.65 (19.52)
Sig Diff.	p <0.001	p <0.001	N/A
w = 0.75	**227.85 (63.60)**	**83.99 (19.64)**	**N/A**
Original w = 0.75	90.46 (21.63)	77.43 (17.20)	94.37 (21.03)
Sig Diff.	p <0.001	0.024	N/A
Imp	**219.40 (49.54)**	**79.03 (14.36)**	**N/A**
Imp Original	80.25 (18.25)	79.18 (18.89)	81.45 (19.03)
Sig Diff.	p <0.001	0.837	N/A

Table J.5: Mean Time Taken in Seconds and Standard Deviation for the Hybrid System in the Line Following Environment in the presence of a Middle Vision Sensor Fault

Weighting	Line Following Environment Path		
	1	2	3
Exp	**116.03 (37.21)**	**114.32 (40.40)**	**123.55 (41.75)**
Exp Original	121.81 (46.49)	119.22 (40.55)	121.15 (35.70)
Sig Diff.	0.736	0.361	0.950
w = 0.25	**85.63 (19.79)**	**85.09 (19.45)**	**91.52 (20.86)**
Original w = 0.25	134.35 (103.35)	206.05 (214.39)	118.71 (32.50)
Sig Diff.	p <0.001	p <0.001	p <0.001
w = 0.5	**83.24 (19.46)**	**83.92 (19.01)**	**86.71 (20.35)**
Original w = 0.5	131.89 (147.99)	118.76 (101.62)	107.65 (19.52)
Sig Diff.	p <0.001	p <0.001	p <0.001
w = 0.75	**82.51 (19.82)**	**78.03 (18.59)**	**87.08 (21.00)**
Original w = 0.75	90.46 (21.63)	77.43 (17.20)	94.37 (21.03)
Sig Diff.	0.005	0.896	0.017
Imp	**77.76 (18.82)**	**77.43 (16.85)**	**83.21 (22.52)**
Imp Original	80.25 (18.25)	79.18 (18.89)	81.45 (19.03)
Sig Diff.	0.305	0.334	0.980

Table J.6: Mean Time Taken in Seconds and Standard Deviation for the Hybrid System in the Line Following Environment in the presence of a Right Vision Sensor Fault

Weighting	Line Following Environment Path		
	1	2	3
Exp	**116.09 (36.69)**	**N/A**	**120.18 (40.20)**
Exp Original	121.81 (46.49)	119.22 (40.55)	121.15 (35.70)
Sig Diff.	0.700	N/A	0.499
w = 0.25	**133.20 (33.80)**	**391.40 (172.01)**	**127.38 (18.60)**
Original w = 0.25	134.35 (103.35)	206.05 (214.39)	118.71 (32.50)
Sig Diff.	0.013	p <0.001	0.369
w = 0.5	**129.69 (135.65)**	**308.63 (106.02)**	**103.28 (21.60)**
Original w = 0.5	131.89 (147.99)	118.76 (101.62)	107.65 (19.52)
Sig Diff.	0.416	p <0.001	0.225
w = 0.75	**86.74 (21.05)**	**227.82 (12.95)**	**87.52 (20.02)**
Original w = 0.75	90.46 (21.63)	77.43 (17.20)	94.37 (21.03)
Sig Diff.	0.209	p <0.001	0.030
Imp	**80.02 (19.72)**	**N/A**	**84.53 (20.58)**
Imp Original	80.25 (18.25)	79.18 (18.89)	81.45 (19.03)
Sig Diff.	0.760	N/A	0.328

Table J.7: Mean Total Distance Travelled by Object in Metres and Standard Deviation for the Hybrid System in the Line Following Environment in the presence of a Left Vision Sensor Fault

Weighting	Line Following Environment Path		
	1	2	3
Exp	**N/A**	**3.34 (0.06)**	**N/A**
Exp Original	3.51 (0.06)	3.33 (0.06)	3.42 (0.05)
Sig Diff.	N/A	p <0.001	N/A
w = 0.25	**7.02 (2.33)**	**6.73 (3.40)**	**N/A**
Original w = 0.25	3.80 (0.99)	4.32 (1.83)	3.51 (0.08)
Sig Diff.	p <0.001	p <0.001	N/A
w = 0.5	**5.02 (0.09)**	**5.12 (2.41)**	**N/A**
Original w = 0.5	3.89 (1.46)	3.63 (0.91)	3.52 (0.07)
Sig Diff.	p <0.001	0.002	N/A
w = 0.75	**4.93 (0.15)**	**3.34 (0.07)**	**N/A**
Original w = 0.75	3.52 (0.06)	3.32 (0.06)	3.49 (0.07)
Sig Diff.	p <0.001	0.053	N/A
Imp	**4.84 (0.13)**	**3.35 (0.05)**	**N/A**
Imp Original	3.50 (0.05)	3.36 (0.07)	3.45 (0.06)
Sig Diff.	p <0.001	0.742	N/A

Table J.8: Mean Total Distance Travelled by Object in Metres and Standard Deviation for the Hybrid System in the Line Following Environment in the presence of a Middle Vision Sensor Fault

Weighting	Line Following Environment Path		
	1	2	3
Exp	**3.51 (0.05)**	**3.33 (0.06)**	**3.45 (0.05)**
Exp Original	3.51 (0.06)	3.33 (0.06)	3.42 (0.05)
Sig Diff.	0.872	0.492	p <0.001
w = 0.25	**3.50 (0.05)**	**3.33 (0.06)**	**3.47 (0.05)**
Original w = 0.25	3.80 (0.99)	4.32 (1.83)	3.51 (0.08)
Sig Diff.	p <0.001	p <0.001	p <0.001
w = 0.5	**3.50 (0.05)**	**3.34 (0.06)**	**3.47 (0.06)**
Original w = 0.5	3.89 (1.46)	3.63 (0.91)	3.52 (0.07)
Sig Diff.	0.003	p <0.001	p <0.001
w = 0.75	**3.50 (0.06)**	**3.33 (0.07)**	**3.48 (0.07)**
Original w = 0.75	3.52 (0.06)	3.32 (0.06)	3.49 (0.07)
Sig Diff.	0.082	0.094	0.424
Imp	**3.49 (0.06)**	**3.34 (0.06)**	**3.48 (0.08)**
Imp Original	3.50 (0.05)	3.36 (0.07)	3.45 (0.06)
Sig Diff.	0.282	0.241	p <0.001

Table J.9: Mean Total Distance Travelled by Object in Metres and Standard Deviation for the Hybrid System in the Line Following Environment in the presence of a Right Vision Sensor Fault

Weighting	Line Following Environment Path		
	1	2	3
Exp	**3.50 (0.05)**	**N/A**	**3.41 (0.05)**
Exp Original	3.50 (0.05)	3.36 (0.07)	3.45 (0.06)
Sig Diff.	0.720	N/A	0.187
w = 0.25	**3.61 (0.029)**	**6.69 (2.56)**	**3.62 (0.41)**
Original w = 0.25	3.80 (0.99)	4.32 (1.83)	3.51 (0.08)
Sig Diff.	0.687	p <0.001	0.923
w = 0.5	**4.55 (2.30)**	**5.19 (1.03)**	**3.46 (0.14)**
Original w = 0.5	3.89 (1.46)	3.63 (0.91)	3.52 (0.07)
Sig Diff.	0.152	p <0.001	0.01
w = 0.75	**3.51 (0.06)**	**4.96 (0.04)**	**3.44 (0.06)**
Original w = 0.75	3.52 (0.06)	3.32 (0.06)	3.49 (0.07)
Sig Diff.	0.174	p <0.001	p <0.001
Imp	**3.50 (0.06)**	**N/A**	**3.45 (0.07)**
Imp Original	3.50 (0.05)	3.36 (0.07)	3.45 (0.06)
Sig Diff.	0.581	N/A	0.769

Table J.10: Mean Maximum Displacement of Object in Metres and Standard Deviation for the Hybrid System in the Line Following Environment in the presence of a Left Vision Sensor Fault

Weighting	Line Following Environment Path		
	1	2	3
Exp	**N/A**	**0.018 (0.005)**	**N/A**
Exp Original	0.018 (0.006)	0.018 (0.006)	0.019 (0.005)
Sig Diff.	N/A	0.736	N/A
w = 0.25	**0.025 (0.008)**	**0.027 (0.007)**	**N/A**
Original w = 0.25	0.027 (0.008)	0.034 (0.009)	0.031 (0.009)
Sig Diff.	0.367	0.0013	N/A
w = 0.5	**0.020 (0.002)**	**0.025 (0.002)**	**N/A**
Original w = 0.5	0.028 (0.007)	0.031 (0.006)	0.031 (0.006)
Sig Diff.	p <0.001	p <0.001	N/A
w = 0.75	**0.026 (0.005)**	**0.031 (0.004)**	**N/A**
Original w = 0.75	0.028 (0.006)	0.032 (0.004)	0.032 (0.006)
Sig Diff.	0.275	0.016	N/A
Imp	**0.028 (0.005)**	**0.031 (0.005)**	**N/A**
Imp Original	0.029 (0.005)	0.031 (0.005)	0.033 (0.006)
Sig Diff.	0.156	0.266	N/A

Table J.11: Mean Maximum Displacement of Object in Metres and Standard Deviation for the Hybrid System in the Line Following Environment in the presence of a Middle Vision Sensor Fault

Weighting	Line Following Environment Path		
	1	2	3
Exp	**0.018 (0.005)**	**0.018 (0.005)**	**0.018 (0.006)**
Exp Original	0.018 (0.006)	0.018 (0.006)	0.019 (0.005)
Sig Diff.	0.885	0.688	0.622
w = 0.25	**0.026 (0.005)**	**0.026 (0.005)**	**0.027 (0.005)**
Original w = 0.25	0.027 (0.008)	0.034 (0.009)	0.031 (0.009)
Sig Diff.	0.437	p <0.001	0.034
w = 0.5	**0.026 (0.005)**	**0.027 (0.004)**	**0.029 (0.005)**
Original w = 0.5	0.028 (0.007)	0.031 (0.006)	0.031 (0.006)
Sig Diff.	0.171	p <0.001	0.113
w = 0.75	**0.028 (0.005)**	**0.030 (0.004)**	**0.030 (0.005)**
Original w = 0.75	0.028 (0.006)	0.032 (0.004)	0.032 (0.006)
Sig Diff.	0.554	p <0.001	0.030
Imp	**0.030 (0.005)**	**0.031 (0.005)**	**0.033 (0.005)**
Imp Original	0.029 (0.005)	0.031 (0.005)	0.033 (0.006)
Sig Diff.	0.264	0.324	0.673

Table J.12: Mean Maximum Displacement of Object in Metres and Standard Deviation for the Hybrid System in the Line Following Environment in the presence of a Right Vision Sensor Fault

Weighting	Line Following Environment Path		
	1	2	3
Exp	**0.018 (0.005)**	**N/A**	**0.019 (0.006)**
Exp Original	0.018 (0.006)	0.018 (0.006)	0.019 (0.005)
Sig Diff.	0.702	N/A	0.551
w = 0.25	**0.022 (0.006)**	**0.030 (0.008)**	**0.026 (0.004)**
Original w = 0.25	0.027 (0.008)	0.034 (0.009)	0.031 (0.009)
Sig Diff.	p <0.001	0.097	0.023
w = 0.5	**0.027 (0.006)**	**0.027 (0.006)**	**0.030 (0.004)**
Original w = 0.5	0.028 (0.007)	0.031 (0.006)	0.031 (0.006)
Sig Diff.	0.890	p <0.001	0.920
w = 0.75	**0.029 (0.006)**	**0.030 (0.002)**	**0.033 (0.005)**
Original w = 0.75	0.028 (0.006)	0.032 (0.004)	0.032 (0.006)
Sig Diff.	0.155	p <0.001	0.235
Imp	**0.030 (0.005)**	**N/A**	**0.031 (0.006)**
Imp Original	0.029 (0.005)	0.031 (0.005)	0.033 (0.006)
Sig Diff.	0.813	N/A	0.169

Table J.13: Mean Percentage Path Fidelity and Standard Deviation for the Hybrid System in the Line Following Environment in the presence of a Left Vision Sensor Fault

Weighting	Line Following Environment Path		
	1	2	3
Exp	**N/A**	**100% (∼0%)**	**N/A**
Exp Original	90.75% (14.93%)	100% (∼0%)	99.40% (3.43%)
Sig Diff.	N/A	1	N/A
w = 0.25	**8.82% (15.16%)**	**45.24% (33.60%)**	**N/A**
Original w = 0.25	78.02 (27.09%)	56.58% (25.54%)	79.35% (19.15%)
Sig Diff.	p <0.001	0.074	N/A
w = 0.5	**1.25% (5.59%)**	**47.81% (43.19%)**	**N/A**
Original w = 0.5	86.48% (22.47%)	71.56% (25.02%)	90.18% (15.64%)
Sig Diff.	p <0.001	0.003	N/A
w = 0.75	**12.08% (12.60%)**	**98.33% (5.56%)**	**N/A**
Original w = 0.75	93.25% (13.23%)	99.50% (2.86%)	91.65% (14.18%)
Sig Diff.	p <0.001	0.074	N/A
Imp	**21.63% (8.62%)**	**82.33% (20.21%)**	**N/A**
Imp Original	93.00 (12.35%)	89.67% (14.17%)	96.57% (9.49%)
Sig Diff.	p <0.001	0.001	N/A

Table J.14: Mean Percentage Path Fidelity and Standard Deviation for the Hybrid System in the Line Following Environment in the presence of a Middle Vision Sensor Fault

Weighting	Line Following Environment Path		
	1	2	3
Exp	**99.00% (4.92%)**	**73.33% (12.08%)**	**99.80% (2.00%)**
Exp Original	90.75% (14.93%)	100% (∼0%)	99.40% (3.43%)
Sig Diff.	p <0 .001	p <0 .001	0.316
w = 0.25	**97.50% (7.54%)**	**100% (∼0%)**	**99.39% (3.45%)**
Original w = 0.25	78.02 (27.09%)	56.58% (25.54%)	79.35% (19.15%)
Sig Diff.	p <0 .001	p <0 .001	p <0 .001
w = 0.5	**96.00% (10.49%)**	**99.83% (1.67%)**	**98.80% (5.56%)**
Original w = 0.5	86.48% (22.47%)	71.56% (25.02%)	90.18% (15.64%)
Sig Diff.	p <0 .001	p <0 .001	p <0 .001
w = 0.75	**99.00% (4.92%)**	**96.00% (9.80%)**	**98.60% (5.13%)**
Original w = 0.75	93.25% (13.23%)	99.50% (2.86%)	91.65% (14.18%)
Sig Diff.	p <0 .001	p <0 .001	p <0 .001
Imp	**97.25% (7.86%)**	**91.83% (12.19%)**	**97.76% (6.35%)**
Imp Original	93.00 (12.35%)	89.67% (14.17%)	96.57% (9.49%)
Sig Diff.	0.006	0.362	0.510

Table J.15: Mean Percentage Path Fidelity and Standard Deviation for the Hybrid System in the Line Following Environment in the presence of a Right Vision Sensor Fault

Weighting	Line Following Environment Path		
	1	2	3
Exp	**90.50% (14.12%)**	**N/A**	**99.80% (2.00%)**
Exp Original	90.75% (14.93%)	100% (∼0%)	99.40% (3.43%)
Sig Diff.	0.744	N/A	0.316
w = 0.25	**70.93% (28.83%)**	**19.70% (9.73%)**	**79.20% (19.36%)**
Original w = 0.25	78.02 (27.09%)	56.58% (25.54%)	79.35% (19.15%)
Sig Diff.	0.143	p <0.001	0.980
w = 0.5	**75.85% (32.92%)**	**11.40% (13.67%)**	**78.03% (19.17%)**
Original w = 0.5	86.48% (22.47%)	71.56% (25.02%)	90.18% (15.64%)
Sig Diff.	0.045	p <0.001	p <0.001
w = 0.75	**89.50% (15.56%)**	**16.67% (∼0.00%)**	**87.61% (16.47%)**
Original w = 0.75	93.25% (13.23%)	99.50% (2.86%)	91.65% (14.18%)
Sig Diff.	0.057	p <0.001	0.078
Imp	**91.00% (15.29%)**	**N/A**	**86.87% (14.61%)**
Imp Original	93.00 (12.35%)	89.67% (14.17%)	96.57% (9.49%)
Sig Diff.	0.462	N/A	p <0.001

J.2 Partial Motor Fault

J.2.1 Partial Motor Fault in Leader Wheels

Table J.16: Percentage Task Completion for the Hybrid System in the Line Following Environment in the presence of a Partial Motor Fault in Leader's Left Wheel

Weighting	Line Following Environment Path		
	1	2	3
Exp	**85.00%**	**73.00%**	**86.00%**
Exp Original	100.00%	100.00%	100.00%
w = 0.25	**94.00%**	**35.00%**	**42.00%**
Original w = 0.25	91.00%	76.00%	62.00%
w = 0.5	**89.00%**	**22.00%**	**49.00%**
Original w = 0.5	98.00%	92.00%	57.00%
w = 0.75	**94.00%**	**40.00%**	**75.00%**
Original w = 0.75	100.00%	100.00%	79.00%
Imp	**85.00%**	**93.00%**	**97.00%**
Imp Original	100.00%	100.00%	99.00%

Table J.17: Percentage Task Completion for the Hybrid System in the Line Following Environment in the presence of a Partial Motor Fault in Leader's Right Wheel

Weighting	Line Following Environment Path		
	1	2	3
Exp	**100.00%**	**67.00%**	**63.00%**
Exp Original	100.00%	100.00%	100.00%
w = 0.25	**91.00%**	**55.00%**	**4.00%**
Original w = 0.25	91.00%	76.00%	62.00%
w = 0.5	**78.00%**	**41.00%**	**1.00%**
Original w = 0.5	98.00%	92.00%	57.00%
w = 0.75	**77.00%**	**61.00%**	**3.00%**
Original w = 0.75	100.00%	100.00%	79.00%
Imp	**100.00%**	**84.00%**	**3.00%**
Imp Original	100.00%	100.00%	99.00%

Table J.18: Percentage Task Completion for the Hybrid System in the Simple and Cluttered Environments in the presence of a Partial Motor Fault in Leader's Left Wheel

Weighting	Path			
	SE 1	CE 1	CE 2	CE 3
Exp	**99.00%**	**32.00%**	**63.00%**	**69.00%**
Exp Original	100.00%	100.00%	60.00%	100.00%
w = 0.25	**100.00%**	**41.00%**	**96.00%**	**94.00%**
Original w = 0.25	100.00%	100.00%	100.00%	100.00%
w = 0.5	**100.00%**	**46.00%**	**93.00%**	**90.00%**
Original w = 0.5	100.00%	100.00%	100.00%	100.00%
w = 0.75	**100.00%**	**51.00%**	**93.00%**	**92.00%**
Original w = 0.75	100.00%	100.00%	100.00%	100.00%
Imp	**100.00%**	**43.00%**	**93.00%**	**93.00%**
Imp Original	100.00%	100.00%	100.00%	100.00%

Table J.19: Percentage Task Completion for the Hybrid System in the Simple and Cluttered Environments in the presence of a Partial Motor Fault in Leader's Right Wheel

Weighting	Path			
	SE	CE	CE	CE
	1	1	2	3
Exp	**100.00%**	**60.00%**	**32.00%**	**68.00%**
Exp Original	100.00%	100.00%	60.00%	100.00%
w = 0.25	**100.00%**	**68.00%**	**75.00%**	**100.00%**
Original w = 0.25	100.00%	100.00%	100.00%	100.00%
w = 0.5	**100.00%**	**80.00%**	**76.00%**	**100.00%**
Original w = 0.5	100.00%	100.00%	100.00%	100.00%
w = 0.75	**100.00%**	**69.00%**	**49.00%**	**100.00%**
Original w = 0.75	100.00%	100.00%	100.00%	100.00%
Imp	**100.00%**	**67.00%**	**38.00%**	**92.00%**
Imp Original	100.00%	100.00%	100.00%	100.00%

Table J.20: Percentage Task Completion for the Hybrid System in the Randomly Generated Environments in the presence of a Partial Motor Fault in Leader's Left Wheel

Weighting	Randomly Generated Environments		
	1	2	3
Exp	**94.00%**	**72.00%**	**0.00%**
Exp Original	100.00%	100.00%	93.00%
w = 0.25	**100.00%**	**94.00%**	**11.00%**
Original w = 0.25	100.00%	100.00%	100.00%
w = 0.5	**100.00%**	**93.00%**	**13.00%**
Original w = 0.5	100.00%	100.00%	100.00%
w = 0.75	**100.00%**	**84.00%**	**12.00%**
Original w = 0.75	100.00%	100.00%	100.00%
Imp	**100.00%**	**95.00%**	**14.00%**
Imp Original	100.00%	100.00%	100.00%

Table J.21: Percentage Task Completion for the Hybrid System in the Randomly Generated Environments in the presence of a Partial Motor Fault in Leader's Right Wheel

Weighting	Randomly Generated Environments		
	1	2	3
Exp	**98.00%**	**90.00%**	**86.00%**
Exp Original	100.00%	100.00%	93.00%
w = 0.25	**100.00%**	**100.00%**	**91.00%**
Original w = 0.25	100.00%	100.00%	100.00%
w = 0.5	**100.00%**	**100.00%**	**87.00%**
Original w = 0.5	100.00%	100.00%	100.00%
w = 0.75	**100.00%**	**100.00%**	**95.00%**
Original w = 0.75	100.00%	100.00%	100.00%
Imp	**100.00%**	**100.00%**	**94.00%**
Imp Original	100.00%	100.00%	100.00%

Table J.22: Mean Time Taken in Seconds and Standard Deviation for the Hybrid System in the Line Following Environment in the presence of a Partial Motor Fault in Leader's Left Wheel

Weighting	Line Following Environment Path		
	1	2	3
Exp	**332.03 (184.73)**	**296.67 (155.93)**	**330.82 (201.08)**
Exp Original	121.81 (46.49)	119.22 (40.55)	121.15 (35.70)
Sig Diff.	p <0.001	p <0.001	p <0.001
w = 0.25	**167.18 (115.07)**	**313.47 (151.68)**	**370.72 (146.28)**
Original w = 0.25	134.35 (103.35)	206.05 (214.39)	118.71 (32.50)
Sig Diff.	p <0.001	p <0.001	p <0.001
w = 0.5	**195.44 (135.62)**	**310.43 (154.01)**	**373.46 (198.22)**
Original w = 0.5	131.89 (147.99)	118.76 (101.62)	107.65 (19.52)
Sig Diff.	p <0.001	p <0.001	p <0.001
w = 0.75	**168.47 (107.35)**	**208.43 (83.65)**	**280.31 (160.52)**
Original w = 0.75	90.46 (21.63)	77.43 (17.20)	94.37 (21.03)
Sig Diff.	p <0.001	p <0.001	p <0.001
Imp	**150.95 (44.70)**	**150.14 (44.02)**	**185.03 (99.72)**
Imp Original	80.25 (18.25)	79.18 (18.89)	81.45 (19.03)
Sig Diff.	p <0.001	p <0.001	p <0.001

Table J.23: Mean Time Taken in Seconds and Standard Deviation for the Hybrid System in the Line Following Environment in the presence of a Partial Motor Fault in Leader's Right Wheel

Weighting	Line Following Environment Path		
	1	2	3
Exp	**256.55 (119.29)**	**243.59 (93.56)**	**319.11 (128.61)**
Exp Original	121.81 (46.49)	119.22 (40.55)	121.15 (35.70)
Sig Diff.	p <0.001	p <0.001	p <0.001
w = 0.25	**213.49 (151.11)**	**371.90 (176.79)**	**248.60 (74.42)**
Original w = 0.25	134.35 (103.35)	206.05 (214.39)	118.71 (32.50)
Sig Diff.	p <0.001	p <0.001	0.005
w = 0.5	**232.11 (134.74)**	**397.78 (162.75)**	**324.05 (0)**
Original w = 0.5	131.89 (147.99)	118.76 (101.62)	107.65 (19.52)
Sig Diff.	p <0.001	p <0.001	0.094
w = 0.75	**194.30 (122.73)**	**315.81 (158.21)**	**139.50 (9.53)**
Original w = 0.75	90.46 (21.63)	77.43 (17.20)	94.37 (21.03)
Sig Diff.	p <0.001	p <0.001	0.005
Imp	**118.89 (26.00)**	**216.52 (125.29)**	**138.92 (39.27)**
Imp Original	80.25 (18.25)	79.18 (18.89)	81.45 (19.03)
Sig Diff.	p <0.001	p <0.001	0.008

Table J.24: Mean Time Taken in Seconds and Standard Deviation for the Hybrid System in the Simple and Cluttered Environments in the presence of a Partial Motor Fault in Leader's Left Wheel

Weighting	Path			
	SE	CE	CE	CE
	1	1	2	3
Exp	**346.95 (162.98)**	**443.72 (133.00)**	**569.82 (101.33)**	**558.93 (102.58)**
Exp Original	170.98 (62.64)	414.36 (127.10)	445.31 (113.61)	431.18 (120.53)
Sig Diff.	$p < 0.001$	0.070	$p < 0.001$	$p < 0.001$
w = 0.25	**182.53 (40.08)**	**436.74 (65.28)**	**404.43 (81.73)**	**408.41 (93.25)**
Original w = 0.25	124.66 (29.48)	270.09 (67.01)	263.68 (60.60)	273.22 (65.83)
Sig Diff.	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$
w = 0.5	**176.43 (39.94)**	**421.05 (85.15)**	**399.95 (91.83)**	**406.47 (91.88)**
Original w = 0.5	129.72 (50.93)	283.73 (66.40)	270.75 (58.86)	257.41 (61.12)
Sig Diff.	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$
w = 0.75	**183.02 (44.72)**	**400.99 (92.98)**	**406.97 (89.24)**	**391.97 (89.07)**
Original w = 0.75	116.27 (27.92)	281.52 (68.64)	263.25 (63.95)	264.54 (59.27)
Sig Diff.	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$
Imp	**174.40 (44.54)**	**438.26 (106.24)**	**409.67 (92.03)**	**371.83 (79.76)**
Imp Original	118.84 (26.18)	271.44 (67.54)	257.93 (58.21)	263.55 (65.87)
Sig Diff.	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$

Table J.25: Mean Time Taken in Seconds and Standard Deviation for the Hybrid System in the Simple and Cluttered Environments in the presence of a Partial Motor Fault in Leader's Right Wheel

Weighting	Path			
	SE	CE	CE	CE
	1	1	2	3
Exp	**406.50 (123.61)**	**561.63 (96.89)**	**635.68 (81.65)**	**553.33 (85.80)**
Exp Original	266.01 (80.07)	414.36 (127.10)	445.31 (113.61)	431.18 (120.53)
Sig Diff.	p <0.001	p <0.001	p <0.001	p <0.001
w = 0.25	**264.43 (56.02)**	**380.25 (77.31)**	**469.26 (83.48)**	**411.02 (95.53)**
Original w = 0.25	172.47 (40.02)	270.09 (67.01)	263.68 (60.60)	273.22 (65.83)
Sig Diff.	1.17E-23	p <0.001	p <0.001	p <0.001
w = 0.5	**260.09 (63.82)**	**413.07 (84.75)**	**460.01 (79.65)**	**419.76 (95.44)**
Original w = 0.5	173.53 (38.21)	283.73 (66.40)	270.75 (58.86)	257.41 (61.12)
Sig Diff.	p <0.001	p <0.001	p <0.001	p <0.001
w = 0.75	**256.24 (55.02)**	**409.48 (90.88)**	**483.70 (82.12)**	**407.00 (93.51)**
Original w = 0.75	174.68 (42.70)	281.52 (68.64)	263.25 (63.95)	264.54 (59.27)
Sig Diff.	p <0.001	p <0.001	p <0.001	p <0.001
Imp	**272.46 (67.86)**	**421.21 (88.53)**	**523.86 (84.72)**	**431.05 (97.74)**
Imp Original	168.28 (41.27)	271.44 (67.54)	257.93 (58.21)	263.55 (65.87)
Sig Diff.	p <0.001	p <0.001	p <0.001	p <0.001

Table J.26: Mean Time Taken in Seconds and Standard Deviation for the Hybrid System in the Randomly Generated Environments in the presence of a Partial Motor Fault in Leader's Left Wheel

Weighting	Randomly Generated Environments		
	1	2	3
Exp	**343.31 (138.33)**	**461.13 (130.61)**	**N/A**
Exp Original	189.45 (57.78)	266.01 (80.07)	181.78 (94.63)
Sig Diff.	p <0.001	p <0.001	N/A
w = 0.25	**222.43 (50.62)**	**264.54 (60.62)**	**137.69 (31.33)**
Original w = 0.25	138.24 (29.51)	172.47 (40.02)	104.11 (24.81)
Sig Diff.	p <0.001	p <0.001	p <0.001
w = 0.5	**203.11 (43.29)**	**260.13 (61.64)**	**119.60 (3.47)**
Original w = 0.5	140.64 (30.78)	173.53 (38.21)	105.65 (22.36)
Sig Diff.	p <0.001	p <0.001	0.032
w = 0.75	**215.88 (47.20)**	**246.97 (51.94)**	**120.15 (2.44)**
Original w = 0.75	137.31 (31.90)	174.68 (42.70)	100.78 (24.22)
Sig Diff.	p <0.001	p <0.001	0.006
Imp	**196.03 (45.56)**	**254.15 (56.13)**	**114.28 (37.26)**
Imp Original	137.92 (34.28)	168.28 (41.27)	95.06 (20.45)
Sig Diff.	p <0.001	p <0.001	p <0.001

Table J.27: Mean Time Taken in Seconds and Standard Deviation for the Hybrid System in the Randomly Generated Environments in the presence of a Partial Motor Fault in Leader's Right Wheel

Weighting	Randomly Generated Environments		
	1	2	3
Exp	**326.09 (142.97)**	**406.50 (123.61)**	**337.22 (137.54)**
Exp Original	189.45 (57.78)	266.01 (80.07)	181.78 (94.63)
Sig Diff.	$p < 0.001$	$p < 0.001$	$p < 0.001$
w = 0.25	**189.62 (37.01)**	**264.43 (56.02)**	**156.38 (27.59)**
Original w = 0.25	138.24 (29.51)	172.47 (40.02)	104.11 (24.81)
Sig Diff.	$p < 0.001$	$p < 0.001$	$p < 0.001$
w = 0.5	**260.09 (40.10)**	**260.09 (63.82)**	**160.60 (30.23)**
Original w = 0.5	140.64 (30.78)	173.53 (38.21)	105.65 (22.36)
Sig Diff.	$p < 0.001$	$p < 0.001$	$p < 0.001$
w = 0.75	**196.65 (43.51)**	**256.24 (55.02)**	**159.25 (36.98)**
Original w = 0.75	137.31 (31.90)	174.68 (42.70)	100.78 (24.22)
Sig Diff.	$p < 0.001$	$p < 0.001$	$p < 0.001$
Imp	**199.69 (46.72)**	**272.46 (67.86)**	**157.39 (28.73)**
Imp Original	137.92 (34.28)	168.28 (41.27)	95.06 (20.45)
Sig Diff.	$p < 0.001$	$p < 0.001$	$p < 0.001$

Table J.28: Mean Total Distance Travelled by Object in Metres and Standard Deviation for the Hybrid System in the Line Following Environment in the presence of a Partial Motor Fault in the Leader's Left Wheel

Weighting	Line Following Environment Path		
	1	2	3
Exp	**3.92 (0.57)**	**3.64 (0.44)**	**3.87 (0.06)**
Exp Original	3.51 (0.06)	3.33 (0.06)	3.42 (0.05)
Sig Diff.	$p < 0.001$	$p < 0.001$	$p < 0.001$
w = 0.25	**5.10 (4.61)**	**7.99 (6.30)**	**12.01 (7.46)**
Original w = 0.25	3.80 (0.99)	4.32 (1.83)	3.51 (0.08)
Sig Diff.	$p < 0.001$	$p < 0.001$	$p < 0.001$
w = 0.5	**7.03 (6.56)**	**8.21 (5.92)**	**14.02 (10.29)**
Original w = 0.5	3.89 (1.46)	3.63 (0.91)	3.52 (0.07)
Sig Diff.	$p < 0.001$	$p < 0.001$	$p < 0.001$
w = 0.75	**5.88 (5.48)**	**5.72 (4.37)**	**9.87 (8.36)**
Original w = 0.75	3.52 (0.06)	3.32 (0.06)	3.49 (0.07)
Sig Diff.	$p < 0.001$	$p < 0.001$	$p < 0.001$
Imp	**4.12 (1.10)**	**3.80 (0.75)**	**5.77 (4.43)**
Imp Original	3.50 (0.05)	3.36 (0.07)	3.45 (0.06)
Sig Diff.	$p < 0.001$	$p < 0.001$	$p < 0.001$

Table J.29: Mean Total Distance Travelled by Object in Metres and Standard Deviation for the Hybrid System in the Line Following Environment in the presence of a Partial Motor Fault in the Leader's Right Wheel

Weighting	Line Following Environment Path		
	1	2	3
Exp	**3.60 (0.05)**	**3.59 (0.33)**	**3.83 (0.47)**
Exp Original	3.50 (0.05)	3.36 (0.07)	3.45 (0.06)
Sig Diff.	p <0.001	p <0.001	p <0.001
w = 0.25	**7.03 (6.47)**	**10.77 (8.15)**	**5.62 (1.20)**
Original w = 0.25	3.80 (0.99)	4.32 (1.83)	3.51 (0.08)
Sig Diff.	p <0.001	p <0.001	p <0.001
w = 0.5	**8.26 (6.80)**	**13.75 (7.39)**	**11.21 (0)**
Original w = 0.5	3.89 (1.46)	3.63 (0.91)	3.52 (0.07)
Sig Diff.	p <0.001	p <0.001	0.094
w = 0.75	**7.12 (6.42)**	**11.16 (7.56)**	**3.78 (0.01)**
Original w = 0.75	3.52 (0.06)	3.32 (0.06)	3.49 (0.07)
Sig Diff.	p <0.001	p <0.001	0.004
Imp	**3.92 (0.35)**	**6.70 (5.25)**	**4.55 (1.52)**
Imp Original	3.50 (0.05)	3.36 (0.07)	3.45 (0.06)
Sig Diff.	p <0.001	p <0.001	p <0.001

Table J.30: Mean Total Distance Travelled by Object in Metres and Standard Deviation for the Hybrid System in the Simple and Cluttered Environments in the presence of a Partial Motor Fault in the Leader's Left Wheel

Weighting	Path			
	SE	CE	CE	CE
	1	1	2	3
Exp	**5.36 (0.03)**	**12.62 (0.03)**	**12.36 (0.04)**	**12.23 (0.08)**
Exp Original	5.27 (0.05)	12.82 (0.20)	12.51 (0.06)	12.40 (0.14)
Sig Diff.	p <0.001	p <0.001	p <0.001	p <0.001
w = 0.25	**5.37 (0.03)**	**12.63 (0.02)**	**12.38 (0.11)**	**12.22 (0.11)**
Original w = 0.25	5.27 (0.05)	12.64 (0.08)	12.43 (0.01)	12.27 (0.02)
Sig Diff.	p <0.001	0.061	p <0.001	p <0.001
w = 0.5	**5.37 (0.03)**	**12.84 (0.21)**	**12.58 (0.28)**	**12.44 (0.26)**
Original w = 0.5	5.28 (0.05)	12.69 (0.05)	12.45 (0.04)	12.28 (0.04)
Sig Diff.	p <0.001	p <0.001	0.179	p <0.001
w = 0.75	**5.41 (0.07)**	**13.11 (0.47)**	**12.91 (0.57)**	**12.70 (0.49)**
Original w = 0.75	5.27 (0.06)	12.76 (0.14)	12.53 (0.12)	12.36 (0.10)
Sig Diff.	p <0.001	p <0.001	p <0.001	p <0.001
Imp	**5.45 (0.12)**	**13.83 (0.94)**	**13.33 (0.87)**	**12.89 (0.68)**
Imp Original	5.28 (0.06)	12.85 (0.25)	12.63 (0.21)	12.52 (0.24)
Sig Diff.	p <0.001	p <0.001	p <0.001	p <0.001

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Table J.31: Mean Total Distance Travelled by Object in Metres and Standard Deviation for the Hybrid System in the Simple and Cluttered Environments in the presence of a Partial Motor Fault in the Leader's Right Wheel

Weighting	Path			
	SE	CE	CE	CE
	1	1	2	3
Exp	**5.37 (0.03)**	**13.12 (0.13)**	**12.87 (0.06)**	**11.79 (1.84)**
Exp Original	5.28 (0.06)	12.85 (0.25)	12.63 (0.21)	12.52 (0.24)
Sig Diff.	p <0.001	p <0.001	p <0.001	0.003
w = 0.25	**5.37 (0.03)**	**13.08 (0.09)**	**12.87 (0.05)**	**12.77 (0.10)**
Original w = 0.25	5.27 (0.05)	12.64 (0.08)	12.43 (0.01)	12.27 (0.02)
Sig Diff.	p <0.001	p <0.001	p <0.001	p <0.001
w = 0.5	**5.37 (0.04)**	**13.30 (0.23)**	**13.19 (0.22)**	**13.05 (0.24)**
Original w = 0.5	5.28 (0.05)	12.69 (0.05)	12.45 (0.04)	12.28 (0.04)
Sig Diff.	p <0.001	p <0.001	p <0.001	p <0.001
w = 0.75	**5.40 (0.07)**	**13.60 (0.50)**	**12.11 (2.01)**	**13.35 (0.50)**
Original w = 0.75	5.27 (0.06)	12.76 (0.14)	12.53 (0.12)	12.36 (0.10)
Sig Diff.	p <0.001	p <0.001	0.158	p <0.001
Imp	**5.45 (0.12)**	**14.04 (0.78)**	**14.68 (0.97)**	**13.88 (0.91)**
Imp Original	5.28 (0.06)	12.85 (0.25)	12.63 (0.21)	12.52 (0.24)
Sig Diff.	p <0.001	p <0.001	p <0.001	p <0.001

Table J.32: Mean Total Distance Travelled by Object in Metres and Standard Deviation for the Hybrid System in the Randomly Generated Environments in the presence of a Partial Motor Fault in the Leader's Left Wheel

Weighting	Randomly Generated Environments		
	1	2	3
Exp	**6.37 (0.05)**	**7.97 (0.03)**	**N/A**
Exp Original	6.18 (0.03)	8.00 (0.09)	4.42 (0.04)
Sig Diff.	p <0.001	0.209	N/A
w = 0.25	**6.37 (0.05)**	**7.97 (0.03)**	**4.69 (0.14)**
Original w = 0.25	6.14 (0.01)	7.90 (0.03)	4.38 (0.04)
Sig Diff.	p <0.001	p <0.001	p <0.001
w = 0.5	**6.39 (0.04)**	**8.02 (0.07)**	**4.66 (0.02)**
Original w = 0.5	6.14 (0.01)	7.90 (0.04)	4.39 (0.04)
Sig Diff.	p <0.001	p <0.001	p <0.001
w = 0.75	**6.43 (0.06)**	**8.09 (0.15)**	**4.66 (0.02)**
Original w = 0.75	6.14 (0.02)	7.92 (0.05)	4.39 (0.05)
Sig Diff.	p <0.001	p <0.001	p <0.001
Imp	**6.50 (0.12)**	**8.27 (0.27)**	**4.65 (0.05)**
Imp Original	6.16 (0.04)	7.97 (0.09)	4.39 (0.05)
Sig Diff.	p <0.001	p <0.001	p <0.001

Table J.33: Mean Total Distance Travelled by Object in Metres and Standard Deviation for the Hybrid System in the Randomly Generated Environments in the presence of a Partial Motor Fault in the Leader's Right Wheel

Weighting	Randomly Generated Environments		
	1	2	3
Exp	**6.07 (0.01)**	**8.21 (0.09)**	**4.45 (0.01)**
Exp Original	6.16 (0.04)	7.97 (0.09)	4.39 (0.05)
Sig Diff.	p <0.001	p <0.001	p <0.001
w = 0.25	**6.03 (0.04)**	**8.17 (0.06)**	**4.46 (0.02)**
Original w = 0.25	6.14 (0.01)	7.90 (0.03)	4.38 (0.04)
Sig Diff.	p <0.001	p <0.001	p <0.001
w = 0.5	**6.04 (0.05)**	**8.23 (0.05)**	**4.47 (0.02)**
Original w = 0.5	6.14 (0.01)	7.90 (0.04)	4.39 (0.04)
Sig Diff.	p <0.001	p <0.001	p <0.001
w = 0.75	**6.09 (0.11)**	**8.35 (0.14)**	**4.49 (0.03)**
Original w = 0.75	6.14 (0.02)	7.92 (0.05)	4.39 (0.05)
Sig Diff.	p <0.001	p <0.001	p <0.001
Imp	**6.18 (0.21)**	**8.67 (0.41)**	**4.51 (0.06)**
Imp Original	6.16 (0.04)	7.97 (0.09)	4.39 (0.05)
Sig Diff.	0.007	p <0.001	p <0.001

Table J.34: Mean Maximum Displacement of Object in Metres and Standard Deviation for the Hybrid System in the Line Following Environment in the presence of a Partial Motor Fault in the Leader's Left Wheel

Weighting	Line Following Environment Path		
	1	2	3
Exp	**0.012 (0.003)**	**0.013 (0.002)**	**0.012 (0.003)**
Exp Original	0.018 (0.006)	0.018 (0.006)	0.019 (0.005)
Sig Diff.	p <0.001	p <0.001	p <0.001
w = 0.25	**0.040 (0.005)**	**0.032 (0.006)**	**0.037 (0.007)**
Original w = 0.25	0.027 (0.008)	0.034 (0.009)	0.031 (0.009)
Sig Diff.	p <0.001	0.614	p <0.001
w = 0.5	**0.040 (0.005)**	**0.032 (0.005)**	**0.037 (0.006)**
Original w = 0.5	0.028 (0.007)	0.031 (0.006)	0.031 (0.006)
Sig Diff.	p <0.001	0.690	p <0.001
w = 0.75	**0.036 (0.007)**	**0.032 (0.005)**	**0.033 (0.006)**
Original w = 0.75	0.028 (0.006)	0.032 (0.004)	0.032 (0.006)
Sig Diff.	p <0.001	0.067	0.438
Imp	**0.033 (0.003)**	**0.032 (0.003)**	**0.032 (0.005)**
Imp Original	0.029 (0.005)	0.031 (0.005)	0.033 (0.006)
Sig Diff.	p <0.001	0.115	0.469

Table J.35: Mean Maximum Displacement of Object in Metres and Standard Deviation for the Hybrid System in the Line Following Environment in the presence of a Partial Motor Fault in the Leader's Right Wheel

Weighting	Line Following Environment Path		
	1	2	3
Exp	**0.010 (0.003)**	**0.014 (0.002)**	**0.013 (0.002)**
Exp Original	0.018 (0.006)	0.018 (0.006)	0.019 (0.005)
Sig Diff.	p <0.001	p <0.001	p <0.001
w = 0.25	**0.042 (0.005)**	**0.036 (0.005)**	**0.032 (0.003)**
Original w = 0.25	0.027 (0.008)	0.034 (0.009)	0.031 (0.009)
Sig Diff.	p <0.001	0.037	0.314
w = 0.5	**0.039 (0.007)**	**0.037 (0.005)**	**0.036 (0)**
Original w = 0.5	0.028 (0.007)	0.031 (0.006)	0.031 (0.006)
Sig Diff.	p <0.001	p <0.001	0.152
w = 0.75	**0.037 (0.007)**	**0.036 (0.005)**	**0.032 (0.003)**
Original w = 0.75	0.028 (0.006)	0.032 (0.004)	0.032 (0.006)
Sig Diff.	p <0.001	p <0.001	0.980
Imp	**0.032 (0.003)**	**0.034 (0.004)**	**0.033 (0.001)**
Imp Original	0.029 (0.005)	0.031 (0.005)	0.033 (0.006)
Sig Diff.	p <0.001	p <0.001	0.953

Table J.36: Mean Maximum Displacement of Object in Metres and Standard Deviation for the Hybrid System in the Simple and Cluttered Environments in the presence of a Partial Motor Fault in the Leader's Left Wheel

Weighting	Path			
	SE	CE	CE	CE
	1	1	2	3
Exp	**0.010 (0.004)**	**0.012 (0.001)**	**0.014 (0.002)**	**0.013 (0.002)**
Exp Original	0.018 (0.006)	0.019 (0.005)	0.016 (0.004)	0.017 (0.005)
Sig Diff.	p <0.001	p <0.001	p <0.001	p <0.001
w = 0.25	**0.017 (0.004)**	**0.027 (0.003)**	**0.025 (0.005)**	**0.026 (0.005)**
Original w = 0.25	0.025 (0.005)	0.029 (0.006)	0.028 (0.005)	0.028 (0.005)
Sig Diff.	p <0.001	0.023	p <0.001	0.008
w = 0.5	**0.021 (0.002)**	**0.029 (0.003)**	**0.027 (0.004)**	**0.028 (0.004)**
Original w = 0.5	0.024 (0.005)	0.030 (0.004)	0.029 (0.004)	0.030 (0.004)
Sig Diff.	p <0.001	0.526	p <0.001	p <0.001
w = 0.75	**0.030 (0.001)**	**0.034 (0.003)**	**0.032 (0.002)**	**0.033 (0.002)**
Original w = 0.75	0.029 (0.004)	0.034 (0.003)	0.034 (0.003)	0.034 (0.003)
Sig Diff.	0.339	0.200	p <0.001	0.111
Imp	**0.036 (0.003)**	**0.036 (0.003)**	**0.035 (0.002)**	**0.035 (0.002)**
Imp Original	0.031 (0.004)	0.037 (0.003)	0.038 (0.002)	0.038 (0.003)
Sig Diff.	p <0.001	p <0.001	p <0.001	p <0.001

Table J.37: Mean Maximum Displacement of Object in Metres and Standard Deviation for the Hybrid System in the Simple and Cluttered Environments in the presence of a Partial Motor Fault in the Leader's Right Wheel

Weighting	Path			
	SE	CE	CE	CE
	1	1	2	3
Exp	**0.011 (0.003)**	**0.014 (0.002)**	**0.012 (0.001)**	**0.012 (0.004)**
Exp Original	0.018 (0.006)	0.019 (0.005)	0.016 (0.004)	0.017 (0.005)
Sig Diff.	p <0.001	p <0.001	p <0.001	p <0.001
w = 0.25	**0.017 (0.004)**	**0.025 (0.003)**	**0.021 (0.002)**	**0.023 (0.003)**
Original w = 0.25	0.025 (0.005)	0.029 (0.006)	0.028 (0.005)	0.028 (0.005)
Sig Diff.	p <0.001	p <0.001	p <0.001	p <0.001
w = 0.5	**0.021 (0.003)**	**0.027 (0.003)**	**0.026 (0.002)**	**0.027 (0.003)**
Original w = 0.5	0.024 (0.005)	0.030 (0.004)	0.029 (0.004)	0.030 (0.004)
Sig Diff.	p <0.001	p <0.001	p <0.001	p <0.001
w = 0.75	**0.024 (0.003)**	**0.033 (0.002)**	**0.030 (0.003)**	**0.032 (0.002)**
Original w = 0.75	0.029 (0.004)	0.034 (0.003)	0.034 (0.003)	0.034 (0.003)
Sig Diff.	p <0.001	0.022	p <0.001	p <0.001
Imp	**0.027 (0.004)**	**0.035 (0.002)**	**0.035 (0.003)**	**0.035 (0.003)**
Imp Original	0.031 (0.004)	0.037 (0.003)	0.038 (0.002)	0.038 (0.003)
Sig Diff.	p <0.001	p <0.001	p <0.001	p <0.001

Table J.38: Mean Maximum Displacement of Object in Metres and Standard Deviation for the Hybrid System in the Randomly Generated Environments in the presence of a Partial Motor Fault in the Leader's Left Wheel

Weighting	Randomly Generated Environments		
	1	2	3
Exp	**0.012 (0.003)**	**0.011 (0.002)**	**N/A**
Exp Original	0.019 (0.005)	0.018 (0.006)	0.017 (0.005)
Sig Diff.	p <0.001	p <0.001	N/A
w = 0.25	**0.017 (0.004)**	**0.023 (0.004)**	**0.028 (0.007)**
Original w = 0.25	0.027 (0.005)	0.027 (0.006)	0.025 (0.006)
Sig Diff.	p <0.001	p <0.001	0.259
w = 0.5	**0.022 (0.002)**	**0.024 (0.004)**	**0.027 (0.001)**
Original w = 0.5	0.026 (0.005)	0.027 (0.005)	0.025 (0.005)
Sig Diff.	p <0.001	p <0.001	0.043
w = 0.75	**0.028 (0.002)**	**0.028 (0.002)**	**0.028 (0.001)**
Original w = 0.75	0.030 (0.003)	0.030 (0.003)	0.029 (0.004)
Sig Diff.	p <0.001	p <0.001	0.628
Imp	**0.032 (0.003)**	**0.031 (0.002)**	**0.028 (0.004)**
Imp Original	0.034 (0.004)	0.034 (0.003)	0.033 (0.004)
Sig Diff.	0.002	p <0.001	p <0.001

Table J.39: Mean Maximum Displacement of Object in Metres and Standard Deviation for the Hybrid System in the Randomly Generated Environments in the presence of a Partial Motor Fault in the Leader's Right Wheel

Weighting	Randomly Generated Environments		
	1	2	3
Exp	**0.013 (0.003)**	**0.013 (0.003)**	**0.011 (0.003)**
Exp Original	0.019 (0.005)	0.018 (0.006)	0.017 (0.005)
Sig Diff.	p <0.001	p <0.001	p <0.001
w = 0.25	**0.022 (0.004)**	**0.023 (0.004)**	**0.019 (0.004)**
Original w = 0.25	0.027 (0.005)	0.027 (0.006)	0.025 (0.006)
Sig Diff.	p <0.001	p <0.001	p <0.001
w = 0.5	**0.023 (0.003)**	**0.025 (0.003)**	**0.020 (0.003)**
Original w = 0.5	0.026 (0.005)	0.027 (0.005)	0.025 (0.005)
Sig Diff.	p <0.001	0.001	p <0.001
w = 0.75	**0.025 (0.002)**	**0.030 (0.002)**	**0.025 (0.003)**
Original w = 0.75	0.030 (0.003)	0.030 (0.003)	0.029 (0.004)
Sig Diff.	p <0.001	0.073	p <0.001
Imp	**0.028 (0.002)**	**0.032 (0.002)**	**0.027 (0.003)**
Imp Original	0.034 (0.004)	0.034 (0.003)	0.033 (0.004)
Sig Diff.	p <0.001	p <0.001	p <0.001

Table J.40: Mean Percentage Path Fidelity and Standard Deviation for the Hybrid System in the Line Following Environment in the presence of a Partial Motor Fault in the Leader's Left Wheel

Weighting	Line Following Environment Path		
	1	2	3
Exp	**90.59% (21.47%)**	**93.84% (15.84%)**	**74.88% (14.12%)**
Exp Original	90.75% (14.93%)	100% (∼0%)	99.40% (3.43%)
Sig Diff.	0.208	p <0.001	p <0.001
w = 0.25	**68.35% (19.11%)**	**85.71% (16.24%)**	**66.19% (21.86%)**
Original w = 0.25	78.02 (27.09%)	56.58% (25.54%)	79.35% (19.15%)
Sig Diff.	p <0.001	p <0.001	0.002
w = 0.5	**58.99% (23.61%)**	**90.15% (12.24%)**	**65.71% (26.46%)**
Original w = 0.5	86.48% (22.47%)	71.56% (25.02%)	90.18% (15.64%)
Sig Diff.	p <0.001	p <0.001	p <0.001
w = 0.75	**61.44% (27.35%)**	**90.42% (14.07%)**	**71.20% (23.54%)**
Original w = 0.75	93.25% (13.23%)	99.50% (2.86%)	91.65% (14.18%)
Sig Diff.	p <0.001	p <0.001	p <0.001
Imp	**87.35% (19.14%)**	**97.85% (5.62%)**	**77.32% (19.07%)**
Imp Original	93.00 (12.35%)	89.67% (14.17%)	96.57% (9.49%)
Sig Diff.	0.053	p <0.001	p <0.001

Table J.41: Mean Percentage Path Fidelity and Standard Deviation for the Hybrid System in the Line Following Environment in the presence of a Partial Motor Fault in the Leader's Right Wheel

Weighting	Line Following Environment Path		
	1	2	3
Exp	**100% (∼0%)**	**19.15% (24.32%)**	**86.67% (27.12%)**
Exp Original	90.75% (14.93%)	100% (∼0%)	99.40% (3.43%)
Sig Diff.	p <0.001	p <0.001	p <0.001
w = 0.25	**68.41% (22.62%)**	**38.48% (17.82%)**	**80.00% (0%)**
Original w = 0.25	78.02 (27.09%)	56.58% (25.54%)	79.35% (19.15%)
Sig Diff.	0.001	p <0.001	0.831
w = 0.5	**59.29% (25.83%)**	**42.28% (19.04%)**	**60.00% (0.00%)**
Original w = 0.5	86.48% (22.47%)	71.56% (25.02%)	90.18% (15.64%)
Sig Diff.	p <0.001	p <0.001	0.092
w = 0.75	**66.56% (21.69%)**	**40.98% (20.32%)**	**53.33% (11.55%)**
Original w = 0.75	93.25% (13.23%)	99.50% (2.86%)	91.65% (14.18%)
Sig Diff.	p <0.001	p <0.001	0.001
Imp	**86.25% (17.54%)**	**35.71% (19.56%)**	**66.67% (11.55%)**
Imp Original	93.00 (12.35%)	89.67% (14.17%)	96.57% (9.49%)
Sig Diff.	0.004	p <0.001	p <0.001

Table J.42: Mean Percentage Path Fidelity and Standard Deviation for the Hybrid System in the Simple and Cluttered Environments in the presence of a Partial Motor Fault in the Leader's Left Wheel

Weighting	Path			
	SE	CE	CE	CE
	1	1	2	3
Exp	**5.21% (1.51%)**	**4.43% (0.57%)**	**3.10% (0.98%)**	**4.60% (0.44%)**
Exp Original	56.36% (21.46%)	64.09% (15.65%)	72.96% (8.33%)	69.04 (15.25%)
Sig Diff.	p <0.001	p <0.001	p <0.001	p <0.001
w = 0.25	**4.22% (0.49%)**	**3.78% (0.25%)**	**4.07% (0.46%)**	**4.07% (1.11%)**
Original w = 0.25	71.04% (7.16%)	75.61% (7.70%)	75.69% (5.67%)	78.94% (5.27%)
Sig Diff.	p <0.001	p <0.001	p <0.001	p <0.001
w = 0.5	**4.27% (0.61%)**	**4.41% (0.39%)**	**4.57% (0.57%)**	**4.68% (1.78%)**
Original w = 0.5	71.77% (6.66%)	76.90% (6.14%)	75.59% (4.38%)	76.78% (5.26%)
Sig Diff.	p <0.001	p <0.001	p <0.001	p <0.001
w = 0.75	**4.74% (1.12%)**	**5.24% (1.49%)**	**5.67% (2.46%)**	**5.46% (2.80%)**
Original w = 0.75	71.61% (7.05%)	75.09% (5.39%)	73.03% (4.04%)	75.83% (4.32%)
Sig Diff.	p <0.001	p <0.001	p <0.001	p <0.001
Imp	**5.47% (2.56%)**	**8.75% (4.77%)**	**7.70% (4.50%)**	**6.29% (4.30%)**
Imp Original	68.40% (5.61%)	70.78% (3.55%)	69.44% (2.80%)	70.56% (3.35%)
Sig Diff.	p <0.001	p <0.001	p <0.001	p <0.001

Table J.43: Mean Percentage Path Fidelity and Standard Deviation for the Hybrid System in the Simple and Cluttered Environments in the presence of a Partial Motor Fault in the Leader's Right Wheel

Weighting	Path			
	SE	CE	CE	CE
	1	1	2	3
Exp	**0% (0%)**	**2.41% (0.50%)**	**0.55% (0.54%)**	**1.66% (1.46%)**
Exp Original	91.00% (2.12%)	64.09% (15.65%)	72.96% (8.33%)	69.04 (15.25%)
Sig Diff.	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$
w = 0.25	**0% (0%)**	**1.11% (0.44%)**	**0.13% (0.22%)**	**0.29% (0.61%)**
Original w = 0.25	91.24% (1.87%)	75.61% (7.70%)	75.69% (5.67%)	78.94% (5.27%)
Sig Diff.	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$
w = 0.5	**0% (0%)**	**0.88% (0.61%)**	**0.23% (0.42%)**	**0.44% (0.68%)**
Original w = 0.5	91.72% (1.71%)	76.90% (6.14%)	75.59% (4.38%)	76.78% (5.26%)
Sig Diff.	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$
w = 0.75	**0% (0%)**	**1.12% (0.93%)**	**0.80% (0.94%)**	**0.86% (1.19%)**
Original w = 0.75	91.33% (1.88%)	75.09% (5.39%)	73.03% (4.04%)	75.83% (4.32%)
Sig Diff.	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$
Imp	**$\sim$0% (0.12%)**	**1.64% (2.20%)**	**1.51% (2.00%)**	**1.86% (2.40%)**
Imp Original	91.79% (1.60%)	70.78% (3.55%)	69.44% (2.80%)	70.56% (3.35%)
Sig Diff.	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$

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Table J.44: Mean Percentage Path Fidelity and Standard Deviation for the Hybrid System in the Randomly Generated Environments in the presence of a Partial Motor Fault in the Leader's Left Wheel

Weighting	Randomly Generated Environments		
	1	2	3
Exp	**1.27% (0.42%)**	**5.21% (1.51%)**	**N/A**
Exp Original	54.36% (23.85%)	56.36% (21.46%)	49.84% (23.26%)
Sig Diff.	p <0.001	p <0.001	N/A
w = 0.25	**1.04% (0.18%)**	**4.22% (0.49%)**	**0.64% (1.46%)**
Original w = 0.25	74.08% (8.48%)	71.04% (7.16%)	63.48% (14.71%)
Sig Diff.	p <0.001	p <0.001	p <0.001
w = 0.5	**0.99% (0.39%)**	**4.27% (0.61%)**	**0% (0%)**
Original w = 0.5	76.73% (8.01%)	71.77% (6.66%)	66.30% (15.08%)
Sig Diff.	p <0.001	p <0.001	p <0.001
w = 0.75	**1.20% (0.40%)**	**4.74% (1.12%)**	**0% (0%)**
Original w = 0.75	75.83% (8.16%)	71.61% (7.05%)	64.37% (17.10%)
Sig Diff.	p <0.001	p <0.001	p <0.001
Imp	**1.27% (0.75%)**	**5.47% (2.56%)**	**0% (0%)**
Imp Original	75.31% (9.04%)	68.40% (5.61%)	61.80% (14.57%)
Sig Diff.	p <0.001	p <0.001	p <0.001

Table J.45: Mean Percentage Path Fidelity and Standard Deviation for the Hybrid System in the Randomly Generated Environments in the presence of a Partial Motor Fault in the Leader's Right Wheel

Weighting	Randomly Generated Environments		
	1	2	3
Exp	**4.04% (2.78%)**	**2.96% (1.23%)**	**1.46% (0.26%)**
Exp Original	54.36% (23.85%)	56.36% (21.46%)	49.84% (23.26%)
Sig Diff.	$p < 0.001$	$p < 0.001$	$p < 0.001$
w = 0.25	**0.62% (0.64%)**	**3.10% (0.99%)**	**1.39% (0.49%)**
Original w = 0.25	74.08% (8.48%)	71.04% (7.16%)	63.48% (14.71%)
Sig Diff.	$p < 0.001$	$p < 0.001$	$p < 0.001$
w = 0.5	**1.05% (0.87%)**	**3.29% (1.25%)**	**1.34% (0.52%)**
Original w = 0.5	76.73% (8.01%)	71.77% (6.66%)	66.30% (15.08%)
Sig Diff.	8.77E-35	1.47E-34	3.82E-34
w = 0.75	**1.46% (1.16%)**	**3.15% (1.15%)**	**1.16% (0.54%)**
Original w = 0.75	75.83% (8.16%)	71.61% (7.05%)	64.37% (17.10%)
Sig Diff.	$p < 0.001$	$p < 0.001$	$p < 0.001$
Imp	**2.54% (2.12%)**	**3.12% (1.27%)**	**1.02% (0.63%)**
Imp Original	75.31% (9.04%)	68.40% (5.61%)	61.80% (14.57%)
Sig Diff.	$p < 0.001$	$p < 0.001$	$p < 0.001$

J.2.2 Partial Motor Fault in Follower Wheels

Table J.46: Percentage Task Completion for the Hybrid System in the Line Following Environment in the presence of a Partial Motor Fault in Follower Wheel 1

Weighting	Line Following Environment Path		
	1	2	3
Exp	**100.00%**	**100.00%**	**100.00%**
Exp Original	100.00%	100.00%	100.00%
w = 0.25	**57.00%**	**54.00%**	**27.00%**
Original w = 0.25	91.00%	76.00%	62.00%
w = 0.5	**75.00%**	**76.00%**	**36.00%**
Original w = 0.5	98.00%	92.00%	57.00%
w = 0.75	**98.00%**	**89.00%**	**64.00%**
Original w = 0.75	100.00%	100.00%	79.00%
Imp	**100.00%**	**100.00%**	**100.00%**
Imp Original	100.00%	100.00%	99.00%

Table J.47: Percentage Task Completion for the Hybrid System in the Line Following Environment in the presence of a Partial Motor Fault in Follower Wheel 2

Weighting	Line Following Environment Path		
	1	2	3
Exp	**100.00%**	**100.00%**	**100.00%**
Exp Original	100.00%	100.00%	100.00%
w = 0.25	**96.00%**	**97.00%**	**76.00%**
Original w = 0.25	91.00%	76.00%	62.00%
w = 0.5	**100.00%**	**97.00%**	**75.00%**
Original w = 0.5	98.00%	92.00%	57.00%
w = 0.75	**100.00%**	**100.00%**	**95.00%**
Original w = 0.75	100.00%	100.00%	79.00%
Imp	**100.00%**	**100.00%**	**95.00%**
Imp Original	100.00%	100.00%	99.00%

Table J.48: Percentage Task Completion for the Hybrid System in the Line Following Environment in the presence of a Partial Motor Fault in Follower Wheel 3

Weighting	Line Following Environment Path		
	1	2	3
Exp	**100.00%**	**100.00%**	**100.00%**
Exp Original	100.00%	100.00%	100.00%
w = 0.25	**98.00%**	**79.00%**	**78.00%**
Original w = 0.25	91.00%	76.00%	62.00%
w = 0.5	**100.00%**	**99.00%**	**82.00%**
Original w = 0.5	98.00%	92.00%	57.00%
w = 0.75	**100.00%**	**100.00%**	**94.00%**
Original w = 0.75	100.00%	100.00%	79.00%
Imp	**100.00%**	**100.00%**	**100.00%**
Imp Original	100.00%	100.00%	99.00%

Table J.49: Percentage Task Completion for the Hybrid System in the Simple and Cluttered Environments in the presence of a Partial Motor Fault in Follower Wheel 1

Weighting	Path			
	SE	CE	CE	CE
	1	1	2	3
Exp	**100.00%**	**35.00%**	**73.00%**	**100.00%**
Exp Original	100.00%	100.00%	60.00%	100.00%
w = 0.25	**100.00%**	**66.00%**	**100.00%**	**100.00%**
Original w = 0.25	100.00%	100.00%	100.00%	100.00%
w = 0.5	**100.00%**	**81.00%**	**100.00%**	**100.00%**
Original w = 0.5	100.00%	100.00%	100.00%	100.00%
w = 0.75	**100.00%**	**81.00%**	**100.00%**	**100.00%**
Original w = 0.75	100.00%	100.00%	100.00%	100.00%
Imp	**100.00%**	**80.00%**	**100.00%**	**100.00%**
Imp Original	100.00%	100.00%	100.00%	100.00%

Table J.50: Percentage Task Completion for the Hybrid System in the Simple and Cluttered Environments in the presence of a Partial Motor Fault in Follower Wheel 2

Weighting	Path			
	SE	CE	CE	CE
	1	1	2	3
Exp	**100.00%**	**22.00%**	**67.00%**	**100.00%**
Exp Original	100.00%	100.00%	60.00%	100.00%
w = 0.25	**100.00%**	**72.00%**	**100.00%**	**100.00%**
Original w = 0.25	100.00%	100.00%	100.00%	100.00%
w = 0.5	**100.00%**	**78.00%**	**100.00%**	**100.00%**
Original w = 0.5	100.00%	100.00%	100.00%	100.00%
w = 0.75	**100.00%**	**69.00%**	**100.00%**	**100.00%**
Original w = 0.75	100.00%	100.00%	100.00%	100.00%
Imp	**100.00%**	**77.00%**	**100.00%**	**100.00%**
Imp Original	100.00%	100.00%	100.00%	100.00%

Table J.51: Percentage Task Completion for the Hybrid System in the Randomly Generated Environments in the presence of a Partial Motor Fault in Follower Wheel 3

Weighting	Path			
	SE	CE	CE	CE
	1	1	2	3
Exp	**100.00%**	**34.00%**	**64.00%**	**100.00%**
Exp Original	100.00%	100.00%	60.00%	100.00%
w = 0.25	**100.00%**	**76.00%**	**100.00%**	**100.00%**
Original w = 0.25	100.00%	100.00%	100.00%	100.00%
w = 0.5	**100.00%**	**81.00%**	**100.00%**	**100.00%**
Original w = 0.5	100.00%	100.00%	100.00%	100.00%
w = 0.75	**100.00%**	**80.00%**	**100.00%**	**100.00%**
Original w = 0.75	100.00%	100.00%	100.00%	100.00%
Imp	**100.00%**	**75.00%**	**100.00%**	**100.00%**
Imp Original	100.00%	100.00%	100.00%	100.00%

Table J.52: Percentage Task Completion for the Hybrid System in the Randomly Generated Environments in the presence of a Partial Motor Fault in Follower Wheel 1

Weighting	Randomly Generated Environments		
	1	2	3
Exp	**100.00%**	**100.00%**	**86.00%**
Exp Original	100.00%	100.00%	93.00%
w = 0.25	**100.00%**	**100.00%**	**100.00%**
Original w = 0.25	100.00%	100.00%	100.00%
w = 0.5	**100.00%**	**100.00%**	**100.00%**
Original w = 0.5	100.00%	100.00%	100.00%
w = 0.75	**100.00%**	**100.00%**	**100.00%**
Original w = 0.75	100.00%	100.00%	100.00%
Imp	**100.00%**	**100.00%**	**100.00%**
Imp Original	100.00%	100.00%	100.00%

Table J.53: Percentage Task Completion for the Hybrid System in the Randomly Generated Environments in the presence of a Partial Motor Fault in Follower Wheel 2

Weighting	Randomly Generated Environments		
	1	2	3
Exp	**100.00%**	**100.00%**	**87.00%**
Exp Original	100.00%	100.00%	93.00%
w = 0.25	**100.00%**	**100.00%**	**100.00%**
Original w = 0.25	100.00%	100.00%	100.00%
w = 0.5	**100.00%**	**100.00%**	**100.00%**
Original w = 0.5	100.00%	100.00%	100.00%
w = 0.75	**100.00%**	**100.00%**	**100.00%**
Original w = 0.75	100.00%	100.00%	100.00%
Imp	**100.00%**	**100.00%**	**100.00%**
Imp Original	100.00%	100.00%	100.00%

Table J.54: Percentage Task Completion for the Hybrid System in the Randomly Generated Environments in the presence of a Partial Motor Fault in Follower Wheel 3

Weighting	Randomly Generated Environments		
	1	2	3
Exp	**100.00%**	**100.00%**	**90.00%**
Exp Original	100.00%	100.00%	93.00%
w = 0.25	**100.00%**	**100.00%**	**100.00%**
Original w = 0.25	100.00%	100.00%	100.00%
w = 0.5	**100.00%**	**100.00%**	**100.00%**
Original w = 0.5	100.00%	100.00%	100.00%
w = 0.75	**100.00%**	**100.00%**	**100.00%**
Original w = 0.75	100.00%	100.00%	100.00%
Imp	**100.00%**	**100.00%**	**100.00%**
Imp Original	100.00%	100.00%	100.00%

Table J.55: Mean Time Taken in Seconds and Standard Deviation for the Hybrid System in the Line Following Environment in the presence of a Partial Motor Fault in Follower Wheel 1

Weighting	Line Following Environment Path		
	1	2	3
Exp	**129.56 (46.06)**	**111.24 (40.16)**	**128.38 (43.97)**
Exp Original	121.81 (46.49)	119.22 (40.55)	121.15 (35.70)
Sig Diff.	p <0.001	0.083	0.442
w = 0.25	**297.36 (266.19)**	**207.73 (72.53)**	**141.06 (21.34)**
Original w = 0.25	134.35 (103.35)	206.05 (214.39)	118.71 (32.50)
Sig Diff.	p <0.001	p <0.001	0.002
w = 0.5	**199.52 (203.80)**	**186.75 (176.56)**	**120.56 (14.03)**
Original w = 0.5	131.89 (147.99)	118.76 (101.62)	107.65 (19.52)
Sig Diff.	p <0.001	0.006	p <0.001
w = 0.75	**105.60 (86.07)**	**127.27 (132.30)**	**101.21 (20.32)**
Original w = 0.75	90.46 (21.63)	77.43 (17.20)	94.37 (21.03)
Sig Diff.	0.326	p <0.001	0.065
Imp	**85.52 (18.98)**	**83.66 (21.10)**	**88.17 (21.01)**
Imp Original	80.25 (18.25)	79.18 (18.89)	81.45 (19.03)
Sig Diff.	0.053	0.245	0.013

Table J.56: Mean Time Taken in Seconds and Standard Deviation for the Hybrid System in the Line Following Environment in the presence of a Partial Motor Fault in Follower Wheel 2

Weighting	Line Following Environment Path		
	1	2	3
Exp	**111.78 (39.95)**	**116.91 (49.30)**	**121.00 (41.92)**
Exp Original	121.81 (46.49)	119.22 (40.55)	121.15 (35.70)
Sig Diff.	0.133	0.336	0.454
w = 0.25	**135.75 (102.64)**	**122.02 (71.72)**	**110.73 (29.20)**
Original w = 0.25	134.35 (103.35)	206.05 (214.39)	118.71 (32.50)
Sig Diff.	0.796	0.102	0.098
w = 0.5	**96.97 (27.35)**	**108.00 (74.34)**	**99.65 (18.96)**
Original w = 0.5	131.89 (147.99)	118.76 (101.62)	107.65 (19.52)
Sig Diff.	0.544	0.376	0.011
w = 0.75	**84.22 (18.19)**	**83.14 (19.78)**	**92.92 (22.04)**
Original w = 0.75	90.46 (21.63)	77.43 (17.20)	94.37 (21.03)
Sig Diff.	0.054	0.030	0.624
Imp	**80.68 (18.78)**	**81.55 (20.04)**	**82.84 (19.88)**
Imp Original	80.25 (18.25)	79.18 (18.89)	81.45 (19.03)
Sig Diff.	0.919	0.661	0.607

Table J.57: Mean Time Taken in Seconds and Standard Deviation for the Hybrid System in the Line Following Environment in the presence of a Partial Motor Fault in Follower Wheel 3

Weighting	Line Following Environment Path		
	1	2	3
Exp	**111.78 (39.95)**	**116.91 (49.30)**	**121.00 (41.92)**
Exp Original	121.81 (46.49)	119.22 (40.55)	121.15 (35.70)
Sig Diff.	0.133	0.336	0.454
w = 0.25	**135.75 (102.64)**	**122.02 (71.72)**	**110.73 (29.20)**
Original w = 0.25	134.35 (103.35)	206.05 (214.39)	118.71 (32.50)
Sig Diff.	0.796	0.102	0.098
w = 0.5	**96.97 (27.35)**	**108.00 (74.34)**	**99.65 (18.96)**
Original w = 0.5	131.89 (147.99)	118.76 (101.62)	107.65 (19.52)
Sig Diff.	0.544	0.376	0.011
w = 0.75	**84.22 (18.19)**	**83.14 (19.78)**	**92.92 (22.04)**
Original w = 0.75	90.46 (21.63)	77.43 (17.20)	94.37 (21.03)
Sig Diff.	0.054	0.030	0.624
Imp	**80.68 (18.78)**	**81.55 (20.04)**	**82.84 (19.88)**
Imp Original	80.25 (18.25)	79.18 (18.89)	81.45 (19.03)
Sig Diff.	0.919	0.661	0.607

Table J.58: Mean Time Taken in Seconds and Standard Deviation for the Hybrid System in the Simple and Cluttered Environments in the presence of a Partial Motor Fault in Follower Wheel 1

Weighting	Path			
	SE	CE	CE	CE
	1	1	2	3
Exp	**177.24 (60.42)**	**323.34 (30.55)**	**448.86 (118.90)**	**384.18 (102.76)**
Exp Original	170.98 (62.64)	414.36 (127.10)	445.31 (113.61)	431.18 (120.53)
Sig Diff.	0.237	p <0.001	0.991	0.003
w = 0.25	**133.72 (30.05)**	**246.61 (39.53)**	**276.41 (64.76)**	**286.04 (65.72)**
Original w = 0.25	124.66 (29.48)	270.09 (67.01)	263.68 (60.60)	273.22 (65.83)
Sig Diff.	0.026	0.270	0.176	0.143
w = 0.5	**123.62 (27.76)**	**260.55 (47.43)**	**282.04 (71.55)**	**274.93 (67.81)**
Original w = 0.5	129.72 (50.93)	283.73 (66.40)	270.75 (58.86)	257.41 (61.12)
Sig Diff.	0.236	0.046	0.369	0.051
w = 0.75	**119.60 (26.61)**	**250.21 (43.01)**	**272.10 (67.40)**	**273.11 (66.11)**
Original w = 0.75	116.27 (27.92)	281.52 (68.64)	263.25 (63.95)	264.54 (59.27)
Sig Diff.	0.223	0.007	0.344	0.451
Imp	**115.05 (27.85)**	**258.10 (50.82)**	**274.78 (67.70)**	**260.59 (59.20)**
Imp Original	118.84 (26.18)	271.44 (67.54)	257.93 (58.21)	263.55 (65.87)
Sig Diff.	0.217	0.403	0.094	0.958

Table J.59: Mean Time Taken in Seconds and Standard Deviation for the Hybrid System in the Simple and Cluttered Environments in the presence of a Partial Motor Fault in Follower Wheel 2

Weighting	Path			
	SE	CE	CE	CE
	1	1	2	3
Exp	**169.41 (57.63)**	**325.50 (10.43)**	**471.95 (116.26)**	**392.30 (106.88)**
Exp Original	170.98 (62.64)	414.36 (127.10)	445.31 (113.61)	431.18 (120.53)
Sig Diff.	0.846	0.005	0.145	0.009
w = 0.25	**127.63 (29.10)**	**255.43 (48.72)**	**291.32 (68.75)**	**271.13 (62.03)**
Original w = 0.25	124.66 (29.48)	270.09 (67.01)	263.68 (60.60)	273.22 (65.83)
Sig Diff.	0.481	0.461	0.003	0.941
w = 0.5	**123.60 (31.24)**	**248.42 (58.37)**	**263.78 (58.92)**	**259.41 (62.92)**
Original w = 0.5	129.72 (50.93)	283.73 (66.40)	270.75 (58.86)	257.41 (61.12)
Sig Diff.	0.102	p <0.001	0.305	0.843
w = 0.75	**115.28 (27.94)**	**257.52 (56.54)**	**261.86 (65.55)**	**262.26 (60.02)**
Original w = 0.75	116.27 (27.92)	281.52 (68.64)	263.25 (63.95)	264.54 (59.27)
Sig Diff.	0.765	0.024	0.959	0.735
Imp	**120.02 (27.00)**	**257.17 (65.18)**	**269.19 (65.82)**	**261.18 (60.39)**
Imp Original	118.84 (26.18)	271.44 (67.54)	257.93 (58.21)	263.55 (65.87)
Sig Diff.	0.759	0.105	0.267	0.919

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Table J.60: Mean Time Taken in Seconds and Standard Deviation for the Hybrid System in the Simple and Cluttered Environments in the presence of a Partial Motor Fault in Follower Wheel 3

Weighting	Path			
	SE	CE	CE	CE
	1	1	2	3
Exp	**164.20 (57.19)**	**327.85 (14.78)**	**484.70 (117.83)**	**407.64 (124.17)**
Exp Original	170.98 (62.64)	414.36 (127.10)	445.31 (113.61)	431.18 (120.53)
Sig Diff.	0.511	0.002	0.046	0.065
w = 0.25	**128.91 (29.68)**	**264.38 (53.16)**	**276.82 (63.55)**	**263.58 (61.04)**
Original w = 0.25	124.66 (29.48)	270.09 (67.01)	263.68 (60.60)	273.22 (65.83)
Sig Diff.	0.305	0.994	0.133	0.297
w = 0.5	**121.26 (27.66)**	**248.41 (39.70)**	**256.52 (58.30)**	**256.57 (58.10)**
Original w = 0.5	129.72 (50.93)	283.73 (66.40)	270.75 (58.86)	257.41 (61.12)
Sig Diff.	0.050	p <0.001	0.046	0.905
w = 0.75	**118.84 (27.94)**	**250.31 (54.78)**	**262.12 (61.55)**	**262.18 (64.16)**
Original w = 0.75	116.27 (27.92)	281.52 (68.64)	263.25 (63.95)	264.54 (59.27)
Sig Diff.	0.407	0.002	0.978	0.577
Imp	**114.72 (28.57)**	**271.27 (63.19)**	**271.78 (66.85)**	**272.53 (65.06)**
Imp Original	118.84 (26.18)	271.44 (67.54)	257.93 (58.21)	263.55 (65.87)
Sig Diff.	0.165	0.821	0.204	0.325

Table J.61: Mean Time Taken in Seconds and Standard Deviation for the Hybrid System in the Randomly Generated Environments in the presence of a Partial Motor Fault in Follower Wheel 1

Weighting	Randomly Generated Environments		
	1	2	3
Exp	**199.88 (63.39)**	**266.17 (79.51)**	**166.66 (73.40)**
Exp Original	189.45 (57.78)	266.01 (80.07)	181.78 (94.63)
Sig Diff.	0.199	0.872	0.226
w = 0.25	**153.17 (31.58)**	**190.63 (41.56)**	**108.38 (24.68)**
Original w = 0.25	138.24 (29.51)	172.47 (40.02)	104.11 (24.81)
Sig Diff.	p <0.001	p <0.001	0.120
w = 0.5	**140.26 (31.52)**	**187.49 (43.93)**	**106.33 (23.02)**
Original w = 0.5	140.64 (30.78)	173.53 (38.21)	105.65 (22.36)
Sig Diff.	0.820	0.031	0.883
w = 0.75	**135.04 (31.07)**	**180.14 (45.04)**	**100.30 (22.35)**
Original w = 0.75	137.31 (31.90)	174.68 (42.70)	100.78 (24.22)
Sig Diff.	0.517	0.335	0.943
Imp	**136.05 (31.14)**	**170.64 (39.61)**	**100.95 (22.68)**
Imp Original	137.92 (34.28)	168.28 (41.27)	95.06 (20.45)
Sig Diff.	0.931	0.356	0.070

Table J.62: Mean Time Taken in Seconds and Standard Deviation for the Hybrid System in the Randomly Generated Environments in the presence of a Partial Motor Fault in Follower Wheel 2

Weighting	Randomly Generated Environments		
	1	2	3
Exp	**204.76 (64.02)**	**264.01 (75.65)**	**167.71 (77.77)**
Exp Original	189.45 (57.78)	266.01 (80.07)	181.78 (94.63)
Sig Diff.	0.050	0.726	0.370
w = 0.25	**144.20 (36.36)**	**172.80 (40.37)**	**102.15 (22.53)**
Original w = 0.25	138.24 (29.51)	172.47 (40.02)	104.11 (24.81)
Sig Diff.	0.482	0.921	0.662
w = 0.5	**138.48 (31.95)**	**173.56 (40.91)**	**97.90 (23.44)**
Original w = 0.5	140.64 (30.78)	173.53 (38.21)	105.65 (22.36)
Sig Diff.	0.471	0.799	0.009
w = 0.75	**139.90 (32.55)**	**179.43 (43.19)**	**98.76 (22.89)**
Original w = 0.75	137.31 (31.90)	174.68 (42.70)	100.78 (24.22)
Sig Diff.	0.668	0.410	0.651
Imp	**139.19 (31.91)**	**164.56 (40.32)**	**100.74 (24.56)**
Imp Original	137.92 (34.28)	168.28 (41.27)	95.06 (20.45)
Sig Diff.	0.661	0.513	0.140

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Table J.63: Mean Time Taken in Seconds and Standard Deviation for the Hybrid System in the Randomly Generated Environments in the presence of a Partial Motor Fault in Follower Wheel 3

Weighting	Randomly Generated Environments		
	1	2	3
Exp	**199.92 (59.51)**	**274.52 (86.33)**	**192.85 (99.87)**
Exp Original	189.45 (57.78)	266.01 (80.07)	181.78 (94.63)
Sig Diff.	0.088	0.352	0.417
w = 0.25	**146.98 (35.72)**	**178.53 (42.24)**	**103.15 (23.96)**
Original w = 0.25	138.24 (29.51)	172.47 (40.02)	104.11 (24.81)
Sig Diff.	0.170	0.344	0.768
w = 0.5	**134.71 (31.03)**	**173.21 (38.49)**	**100.14 (22.16)**
Original w = 0.5	140.64 (30.78)	173.53 (38.21)	105.65 (22.36)
Sig Diff.	0.132	0.888	0.067
w = 0.75	**132.55 (31.31)**	**176.40 (42.84)**	**104.62 (23.49)**
Original w = 0.75	137.31 (31.90)	174.68 (42.70)	100.78 (24.22)
Sig Diff.	0.174	0.800	0.196
Imp	**139.07 (30.64)**	**178.92 (42.27)**	**102.65 (21.37)**
Imp Original	137.92 (34.28)	168.28 (41.27)	95.06 (20.45)
Sig Diff.	0.576	0.054	0.010

Table J.64: Mean Total Distance Travelled by Object in Metres and Standard Deviation for the Hybrid System in the Line Following Environment in the presence of a Partial Motor Fault in Follower Wheel 1

Weighting	Line Following Environment Path		
	1	2	3
Exp	**3.52 (0.06)**	**3.32 (0.06)**	**3.43 (0.05)**
Exp Original	3.51 (0.06)	3.33 (0.06)	3.42 (0.05)
Sig Diff.	0.135	0.072	0.294
w = 0.25	**5.29 (2.52)**	**4.32 (0.85)**	**3.57 (0.07)**
Original w = 0.25	3.80 (0.99)	4.32 (1.83)	3.51 (0.08)
Sig Diff.	p <0.001	0.035	0.003
w = 0.5	**4.50 (1.94)**	**4.26 (1.73)**	**3.55 (0.05)**
Original w = 0.5	3.89 (1.46)	3.63 (0.91)	3.52 (0.07)
Sig Diff.	p <0.001	0.014	0.007
w = 0.75	**3.66 (0.84)**	**3.75 (1.49)**	**3.50 (0.05)**
Original w = 0.75	3.52 (0.06)	3.32 (0.06)	3.49 (0.07)
Sig Diff.	0.603	p <0.001	0.4321
Imp	**3.51 (0.05)**	**3.34 (0.007)**	**3.45 (0.06)**
Imp Original	3.50 (0.05)	3.36 (0.07)	3.45 (0.06)
Sig Diff.	0.430	0.044	0.965

Table J.65: Mean Total Distance Travelled by Object in Metres and Standard Deviation for the Hybrid System in the Line Following Environment in the presence of a Partial Motor Fault in Follower Wheel 2

Weighting	Line Following Environment Path		
	1	2	3
Exp	**3.49 (0.06)**	**3.32 (0.06)**	**3.42 (0.05)**
Exp Original	3.51 (0.06)	3.33 (0.06)	3.42 (0.05)
Sig Diff.	0.091	0.061	0.843
w = 0.25	**3.79 (0.96)**	**3.47 (0.64)**	**3.49 (0.08)**
Original w = 0.25	3.80 (0.99)	4.32 (1.83)	3.51 (0.08)
Sig Diff.	0.006	$p < 0.001$	0.044
w = 0.5	**3.53 (0.21)**	**3.51 (0.74)**	**3.49 (0.07)**
Original w = 0.5	3.89 (1.46)	3.63 (0.91)	3.52 (0.07)
Sig Diff.	0.279	$p < 0.001$	0.043
w = 0.75	**3.50 (0.05)**	**3.33 (0.07)**	**3.48 (0.07)**
Original w = 0.75	3.52 (0.06)	3.32 (0.06)	3.49 (0.07)
Sig Diff.	0.024	0.200	0.209
Imp	**3.50 (0.06)**	**3.35 (0.07)**	**3.45 (0.06)**
Imp Original	3.50 (0.05)	3.36 (0.07)	3.45 (0.06)
Sig Diff.	0.925	0.819	0.656

Table J.66: Mean Total Distance Travelled by Object in Metres and Standard Deviation for the Hybrid System in the Line Following Environment in the presence of a Partial Motor Fault in Follower Wheel 3

Weighting	Line Following Environment Path		
	1	2	3
Exp	**3.50 (0.06)**	**3.34 (0.06)**	**3.43 (0.05)**
Exp Original	3.50 (0.05)	3.36 (0.07)	3.45 (0.06)
Sig Diff.	0.439	0.743	0.214
w = 0.25	**3.66 (0.87)**	**3.81 (1.31)**	**3.48 (0.05)**
Original w = 0.25	3.80 (0.99)	4.32 (1.83)	3.51 (0.08)
Sig Diff.	$p < 0.001$	0.001	0.009
w = 0.5	**3.51 (0.05)**	**3.36 (0.05)**	**3.49 (0.07)**
Original w = 0.5	3.89 (1.46)	3.63 (0.91)	3.52 (0.07)
Sig Diff.	0.193	$p < 0.001$	0.042
w = 0.75	**3.51 (0.05)**	**3.35 (0.07)**	**3.45 (0.07)**
Original w = 0.75	3.52 (0.06)	3.32 (0.06)	3.49 (0.07)
Sig Diff.	0.220	$p < 0.001$	$p < 0.001$
Imp	**3.51 (0.06)**	**3.36 (0.06)**	**3.46 (0.06)**
Imp Original	3.50 (0.05)	3.36 (0.07)	3.45 (0.06)
Sig Diff.	0.652	0.848	0.137

Table J.67: Mean Total Distance Travelled by Object in Metres and Standard Deviation for the Hybrid System in Simple and Cluttered Environments in the presence of a Partial Motor Fault in Follower Wheel 1

Weighting	Path			
	SE	CE	CE	CE
	1	1	2	3
Exp	**5.27 (0.05)**	**13.04 (0.11)**	**12.50 (0.06)**	**12.42 (0.14)**
Exp Original	5.27 (0.05)	12.82 (0.20)	12.51 (0.06)	12.40 (0.14)
Sig Diff.	0.3679	p <0.001	0.2808	0.215
w = 0.25	**5.27 (0.05)**	**12.69 (0.03)**	**12.41 (0.01)**	**12.25 (0.02)**
Original w = 0.25	5.27 (0.05)	12.64 (0.08)	12.43 (0.01)	12.27 (0.02)
Sig Diff.	0.997	p <0.001	p <0.001	p <0.001
w = 0.5	**5.26 (0.05)**	**12.69 (0.02)**	**12.43 (0.02)**	**12.25 (0.01)**
Original w = 0.5	5.28 (0.05)	12.69 (0.05)	12.45 (0.04)	12.28 (0.04)
Sig Diff.	0.011	0.028	p <0.001	p <0.001
w = 0.75	**5.26 (0.05)**	**12.70 (0.02)**	**12.46 (0.06)**	**12.28 (0.04)**
Original w = 0.75	5.27 (0.06)	12.76 (0.14)	12.53 (0.12)	12.36 (0.10)
Sig Diff.	0.686	p <0.001	p <0.001	p <0.001
Imp	**5.26 (0.06)**	**12.73 (0.03)**	**12.49 (0.08)**	**12.30 (0.06)**
Imp Original	5.28 (0.06)	12.85 (0.25)	12.63 (0.21)	12.52 (0.24)
Sig Diff.	0.005	p <0.001	p <0.001	p <0.001

Table J.68: Mean Total Distance Travelled by Object in Metres and Standard Deviation for the Hybrid System in Simple and Cluttered Environments in the presence of a Partial Motor Fault in Follower Wheel 2

Weighting	Path			
	SE	CE	CE	CE
	1	1	2	3
Exp	**5.27 (0.05)**	**13.03 (0.07)**	**12.49 (0.06)**	**12.43 (0.14)**
Exp Original	5.27 (0.05)	12.82 (0.20)	12.51 (0.06)	12.40 (0.14)
Sig Diff.	0.910	p <0.001	0.042	0.150
w = 0.25	**5.27 (0.05)**	**12.69 (0.03)**	**12.42 (0.01)**	**12.25 (0.02)**
Original w = 0.25	5.27 (0.05)	12.64 (0.08)	12.43 (0.01)	12.27 (0.02)
Sig Diff.	0.710	p <0.001	p <0.001	p <0.001
w = 0.5	**5.27 (0.06)**	**12.70 (0.03)**	**12.44 (0.04)**	**12.27 (0.03)**
Original w = 0.5	5.28 (0.05)	12.69 (0.05)	12.45 (0.04)	12.28 (0.04)
Sig Diff.	0.077	0.184	p <0.001	0.002
w = 0.75	**5.26 (0.06)**	**12.74 (0.06)**	**12.49 (0.10)**	**12.31 (0.07)**
Original w = 0.75	5.27 (0.06)	12.76 (0.14)	12.53 (0.12)	12.36 (0.10)
Sig Diff.	0.492	0.175	p <0.001	p <0.001
Imp	**5.28 (0.06)**	**12.83 (0.18)**	**12.62 (0.22)**	**12.42 (0.17)**
Imp Original	5.28 (0.06)	12.85 (0.25)	12.63 (0.21)	12.52 (0.24)
Sig Diff.	0.805	0.376	0.041	p <0.001

Table J.69: Mean Total Distance Travelled by Object in Metres and Standard Deviation for the Hybrid System in Simple and Cluttered Environments in the presence of a Partial Motor Fault in Follower Wheel 3

Weighting	Path			
	SE	CE	CE	CE
	1	1	2	3
Exp	**5.26 (0.05)**	**13.03 (0.09)**	**12.49 (0.06)**	**12.42 (0.15)**
Exp Original	5.28 (0.06)	12.85 (0.25)	12.63 (0.21)	12.52 (0.24)
Sig Diff.	0.319	p <0.001	0.010	0.454
w = 0.25	**5.27 (0.05)**	**12.69 (0.03)**	**12.42 (0.01)**	**12.25 (0.02)**
Original w = 0.25	5.27 (0.05)	12.64 (0.08)	12.43 (0.01)	12.27 (0.02)
Sig Diff.	0.619	0.002	p <0.001	p <0.001
w = 0.5	**5.27 (0.05)**	**12.69 (0.02)**	**12.44 (0.03)**	**12.26 (0.02)**
Original w = 0.5	5.28 (0.05)	12.69 (0.05)	12.45 (0.04)	12.28 (0.04)
Sig Diff.	0.051	0.803	p <0.001	p <0.001
w = 0.75	**5.27 (0.06)**	**12.73 (0.05)**	**12.50 (0.09)**	**12.32 (0.09)**
Original w = 0.75	5.27 (0.06)	12.76 (0.14)	12.53 (0.12)	12.36 (0.10)
Sig Diff.	0.707	0.014	p <0.001	p <0.001
Imp	**5.26 (0.06)**	**12.87 (0.21)**	**12.63 (0.22)**	**12.47 (0.20)**
Imp Original	5.28 (0.06)	12.85 (0.25)	12.63 (0.21)	12.52 (0.24)
Sig Diff.	0.049	0.482	0.334	0.020

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Table J.70: Mean Total Distance Travelled by Object in Metres and Standard Deviation for the Hybrid System in Randomly Generated Environments in the presence of a Partial Motor Fault in Follower Wheel 1

Weighting	Randomly Generated Environments		
	1	2	3
Exp	**6.17 (0.03)**	**8.02 (0.08)**	**4.38 (0.02)**
Exp Original	6.18 (0.03)	8.00 (0.09)	4.42 (0.04)
Sig Diff.	0.058	0.024	p <0.001
w = 0.25	**6.15 (0.02)**	**7.92 (0.01)**	**4.35 (0.03)**
Original w = 0.25	6.14 (0.01)	7.90 (0.03)	4.38 (0.04)
Sig Diff.	0.082	0.185	p <0.001
w = 0.5	**6.14 (0.01)**	**7.92 (0.01)**	**4.35 (0.04)**
Original w = 0.5	6.14 (0.01)	7.90 (0.04)	4.39 (0.04)
Sig Diff.	0.496	0.013	p <0.001
w = 0.75	**6.14 (0.01)**	**7.92 (0.01)**	**4.35 (0.04)**
Original w = 0.75	6.14 (0.02)	7.92 (0.05)	4.39 (0.05)
Sig Diff.	0.186	0.260	p <0.001
Imp	**6.14 (0.01)**	**7.93 (0.02)**	**4.35 (0.04)**
Imp Original	6.16 (0.04)	7.97 (0.09)	4.39 (0.05)
Sig Diff.	p <0.001	p <0.001	p <0.001

Table J.71: Mean Total Distance Travelled by Object in Metres and Standard Deviation for the Hybrid System in Randomly Generated Environments in the presence of a Partial Motor Fault in Follower Wheel 2

Weighting	Randomly Generated Environments		
	1	2	3
Exp	**6.17 (0.03)**	**8.03 (0.08)**	**4.38 (0.02)**
Exp Original	6.18 (0.03)	8.00 (0.09)	4.42 (0.04)
Sig Diff.	0.723	0.011	p <0.001
w = 0.25	**6.14 (0.01)**	**7.93 (0.01)**	**4.35 (0.03)**
Original w = 0.25	6.14 (0.01)	7.90 (0.03)	4.38 (0.04)
Sig Diff.	0.820	p <0.001	p <0.001
w = 0.5	**6.14 (0.01)**	**7.93 (0.01)**	**4.35 (0.03)**
Original w = 0.5	6.14 (0.01)	7.90 (0.04)	4.39 (0.04)
Sig Diff.	0.324	p <0.001	p <0.001
w = 0.75	**6.14 (0.02)**	**7.95 (0.03)**	**4.36 (0.04)**
Original w = 0.75	6.14 (0.02)	7.92 (0.05)	4.39 (0.05)
Sig Diff.	0.555	p <0.001	p <0.001
Imp	**6.15 (0.03)**	**7.98 (0.06)**	**4.36 (0.04)**
Imp Original	6.16 (0.04)	7.97 (0.09)	4.39 (0.05)
Sig Diff.	0.622	0.074	p <0.001

Table J.72: Mean Total Distance Travelled by Object in Metres and Standard Deviation for the Hybrid System in Randomly Generated Environments in the presence of a Partial Motor Fault in Follower Wheel 3

Weighting	Randomly Generated Environments		
	1	2	3
Exp	**6.17 (0.03)**	**8.02 (0.08)**	**4.39 (0.01)**
Exp Original	6.16 (0.04)	7.97 (0.09)	4.39 (0.05)
Sig Diff.	0.443	0.024	p <0.001
w = 0.25	**6.14 (0.01)**	**7.93 (0.01)**	**4.35 (0.04)**
Original w = 0.25	6.14 (0.01)	7.90 (0.03)	4.38 (0.04)
Sig Diff.	0.099	p <0.001	p <0.001
w = 0.5	**6.14 (0.01)**	**7.92 (0.01)**	**4.36 (0.03)**
Original w = 0.5	6.14 (0.01)	7.90 (0.04)	4.39 (0.04)
Sig Diff.	0.263	p <0.001	p <0.001
w = 0.75	**6.14 (0.01)**	**7.95 (0.03)**	**4.37 (0.03)**
Original w = 0.75	6.14 (0.02)	7.92 (0.05)	4.39 (0.05)
Sig Diff.	0.049	p <0.001	0.001
Imp	**6.15 (0.03)**	**7.99 (0.07)**	**4.37 (0.03)**
Imp Original	6.16 (0.04)	7.97 (0.09)	4.39 (0.05)
Sig Diff.	0.404	0.003	0.007

Table J.73: Mean Maximum Displacement of Object in Metres and Standard Deviation for the Hybrid System in the Line Following Environment in the presence of a Partial Motor Fault in Follower Wheel 1

Weighting	Line Following Environment Path		
	1	2	3
Exp	**0.017 (0.006)**	**0.019 (0.006)**	**0.018 (0.006)**
Exp Original	0.018 (0.006)	0.018 (0.006)	0.019 (0.005)
Sig Diff.	0.123	0.084	0.459
w = 0.25	**0.027 (0.008)**	**0.027 (0.006)**	**0.024 (0.004)**
Original w = 0.25	0.027 (0.008)	0.034 (0.009)	0.031 (0.009)
Sig Diff.	0.973	p <0.001	p <0.001
w = 0.5	**0.026 (0.007)**	**0.030 (0.007)**	**0.027 (0.002)**
Original w = 0.5	0.028 (0.007)	0.031 (0.006)	0.031 (0.006)
Sig Diff.	0.013	0.100	p <0.001
w = 0.75	**0.027 (0.006)**	**0.030 (0.007)**	**0.030 (0.006)**
Original w = 0.75	0.028 (0.006)	0.032 (0.004)	0.032 (0.006)
Sig Diff.	0.207	p <0.001	p <0.001
Imp	**0.019 (0.006)**	**0.019 (0.006)**	**0.019 (0.006)**
Imp Original	0.018 (0.006)	0.018 (0.006)	0.019 (0.005)
Sig Diff.	0.290	0.132	0.832

Table J.74: Mean Maximum Displacement of Object in Metres and Standard Deviation for the Hybrid System in the Line Following Environment in the presence of a Partial Motor Fault in Follower Wheel 2

Weighting	Line Following Environment Path		
	1	2	3
Exp	**0.029 (0.005)**	**0.030 (0.005)**	**0.032 (0.006)**
Exp Original	0.029 (0.005)	0.031 (0.005)	0.033 (0.006)
Sig Diff.	0.3077	0.4854	0.4746
w = 0.25	**0.026 (0.007)**	**0.026 (0.008)**	**0.029 (0.006)**
Original w = 0.25	0.027 (0.008)	0.034 (0.009)	0.031 (0.009)
Sig Diff.	0.283	p <0.001	0.763
w = 0.5	**0.027 (0.006)**	**0.030 (0.006)**	**0.031 (0.005)**
Original w = 0.5	0.028 (0.007)	0.031 (0.006)	0.031 (0.006)
Sig Diff.	0.527	0.0024	0.061
w = 0.75	**0.028 (0.005)**	**0.031 (0.004)**	**0.032 (0.006)**
Original w = 0.75	0.028 (0.006)	0.032 (0.004)	0.032 (0.006)
Sig Diff.	0.294	p <0.001	0.692
Imp	**0.029 (0.005)**	**0.030 (0.005)**	**0.032 (0.006)**
Imp Original	0.029 (0.005)	0.031 (0.005)	0.033 (0.006)
Sig Diff.	0.308	0.485	0.475

Table J.75: Mean Maximum Displacement of Object in Metres and Standard Deviation for the Hybrid System in the Line Following Environment in the presence of a Partial Motor Fault in Follower Wheel 3

Weighting	Line Following Environment Path		
	1	2	3
Exp	**0.019 (0.005)**	**0.017 (0.006)**	**0.018 (0.005)**
Exp Original	0.018 (0.006)	0.018 (0.006)	0.019 (0.005)
Sig Diff.	0.575	0.417	0.194
w = 0.25	**0.025 (0.006)**	**0.030 (0.008)**	**0.028 (0.006)**
Original w = 0.25	0.027 (0.008)	0.034 (0.009)	0.031 (0.009)
Sig Diff.	0.035	0.009	0.099
w = 0.5	**0.027 (0.005)**	**0.030 (0.005)**	**0.030 (0.006)**
Original w = 0.5	0.028 (0.007)	0.031 (0.006)	0.031 (0.006)
Sig Diff.	0.251	0.122	0.549
w = 0.75	**0.028 (0.005)**	**0.030 (0.004)**	**0.033 (0.005)**
Original w = 0.75	0.028 (0.006)	0.032 (0.004)	0.032 (0.006)
Sig Diff.	0.317	$p < 0.001$	0.412
Imp	**0.029 (0.005)**	**0.030 (0.005)**	**0.031 (0.005)**
Imp Original	0.029 (0.005)	0.031 (0.005)	0.033 (0.006)
Sig Diff.	0.315	0.577	0.028

Table J.76: Mean Maximum Displacement of Object in Metres and Standard Deviation for the Hybrid System in the Simple and Cluttered Environments in the presence of a Partial Motor Fault in Follower Wheel 1

Weighting	Path			
	SE	CE	CE	CE
	1	1	2	3
Exp	**0.017 (0.005)**	**0.023 (0.002)**	**0.016 (0.004)**	**0.019 (0.005)**
Exp Original	0.018 (0.006)	0.019 (0.005)	0.016 (0.004)	0.017 (0.005)
Sig Diff.	0.225	p <0.001	0.980	0.005
w = 0.25	**0.024 (0.005)**	**0.032 (0.004)**	**0.028 (0.006)**	**0.027 (0.005)**
Original w = 0.25	0.025 (0.005)	0.029 (0.006)	0.028 (0.005)	0.028 (0.005)
Sig Diff.	0.146	0.032	0.508	0.336
w = 0.5	**0.025 (0.005)**	**0.030 (0.004)**	**0.027 (0.006)**	**0.028 (0.006)**
Original w = 0.5	0.024 (0.005)	0.030 (0.004)	0.029 (0.004)	0.030 (0.004)
Sig Diff.	0.318	0.779	0.006	0.002
w = 0.75	**0.026 (0.005)**	**0.031 (0.004)**	**0.029 (0.005)**	**0.028 (0.005)**
Original w = 0.75	0.029 (0.004)	0.034 (0.003)	0.034 (0.003)	0.034 (0.003)
Sig Diff.	p <0.001	p <0.001	p <0.001	p <0.001
Imp	**0.018 (0.005)**	**0.023 (0.001)**	**0.015 (0.004)**	**0.019 (0.005)**
Imp Original	0.018 (0.006)	0.019 (0.005)	0.016 (0.004)	0.017 (0.005)
Sig Diff.	0.812	p <0.001	0.155	0.011

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Table J.77: Mean Maximum Displacement of Object in Metres and Standard Deviation for the Hybrid System in the Simple and Cluttered Environments in the presence of a Partial Motor Fault in Follower Wheel 2

Weighting	Path			
	SE	CE	CE	CE
	1	1	2	3
Exp	**0.032 (0.004)**	**0.038 (0.003)**	**0.038 (0.003)**	**0.038 (0.003)**
Exp Original	0.031 (0.004)	0.037 (0.003)	0.038 (0.002)	0.038 (0.003)
Sig Diff.	0.608	0.863	0.209	0.066
w = 0.25	**0.024 (0.006)**	**0.030 (0.005)**	**0.026 (0.006)**	**0.028 (0.005)**
Original w = 0.25	0.025 (0.005)	0.029 (0.006)	0.028 (0.005)	0.028 (0.005)
Sig Diff.	0.472	0.387	0.002	0.836
w = 0.5	**0.026 (0.005)**	**0.032 (0.005)**	**0.029 (0.004)**	**0.030 (0.004)**
Original w = 0.5	0.024 (0.005)	0.030 (0.004)	0.029 (0.004)	0.030 (0.004)
Sig Diff.	0.093	p <0.001	0.661	0.702
w = 0.75	**0.030 (0.004)**	**0.034 (0.003)**	**0.034 (0.003)**	**0.033 (0.003)**
Original w = 0.75	0.029 (0.004)	0.034 (0.003)	0.034 (0.003)	0.034 (0.003)
Sig Diff.	0.526	0.119	0.405	0.858
Imp	**0.032 (0.004)**	**0.038 (0.003)**	**0.038 (0.003)**	**0.038 (0.003)**
Imp Original	0.031 (0.004)	0.037 (0.003)	0.038 (0.002)	0.038 (0.003)
Sig Diff.	0.609	0.863	0.209	0.066

Table J.78: Mean Maximum Displacement of Object in Metres and Standard Deviation for the Hybrid System in the Simple and Cluttered Environments in the presence of a Partial Motor Fault in Follower Wheel 3

Weighting	Path			
	SE	CE	CE	CE
	1	1	2	3
Exp	**0.019 (0.005)**	**0.023 (0.002)**	**0.015 (0.004)**	**0.019 (0.006)**
Exp Original	0.018 (0.006)	0.019 (0.005)	0.016 (0.004)	0.017 (0.005)
Sig Diff.	0.530	p <0.001	0.052	0.067
w = 0.25	**0.024 (0.006)**	**0.030 (0.005)**	**0.027 (0.006)**	**0.028 (0.005)**
Original w = 0.25	0.025 (0.005)	0.029 (0.006)	0.028 (0.005)	0.028 (0.005)
Sig Diff.	0.296	0.837	0.090	0.472
w = 0.5	**0.026 (0.005)**	**0.031 (0.004)**	**0.030 (0.004)**	**0.030 (0.004)**
Original w = 0.5	0.024 (0.005)	0.030 (0.004)	0.029 (0.004)	0.030 (0.004)
Sig Diff.	0.054	0.005	0.137	0.788
w = 0.75	**0.028 (0.004)**	**0.035 (0.003)**	**0.034 (0.003)**	**0.033 (0.003)**
Original w = 0.75	0.029 (0.004)	0.034 (0.003)	0.034 (0.003)	0.034 (0.003)
Sig Diff.	0.116	0.020	0.261	0.894
Imp	**0.031 (0.004)**	**0.037 (0.003)**	**0.038 (0.003)**	**0.037 (0.003)**
Imp Original	0.031 (0.004)	0.037 (0.003)	0.038 (0.002)	0.038 (0.003)
Sig Diff.	0.549	0.493	0.489	0.013

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Table J.79: Mean Maximum Displacement of Object in Metres and Standard Deviation for the Hybrid System in the Randomly Generated Environments in the presence of a Partial Motor Fault in Follower Wheel 1

Weighting	Randomly Generated Environments		
	1	2	3
Exp	**0.018 (0.005)**	**0.018 (0.006)**	**0.017 (0.005)**
Exp Original	0.019 (0.005)	0.018 (0.006)	0.017 (0.005)
Sig Diff.	0.199	0.974	0.886
w = 0.25	**0.025 (0.005)**	**0.025 (0.005)**	**0.025 (0.005)**
Original w = 0.25	0.027 (0.005)	0.027 (0.006)	0.025 (0.006)
Sig Diff.	0.048	0.024	0.463
w = 0.5	**0.026 (0.006)**	**0.025 (0.006)**	**0.024 (0.006)**
Original w = 0.5	0.026 (0.005)	0.027 (0.005)	0.025 (0.005)
Sig Diff.	0.432	0.018	0.614
w = 0.75	**0.027 (0.006)**	**0.026 (0.006)**	**0.026 (0.006)**
Original w = 0.75	0.030 (0.003)	0.030 (0.003)	0.029 (0.004)
Sig Diff.	0.005	$p < 0.001$	$p < 0.001$
Imp	**0.018 (0.006)**	**0.018 (0.005)**	**0.017 (0.005)**
Imp Original	0.019 (0.005)	0.018 (0.006)	0.017 (0.005)
Sig Diff.	0.077	0.967	0.867

Table J.80: Mean Maximum Displacement of Object in Metres and Standard Deviation for the Hybrid System in the Randomly Generated Environments in the presence of a Partial Motor Fault in Follower Wheel 2

Weighting	Randomly Generated Environments		
	1	2	3
Exp	**0.033 (0.004)**	**0.035 (0.003)**	**0.031 (0.005)**
Exp Original	0.034 (0.004)	0.034 (0.003)	0.033 (0.004)
Sig Diff.	0.041	0.785	0.054
w = 0.25	**0.026 (0.006)**	**0.027 (0.006)**	**0.026 (0.006)**
Original w = 0.25	0.027 (0.005)	0.027 (0.006)	0.025 (0.006)
Sig Diff.	0.4459	0.949	0.719
w = 0.5	**0.026 (0.005)**	**0.027 (0.005)**	**0.026 (0.005)**
Original w = 0.5	0.026 (0.005)	0.027 (0.005)	0.025 (0.005)
Sig Diff.	0.558	0.759	0.017
w = 0.75	**0.029 (0.003)**	**0.030 (0.003)**	**0.029 (0.004)**
Original w = 0.75	0.030 (0.003)	0.030 (0.003)	0.029 (0.004)
Sig Diff.	0.159	0.993	0.816
Imp	**0.033 (0.004)**	**0.035 (0.003)**	**0.031 (0.005)**
Imp Original	0.034 (0.004)	0.034 (0.003)	0.033 (0.004)
Sig Diff.	0.041	0.785	0.054

Table J.81: Mean Maximum Displacement of Object in Metres and Standard Deviation for the Hybrid System in the Randomly Generated Environments in the presence of a Partial Motor Fault in Follower Wheel 3

Weighting	Randomly Generated Environments		
	1	2	3
Exp	**0.018 (0.005)**	**0.018 (0.006)**	**0.017 (0.005)**
Exp Original	0.019 (0.005)	0.018 (0.006)	0.017 (0.005)
Sig Diff.	0.128	0.591	0.737
w = 0.25	**0.026 (0.006)**	**0.027 (0.006)**	**0.025(0.006)**
Original w = 0.25	0.027 (0.005)	0.027 (0.006)	0.025 (0.006)
Sig Diff.	0.172	0.467	0.841
w = 0.5	**0.027 (0.006)**	**0.027 (0.005)**	**0.026 (0.005)**
Original w = 0.5	0.026 (0.005)	0.027 (0.005)	0.025 (0.005)
Sig Diff.	0.148	0.829	0.102
w = 0.75	**0.030 (0.003)**	**0.030 (0.003)**	**0.028 (0.004)**
Original w = 0.75	0.030 (0.003)	0.030 (0.003)	0.029 (0.004)
Sig Diff.	0.735	0.526	0.113
Imp	**0.033 (0.004)**	**0.034 (0.003)**	**0.030 (0.005)**
Imp Original	0.034 (0.004)	0.034 (0.003)	0.033 (0.004)
Sig Diff.	0.065	0.070	0.001

Table J.82: Mean Percentage Path Fidelity and Standard Deviation for the Hybrid System in the Line Following Environment in the presence of a Partial Motor Fault in Follower Wheel 1

Weighting	Line Following Environment Path		
	1	2	3
Exp	**94.75% (11.4%)**	**99.83% (1.67%)**	**100% (∼0%)**
Exp Original	90.75% (14.93%)	100% (∼0%)	99.40% (3.43%)
Sig Diff.	0.043	0.322	0.083
w = 0.25	**62.28% (31.74%)**	**42.28% (33.29%)**	**82.96% (16.36%)**
Original w = 0.25	78.02 (27.09%)	56.58% (25.54%)	79.35% (19.15%)
Sig Diff.	0.003	0.006	0.480
w = 0.5	**76.00% (33.75%)**	**54.82% (33.86%)**	**90.00% (11.21%)**
Original w = 0.5	86.48% (22.47%)	71.56% (25.02%)	90.18% (15.64%)
Sig Diff.	0.099	0.002	0.455
w = 0.75	**85.46% (20.28%)**	**82.77% (32.32%)**	**91.25% (14.20%)**
Original w = 0.75	93.25% (13.23%)	99.50% (2.86%)	91.65% (14.18%)
Sig Diff.	0.002	p <0.001	0.804
Imp	**90.50% (13.19%)**	**99.67% (2.35%)**	**65.00% (9.59%)**
Imp Original	93.00 (12.35%)	89.67% (14.17%)	96.57% (9.49%)
Sig Diff.	0.137	p <0.001	0.119

Table J.83: Mean Percentage Path Fidelity and Standard Deviation for the Hybrid System in the Line Following Environment in the presence of a Partial Motor Fault in Follower Wheel 2

Weighting	Line Following Environment Path		
	1	2	3
Exp	**99.75% (2.50%)**	**100% (∼0%)**	**99.80% (2.00%)**
Exp Original	90.75% (14.93%)	100% (∼0%)	99.40% (3.43%)
Sig Diff.	p <0.001	1	0.316
w = 0.25	**87.50% (17.01%)**	**82.30% (18.61%)**	**90.00% (12.86%)**
Original w = 0.25	78.02 (27.09%)	56.58% (25.54%)	79.35% (19.15%)
Sig Diff.	0.036	p <0.001	p <0.001
w = 0.5	**90.50% (15.40%)**	**82.82% (26.18%)**	**90.93% (14.06%)**
Original w = 0.5	86.48% (22.47%)	71.56% (25.02%)	90.18% (15.64%)
Sig Diff.	0.468	p <0.001	0.911
w = 0.75	**92.50% (13.99%)**	**99.67% (2.35%)**	**91.79% (12.20%)**
Original w = 0.75	93.25% (13.23%)	99.50% (2.86%)	91.65% (14.18%)
Sig Diff.	0.789	0.655	0.714
Imp	**98.00% (6.82(%)**	**92.17% (13.29%)**	**97.26% (6.91%)**
Imp Original	93.00 (12.35%)	89.67% (14.17%)	96.57% (9.49%)
Sig Diff.	p <0.001	0.148	0.885

Table J.84: Mean Percentage Path Fidelity and Standard Deviation for the Hybrid System in the Line Following Environment in the presence of a Partial Motor Fault in Follower Wheel 3

Weighting	Line Following Environment Path		
	1	2	3
Exp	**90.50% (14.98%)**	**89.00% (10.11%)**	**99.80% (2.00%)**
Exp Original	90.75% (14.93%)	100% (∼0%)	99.40% (3.43%)
Sig Diff.	0.889	p <0.001	0.316
w = 0.25	**90.82% (15.39%)**	**69.83% (22.34%)**	**91.03% (12.75%)**
Original w = 0.25	78.02 (27.09%)	56.58% (25.54%)	79.35% (19.15%)
Sig Diff.	p <0.001	0.001	p <0.001
w = 0.5	**94.00% (12.87%)**	**78.79% (17.47%)**	**89.27% (15.77%)**
Original w = 0.5	86.48% (22.47%)	71.56% (25.02%)	90.18% (15.64%)
Sig Diff.	0.017	0.102	0.655
w = 0.75	**91.25% (16.04%)**	**98.50% (4.79%)**	**95.32% (9.47%)**
Original w = 0.75	93.25% (13.23%)	99.50% (2.86%)	91.65% (14.18%)
Sig Diff.	0.567	0.075	0.114
Imp	**91.25% (13.47%)**	**88.83% (14.03%)**	**96.60% (8.07%)**
Imp Original	93.00 (12.35%)	89.67% (14.17%)	96.57% (9.49%)
Sig Diff.	0.343	0.576	0.745

Table J.85: Mean Percentage Path Fidelity and Standard Deviation for the Hybrid System in the Simple and Cluttered Environments in the presence of a Partial Motor Fault in Follower Wheel 1

Weighting	Path			
	SE	CE	CE	CE
	1	1	2	3
Exp	**91.08% (1.93%)**	**50.25% (7.99%)**	**72.87% (9.01%)**	**62.85% (15.72%)**
Exp Original	91.00% (2.12%)	64.09% (15.65%)	72.96% (8.33%)	69.04 (15.25%)
Sig Diff.	0.846	p <0.001	0.915	0.004
w = 0.25	**91.00% (2.16%)**	**72.27% (5.47%)**	**76.22% (6.25%)**	**79.42% (5.39%)**
Original w = 0.25	91.24% (1.87%)	75.61% (7.70%)	75.69% (5.67%)	78.94% (5.27%)
Sig Diff.	0.638	0.018	0.585	0.446
w = 0.5	**91.17% (1.69%)**	**75.04% (5.11%)**	**76.36% (5.69%)**	**78.33% (5.05%)**
Original w = 0.5	91.72% (1.71%)	76.90% (6.14%)	75.59% (4.38%)	76.78% (5.26%)
Sig Diff.	0.017	0.049	0.556	0.048
w = 0.75	**91.05% (1.69%)**	**73.24% (4.38%)**	**75.14% (5.21%)**	**77.85% (5.31%)**
Original w = 0.75	91.33% (1.88%)	75.09% (5.39%)	73.03% (4.04%)	75.83% (4.32%)
Sig Diff.	0.306	0.010	0.005	0.001
Imp	**90.71% (1.92%)**	**73.57% (5.20%)**	**74.99% (5.28%)**	**76.60% (5.36%)**
Imp Original	91.79% (1.60%)	70.78% (3.55%)	69.44% (2.80%)	70.56% (3.35%)
Sig Diff.	p <0.001	0.002	p <0.001	p <0.001

Table J.86: Mean Percentage Path Fidelity and Standard Deviation for the Hybrid System in the Simple and Cluttered Environments in the presence of a Partial Motor Fault in Follower Wheel 2

Weighting	Path			
	SE	CE	CE	CE
	1	1	2	3
Exp	**90.66% (2.28%)**	**49.31% (5.21%)**	**74.15% (9.01%)**	**62.40% (16.83%)**
Exp Original	91.00% (2.12%)	64.09% (15.65%)	72.96% (8.33%)	69.04 (15.25%)
Sig Diff.	0.343	p <0.001	0.3806	0.0018
w = 0.25	**91.05% (2.03%)**	**74.33% (5.82%)**	**78.25% (6.48%)**	**78.57% (5.86%)**
Original w = 0.25	91.24% (1.87%)	75.61% (7.70%)	75.69% (5.67%)	78.94% (5.27%)
Sig Diff.	0.5597	0.5397	0.0029	0.8011
w = 0.5	**91.13% (2.08%)**	**73.56% (6.24%)**	**75.35% (4.19%)**	**77.19% (5.42%)**
Original w = 0.5	91.72% (1.71%)	76.90% (6.14%)	75.59% (4.38%)	76.78% (5.26%)
Sig Diff.	0.0494	p <0.001	0.614	0.550
w = 0.75	**91.07% (1.99%)**	**73.73% (5.21%)**	**73.80% (4.61%)**	**76.25% (4.92%)**
Original w = 0.75	91.33% (1.88%)	75.09% (5.39%)	73.03% (4.04%)	75.83% (4.32%)
Sig Diff.	0.336	0.094	0.400	0.281
Imp	**90.66 (2.28%)**	**71.48% (4.31%)**	**71.36% (3.59%)**	**73.27% (3.84%)**
Imp Original	91.79% (1.60%)	70.78% (3.55%)	69.44% (2.80%)	70.56% (3.35%)
Sig Diff.	p <0.001	0.852	p <0.001	p <0.001

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Table J.87: Mean Percentage Path Fidelity and Standard Deviation for the Hybrid System in the Simple and Cluttered Environments in the presence of a Partial Motor Fault in Follower Wheel 3

Weighting	Path			
	SE	CE	CE	CE
	1	1	2	3
Exp	**99.80% (2.00%)**	**49.07% (6.67%)**	**74.64% (9.27%)**	**63.36% (17.54%)**
Exp Original	99.40% (3.43%)	64.09% (15.65%)	72.96% (8.33%)	69.04 (15.25%)
Sig Diff.	0.316	p <0.001	0.186	0.013
w = 0.25	**91.03% (12.75%)**	**75.50% (6.50%)**	**76.90% (6.33%)**	**77.89% (5.64%)**
Original w = 0.25	79.35% (19.15%)	75.61% (7.70%)	75.69% (5.67%)	78.94% (5.27%)
Sig Diff.	p <0.001	0.847	0.156	0.205
w = 0.5	**89.27% (15.77%)**	**74.06% (4.78%)**	**74.63% (4.72%)**	**76.99% (4.88%)**
Original w = 0.5	90.18% (15.64%)	76.90% (6.14%)	75.59% (4.38%)	76.78% (5.26%)
Sig Diff.	0.655	0.002	0.170	0.725
w = 0.75	**95.32% (9.47%)**	**73.41% (5.41%)**	**73.04% (4.20%)**	**75.76% (4.87%)**
Original w = 0.75	91.65% (14.18%)	75.09% (5.39%)	73.03% (4.04%)	75.83% (4.32%)
Sig Diff.	0.114	0.030	0.934	0.922
Imp	**96.60% (8.07%)**	**72.15% (3.29%)**	**70.35% (2.99%)**	**72.02% (3.60%)**
Imp Original	96.57% (9.49%)	70.78% (3.55%)	69.44% (2.80%)	70.56% (3.35%)
Sig Diff.	0.745	0.012	0.048	0.002

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Table J.88: Mean Percentage Path Fidelity and Standard Deviation for the Hybrid System in the Randomly Generated Environments in the presence of a Partial Motor Fault in Follower Wheel 1

Weighting	Randomly Generated Environments		
	1	2	3
Exp	**58.62% (24.18%)**	**57.15% (21.08%)**	**50.31% (23.85%)**
Exp Original	54.36% (23.85%)	56.36% (21.46%)	49.84% (23.26%)
Sig Diff.	0.2566	0.8335	0.8193
w = 0.25	**75.80% (10.38%)**	**73.75% (8.15%)**	**64.34% (17.88%)**
Original w = 0.25	74.08% (8.48%)	71.04% (7.16%)	63.48% (14.71%)
Sig Diff.	0.069	0.003	0.872
w = 0.5	**75.72% (8.37%)**	**73.99% (7.78%)**	**66.10% (16.17%)**
Original w = 0.5	76.73% (8.01%)	71.77% (6.66%)	66.30% (15.08%)
Sig Diff.	0.357	0.040	0.970
w = 0.75	**75.17% (8.29%)**	**72.50% (7.45%)**	**62.75% (14.87%)**
Original w = 0.75	75.83% (8.16%)	71.61% (7.05%)	64.37% (17.10%)
Sig Diff.	0.652	0.323	0.527
Imp	**75.66% (7.99%)**	**70.80% (6.45%)**	**63.30% (15.26%)**
Imp Original	75.31% (9.04%)	68.40% (5.61%)	61.80% (14.57%)
Sig Diff.	0.990	0.045	0.512

Table J.89: Mean Percentage Path Fidelity and Standard Deviation for the Hybrid System in the Randomly Generated Environments in the presence of a Partial Motor Fault in Follower Wheel 2

Weighting	Randomly Generated Environments		
	1	2	3
Exp	**57.01% (24.05%)**	**54.25% (21.31%)**	**47.94% (21.94%)**
Exp Original	54.36% (23.85%)	56.36% (21.46%)	49.84% (23.26%)
Sig Diff.	0.345	0.510	0.442
w = 0.25	**74.58% (9.65%)**	**70.93% (6.84%)**	**60.79% (13.72%)**
Original w = 0.25	74.08% (8.48%)	71.04% (7.16%)	63.48% (14.71%)
Sig Diff.	0.835	0.978	0.141
w = 0.5	**75.29% (8.64%)**	**71.81% (7.18%)**	**59.62% (15.97%)**
Original w = 0.5	76.73% (8.01%)	71.77% (6.66%)	66.30% (15.08%)
Sig Diff.	0.241	0.863	0.001
w = 0.75	**76.18% (9.13%)**	**72.87% (7.45%)**	**62.68% (16.54%)**
Original w = 0.75	75.83% (8.16%)	71.61% (7.05%)	64.37% (17.10%)
Sig Diff.	0.686	0.222	0.524
Imp	**76.20% (8.83%)**	**68.84 (6.57%)**	**65.08% (17.01%)**
Imp Original	75.31% (9.04%)	68.40% (5.61%)	61.80% (14.57%)
Sig Diff.	0.443	0.596	0.172

Table J.90: Mean Percentage Path Fidelity and Standard Deviation for the Hybrid System in the Randomly Generated Environments in the presence of a Partial Motor Fault in Follower Wheel 3

Weighting	Randomly Generated Environments		
	1	2	3
Exp	**57.24% (23.22%)**	**55.95% (22.47%)**	**48.81% (23.74%)**
Exp Original	54.36% (23.85%)	56.36% (21.46%)	49.84% (23.26%)
Sig Diff.	0.484	0.880	0.680
w = 0.25	**75.18% (9.81%)**	**71.36% (7.33%)**	**60.68% (14.79%)**
Original w = 0.25	74.08% (8.48%)	71.04% (7.16%)	63.48% (14.71%)
Sig Diff.	0.432	0.591	0.122
w = 0.5	**73.88% (8.65%)**	**71.70% (6.60%)**	**60.89% (15.44%)**
Original w = 0.5	76.73% (8.01%)	71.77% (6.66%)	66.30% (15.08%)
Sig Diff.	0.033	0.920	0.010
w = 0.75	**73.75% (9.62%)**	**72.37% (7.30%)**	**67.17% (16.91%)**
Original w = 0.75	75.83% (8.16%)	71.61% (7.05%)	64.37% (17.10%)
Sig Diff.	0.139	0.435	0.209
Imp	**76.28% (8.37%)**	**70.66% (5.91%)**	**66.61% (15.05%)**
Imp Original	75.31% (9.04%)	68.40% (5.61%)	61.80% (14.57%)
Sig Diff.	0.489	0.005	0.020