

Novel Actuation System and Morphologies for Tensegrity Robots

Apicit Tantaworrasilp

Submitted in accordance with the requirements for the degree of
Doctor of Philosophy

University of Leeds
School of Mechanical Engineering

March 2021

The candidate confirms that the work submitted is his own, except where work which has formed part of jointly authored publication has been included. The contribution of the candidate and the other author to this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others.

The publication that is referenced in the thesis is “Metamorphic Tensegrity Structure for Pipe Inspection”, authored by Apicit Tantaworrasilp and Robert C Richardson, presented in International Conference on Advanced Control, Automation and Robotics (ICACAR 2019) in Phuket, Thailand, 18-20 January 2019 and published in open-access of IOPSCIENCE in 2020.

The work published in this paper is included in the thesis as follow:

- Chapter 3 expands upon section 2 in the paper regarding the conceptual design of the structural deformation method.
- Chapter 4 expands upon the concept, mechanical design and implementation of the restrictor mechanism that is renamed as a passive-retractable joint with a cable locking mechanism (PRM) in the thesis.

The paper’s primary author was responsible for all of the content in the paper. The co-author of the paper is the project supervisor and was responsible for reviewing the paper

This copy has been supplied on the understanding that it is copyright material and that no quotation from the thesis may be published without proper acknowledgement.

The right of Apicit Tantaworrasilp to be identified as the author of this work has been asserted by him in accordance with the Copyright, Designs and Patents Act 1988.

© 2021 The University of Leeds and Apicit Tantaworrasilp.

Acknowledgements

I would like to thank all the people who helped me directly or indirectly throughout this project. First and foremost, I would like to thank sincerely my supervisors Professor Robert C. Richardson for his patience and effort spent on providing me required facilities and constructive suggestions during this study. Without his guidance, support and encouragement, this project could not be accomplished. Meanwhile, I wholeheartedly thank the National Electronics and Computer Technology Centre (NECTEC) and Royal Thai Government for offering me a full research scholarship which makes it possible for me to live and study in Leeds.

I would express my deepest gratitude here to my great parents, Miss Gumlai and Mr Wichai Tantaworrasilp who keep offering me unconditional support especially taking care of my son. I am thankful for my elder sister Miss Tassawan and my brother Associate Professor Dr Apichat who motivated me to encounter many problems and realised that the natural PhD pathway is arduous, and every PhD student must step over that situation. In addition, I am thankful to my lovely wife Mrs Molwadee who has been accompanying, encouraging and looking after me throughout my life to accomplish this destination.

I would like to thank Dr Jason, Dr George, Dr Nick and Dr Andy who helped advised and discussed some ideas for electronics and software developments. I would like to thank Mr Tony, Mr Edward, Mr Crawford and Mr Graham who are the University technicians who provided kindly supports regarding mechatronics components, laser cutting works and manufactured-mechanical parts for this project.

I am grateful that I can conduct my research with a lot of amazing officemates with different backgrounds from different countries which are Weibing, Taegyun, Imran, Nick and Jake. Thanks to them giving me a lot of discussions on research and other interesting topics, which makes me have some idea and leisure time to keep sane during the arduous journey.

I would like to sincerely thank my Thai colleague at NECTEC: Ms Kullaprapa, Dr Kittipong, Dr Wuttiaphat, Dr Piched, Dr Teesid, Mr Prokob, Mr Udom and Dr Kanokvate who consulted me with useful knowledge and encouraged me during my study. I would like to thank Associate Professor Dr Jongkol Ngamwiwit who shared and consulted her great experiences on PhD study and provided me with the recommended letter to apply PhD position at the University of Leeds.

Abstract

This thesis presents a novel actuation system and morphologies for tensegrity robots. The research aim is to design a structural deformation method utilising adjustable-length strut elements (SEs) in cooperation with passive-retractable joints with cable locking mechanisms (PRMs). This structural deformation method is employed for robot configurations for locomotion tasks such as crawling and climbing motions.

A tensegrity structure consists of compressive elements and tensile elements. Each compressive element, or strut element, is connected by the tensile elements, or cables; the structure operates like a cable network structure without any rigid joints. Tensegrity structures thus have unique properties in terms of their weight, force distribution, modularity, and fault tolerance. These unique properties are proving useful in the field of exploration and inspection robotics. Compliant and lightweight tensegrity robots can, for example, withstand external impact forces to protect payloads and their mechanisms due to their force distribution properties. Tensegrity robots can operate even when some cables have failed. Unlike conventional modular robots, which have rigid joints for locomotion mechanisms, tensegrity robots are flexible; their compliant structure allows them to access diverse geological and dangerous areas inaccessible to humans. Both strut and cables can be assembled and reassembled easily due to tensegrity robots' modularity. Tensegrity robots can be constructed in various geometries providing a wide range of locomotion types such as rolling, crawling, climbing, and jumping depending on the application requirements.

However, several limitations must be addressed. Firstly, the structural configurations for existing tensegrity robots do not change quickly. Furthermore, the existing mechanisms for spooling cables are time-consuming; the mechanisms require high torque together with low speed to sufficiently actuate the cables for robot configuration. Secondly, the power use for locomotion is high, causing a short-operative time when the robots are powered by batteries. Current actuated cable mechanisms use high-torque and active actuators to spool cables for structural configurations; actuated-cable mechanisms require constant energy while actuating cables, resulting in high-energy consumption. Thirdly, existing individual element mechanisms that relate to actuation methods need to be reduced because they require high-torque actuators to pull cables for configuration, and the high-torque actuator, in turn, has high power demands.

A new structural deformation or actuation method that can overcome these limitations is needed. This method would have to enable quick changes in robot configurations, allowing for swapping between soft and hard structures while using less energy and staying lightweight. This new method can be achieved via the proposed cooperation between adjustable-length strut elements (SEs) and a set of passive-retractable joints with a cable locking mechanism (PRMs). Fundamentally, an SE can change its length to exert pushing and pulling forces actively, whereas PRMs can passively exert a small rotational force and produce a braking force to restrict cable lengths to perform robot configurations. 3-DOF and 5-DOF tensegrity structures were developed and successfully tested in end-effector position and angle controls by applying the locking and unlocking stage procedures of the PRMs and changing SE-slider lengths. The forward kinematics equations were derived, analysed, and physically demonstrated to identify the end-effector position and angle of the given cable lengths of the PRMs. PRM and SE control procedures were produced by new control rules to achieve a closed-loop control system. After demonstrating the proposed concept, the speed for changing robot structure was evaluated by developing and demonstrating different tensegrity robot motions that can extend and retract sizes and swap between soft and hard structures.

The experimental results demonstrate that the proposed deformation concept was successful in demonstrating the position and angle controls of the 3- and 5-DOF systems. This method could be used to develop different reconfigurable tensegrity robots capable of performing locomotion tasks by swapping between soft and hard structures quickly thanks to cooperation between the SEs and PRMs. Due to the PRM requires less power to restrict and release a cable during changing SE lengths for structural configurations, a development of a tensegrity robot using low energy consumption may be possible.

Table of Contents

Acknowledgements	ii
Abstract	iii
Table of Contents.....	v
List of Tables.....	ix
List of Figures	xi
List of Abbreviations	xviii
List of Publications.....	xx
Chapter 1 Introduction	1
1.1 Background	1
1.2 Motivation	2
1.3 Aims and Objectives.....	3
1.4 Contributions and Publication.....	4
1.4.1 Contributions	4
1.4.2 Publication.....	5
1.5 Thesis Organisation.....	5
Chapter 2 Literature Review.....	8
2.1 Introduction.....	8
2.2 Tensegrity Robotics.....	10
2.3 Tensegrity Robot Structures and Mechanical Designs	12
2.3.1 Triangular Tensegrity Prism	12
2.3.2 Quadrilateral Tensegrity Prism.....	15
2.3.3 Icosahedron Tensegrity Prism.....	15
2.3.4 Rhombicuboctahedron Tensegrity Structure	25
2.3.5 Tetrahedron and Bio-Inspired Tensegrity Structure.....	26
2.3.6 Other Forms of Tensegrity Robots	35
2.4 Tensegrity Robot Locomotion.....	39
2.4.1 Rolling locomotion.....	39
2.4.2 Crawling locomotion	42
2.4.3 Climbing locomotion	44
2.4.4 Jumping locomotion	45
2.5 The Actuation Method of Tensegrity Robots	45
2.5.1 Cable Actuation Method.....	45
2.5.2 Strut Actuation Method.....	46

2.6	Individual Element Designs for Tensegrity Robot.....	48
2.7	Tensegrity Robot Constraints	51
2.8	Literature Summary	51
Chapter 3 New Structural Deformation Concept.....		57
3.1	Differences between Existing and New Structural Deformation Concepts	57
3.2	Different Classes of Tensegrity Structures Using a Proposed Actuation Concept	60
3.3	New Concept of the Passive-Retractable Joint with a Cable Locking Mechanism (PRM).....	62
3.3.1	Single SE and Two PRMs for 3-DOF Structure	63
3.3.2	Single SE and Four PRMs for 5-DOF System	70
3.4	Summary	83
Chapter 4 Individual Element Design and Implementations		84
4.1	Individual Element Requirements	84
4.1.1	Strut Element	84
4.1.2	Tensile Element	87
4.2	Individual Element Implementation.....	95
4.2.1	Mechanical Design.....	95
4.2.2	Individual Module Manufacture and Assembly	108
4.3	Electronic Design and Implementations	110
4.4	Summary	113
Chapter 5 Individual Element Testing		115
5.1	Strut Element Testing	115
5.1.1	LA-Slider Length Feedback Scaling	115
5.1.2	Open-Loop Control Experiments without Payloads.....	118
5.1.3	Open-Loop Control Experiments with Payloads.....	120
5.1.4	Closed-Loop Position Control	121
5.1.5	Force Sensor Scaling	128
5.1.6	Wall Pressing Performance.....	130
5.2	Passive-Retractable Joint with a Cable Locking Mechanism	135
5.2.1	Cable Length Feedback Scaling	135
5.2.2	Cable Force Calibrations.....	136
5.2.3	Maximum Braking Force	138
5.2.4	Locking and Unlocking Delay Time Experiments	139
5.3	Summary	141

Chapter 6 Control and Structural Deformation Validations	142
6.1 3-DOF System Experiments.....	142
6.1.1 3-DOF Structure.....	142
6.1.2 LA-Base Position Control Demonstrations	143
6.2 5-DOF System Experiments.....	158
6.2.1 5-DOF Structure.....	158
6.2.2 End-Effector Position Control Demonstrations	162
6.2.3 Configuration Time and Power Usage Analysis	181
6.3 Summary.....	185
Chapter 7 Case Study: Structural Configurations for Locomotion tasks	187
7.1 Environmental Requirements	187
7.2 Robot Requirements.....	187
7.3 Basic Wall-Pressing Robot Locomotion.....	188
7.4 Crawling Robot Based on New Actuation Method	191
7.4.1 Robot Configuration Analysis	191
7.4.2 Physical Robot Demonstrations	193
7.5 Other Advantages of the PRM for Robot Configurations	199
7.6 3D Robot Configurations	202
7.6.1 3D Shape-Changing Ability	203
7.6.2 Soft/Hard Structure Adaptation Ability.....	204
7.6.3 Angular Correcting Ability for Climbing Locomotion	206
7.6.4 Strut Level Adjustment Ability.....	213
7.7 Summary.....	215
Chapter 8 Conclusions and Future Work.....	216
8.1 Assessment of Research Objectives.....	216
8.2 Conclusions.....	219
8.2.1 Design.....	219
8.2.2 Modelling.....	220
8.2.3 Control	221
8.3 Summary of Key Accomplishments and Limitations	221
8.4 Future Directions	223
8.4.1 Design.....	223
8.4.2 Modelling.....	223
8.4.3 Control	224

Appendix A	225
A.1 Strut Element Manufacture and Assembly	225
A.2 Passive-Retractable Joint with a Cable Locking Mechanism (PRM) Manufacture and Assembly	227
Appendix B	230
B.1 Electronic Board Design and Development	230
Appendix C	240
C.1 LA-slider Displacement Scaling	240
C.2 The summary data of the LA-Y1, LA-Y2, LA-Z1 and LA-Z2	242
C.3 Proportional Gain Finding for Close-Loop Control	243
C.4 Inconstant-Force Payload Experiments	245
C.5 Force Sensor Scaling Procedure	247
Appendix D	254
D.1 Braking Delay Time Compensation	254
Appendix E	260
E.1 Custom-Circular Scale Development and Test	260
E.2 Forward Kinematic Accuracy Experimentations	261
Appendix F	265
F.1 One Degree of Freedom (1-DOF) System Experiments	265
F.2 Two Degrees of Freedom (2-DOF) System Experiments	267
F.3 Five Degree of Freedom (5-DOF) System Experiments	271
References	280

List of Tables

Table 2.1 Actuated cables policies for rolling motion	41
Table 2.2 Summary of the advantages and disadvantages.....	47
Table 2.3 Comparison of the reviewed tensegrity robots	53
Table 3.1 Differences between effective existing and proposed	59
Table 3.2 Examples of class 1, 2 and 3 tensegrity robots	61
Table 4.1 Summary of the SE requirements.	86
Table 4.2 Property requirements of the PRM.....	95
Table 5.1 Experimental results of the LA-slider displacement	123
Table 5.2 Summary of experimental results of the multi-step	124
Table 5.3 Tension spring specifications and target positions.	125
Table 5.4 Summary of the multiple-target displacements	127
Table 5.5 Experimental result summary of the multiple-step.....	128
Table 5.6 The force sensor scaling experimental data.	129
Table 5.7 End-cap-angle allowance (θE)	131
Table 5.8 Experimental results of the pressing force	134
Table 5.9 the cable length per count value of six PRMs.....	135
Table 5.10 Experimental results of the maximum braking force.	139
Table 5.11 Strut element (SE) or linear actuator (LA) module.....	141
Table 5.12 Passive-retractable joint with cable locking	141
Table 6.1 Control procedures of the LA-slider lengths	143
Table 6.2 Experimental data results of the multiple-step input	150
Table 6.3 Experimental data results when defining the LA-base.....	152
Table 6.4 Experimental result summary of the 45°	157
Table 6.5 Experimental results summary of the 135°	158
Table 6.6 Initial parameters for the kinematics equations.	160
Table 6.7 Experimental results of the calculated angle	162
Table 6.8 Control rule for locking/unlocking procedures.....	166
Table 6.9 Repetitive experimental result summary.....	168
Table 6.10 Repetitive experimental result summary.....	171
Table 6.11 Third and fourth repetitive experimental result summary.	171
Table 6.12 The control rules of the position and angle control	173
Table 6.13 Experimental results of the end-effector position	180
Table 6.14 Experimental results of different target positions	180

Table 6.15 Configuration time comparison	185
Table 7.1 Extending and retracting procedures of all LA sliders	189
Table 7.2 The LA and PRM control procedures for the forward	195
Table 7.3 The LAs and PRMs control procedures for the backward ...	196
Table 7.4 Control procedures of three LAs and six-PRM.....	198

List of Figures

Figure 2.1 Tensegrity structure and class:	9
Figure 2.2 The fold and expand capabilities of class 1	10
Figure 2.3 Example of tensegrity structures	10
Figure 2.4 TR-3 design [36]:	13
Figure 2.5 The prototype structure and mechanical parts	14
Figure 2.6 The TR-4 design: (a) the TR-4 model.....	15
Figure 2.7 Icosahedron tensegrity prism.....	16
Figure 2.8 The experiment of 10m (30') drop test [6]	17
Figure 2.9 The prototype of a six-strut tensegrity robot [52, 53].	18
Figure 2.10 The prototype of ReCTeR [31]:	18
Figure 2.11 The ReCTeR end cap mechanism [31]:	19
Figure 2.12 SUPERball end cap components [31].	20
Figure 2.13 The new mechanical design of SUPERball end cap [51] - ..	21
Figure 2.14 Outdoor experiment of SUPERball locomotion [11].	21
Figure 2.15 A series of the SUPERball:.....	22
Figure 2.16 SUPERball demonstrations [56]:	23
Figure 2.17 The rapid prototype of an icosahedron tensegrity robot ...	23
Figure 2.18 TT-3 control module and structure [8]:	24
Figure 2.19 The three experiments of TT-3 locomotion [8]:	25
Figure 2.20 The T12-R tensegrity robot [57]:	26
Figure 2.21 The 15-strut tensegrity structure model	27
Figure 2.22 Caterpillar body and muscles [46]......	27
Figure 2.23 The model of Caterpillar mechanism [46]:	27
Figure 2.24 The diagram of high and low-level control [46]......	28
Figure 2.25 The model locomotion with high slope terrain [46].	28
Figure 2.26 The spine tensegrity model [41]:	29
Figure 2.27 The simulation results of Tetraspine's locomotion [41]:	30
Figure 2.28 The series of Tetraspine prototypes [11]:	30
Figure 2.29 The design of ULTRA Spine with cable linkages [65].	32
Figure 2.30 The prototype of DuCTT [15]:.....	33
Figure 2.31 The preliminary test of DuCTT [15]......	33
Figure 2.32 DuCTTv2 prototype [14]:	34
Figure 2.33 Spherical mobile robot prototype [10]:	36

Figure 2.34 Isometric view of the tensegrity structure [70].....	37
Figure 2.35 Example of a tensegrity structure [70, 71]:.....	38
Figure 2.36 Experimental setup for the tensegrity structure [71].....	38
Figure 2.37 Basic locomotion by body deformation [50].	39
Figure 2.38 SUPERball performing a single roll.....	40
Figure 2.39 Open to closed (OC) step policies for rolling	41
Figure 2.40 Closed to open (CO) step policies to roll.....	41
Figure 2.41 TR-3 crawling simulation [33]:	43
Figure 2.42 The captured images of the crawling locomotion	43
Figure 2.43 Trajectory of the COM of the TR-3 robot.....	43
Figure 2.44 Climbing motion procedures for DuCTT [14].	44
Figure 2.45 Jumping robot based on six-strut tensegrity structure.....	45
Figure 2.46 Class 2 tensegrity robot	45
Figure 2.47 Class 2 tensegrity robot	46
Figure 2.48 Examples of the individual element designs.....	49
Figure 2.49 Example of the individual element designs.....	49
Figure 2.50 Example of the individual element designs.....	50
Figure 3.1 Structural configuration concept	57
Figure 3.2 Structural configuration concept	58
Figure 3.3 Structural configuration concept	58
Figure 3.4 Structural configuration concept	58
Figure 3.5 Proposed structural configuration concept	59
Figure 3.6 The locking stage of the new PRM.	62
Figure 3.7 The unlocking stage of the PRM:	63
Figure 3.8 The single SE and two PRMs structure (top view).....	63
Figure 3.9 The end-effector movement capability	64
Figure 3.10 The left-motion behaviour per movement cycle.....	66
Figure 3.11 The right-motion behaviour per cycle.....	67
Figure 3.12 Kinematic diagram of the 3-DOF structure:.....	68
Figure 3.13 Basic concept of the proposed tensegrity structure.	69
Figure 3.14 The structural configuration of the triangular structure.....	69
Figure 3.15 Kinematic diagram of the triangular structure.	69
Figure 3.16 The 5-DOF structure planar.....	71
Figure 3.17 The end-effector movement limitations:	72
Figure 3.18 The strut-element angle adjustment restriction	72
Figure 3.19 Workspace analysis of the end-effector positions.	73

Figure 3.20 The end-effector straight path motion:	74
Figure 3.21 Movement analysis example for the zigzag motion	75
Figure 3.22 Strut element angle adjustments for CW rotation.....	77
Figure 3.23 The SE angle adjustments for CCW rotation.....	79
Figure 3.24 The 5DOF kinematics diagram.....	80
Figure 3.25 Kinematic diagram of the strut-base.	81
Figure 3.26 New reference frame of the structure,.....	82
Figure 4.1 Diagram of the forces acting at contact points	85
Figure 4.2 The diagram of the forces acting at contact points	85
Figure 4.3 Power spring configurations	87
Figure 4.4 The schematics of a power spring [88]:	88
Figure 4.5. The torque-turn curve of the power spring [88]	89
Figure 4.6 The minimum requirement of the cable-pulling force.....	90
Figure 4.7 Example types of mechanical locking devices [90]:	92
Figure 4.8 Examples of friction-based locking devices [90]:	92
Figure 4.9 The example types of singularity locking devices [90]:	93
Figure 4.10 Locking component conceptual design:	93
Figure 4.11 Force analysis of the locking component:	94
Figure 4.12 Image of the micro-LA from Actuonix motion devices	96
Figure 4.13 Images of the thin film potentiometer installation.	96
Figure 4.14 Image of the selected FSR.	97
Figure 4.15 Image of MPU6050	97
Figure 4.16 3D model of the end cap attached to the LA-slider.....	98
Figure 4.17 3D model of the end cap attached to the LA-base	98
Figure 4.18 3D model of the strut module.....	99
Figure 4.19 Images of the retractable key chain (RC):.....	100
Figure 4.20 The cable-pulling force demonstration.	100
Figure 4.21 Relationship between the pulling force and the cable.....	101
Figure 4.22 Captured video of the pulling forces demonstrations	101
Figure 4.23 Image of the selected miniature DC-geared motor.	103
Figure 4.24 Further details of the PRM mechanisms.....	103
Figure 4.25 Mechanical design of the rotational components	104
Figure 4.26 Design of the rotational part assembly procedure.....	105
Figure 4.27 Miniature magnetic rotary encoder with 512 CPR.....	105
Figure 4.28 Cable length measurement mechanism design	106
Figure 4.29 3D model of the braking mechanism.....	106

Figure 4.30 Braking component motions in the locking stage.	107
Figure 4.31 Braking component motions in the unlocking stage.....	107
Figure 4.32 Design of the cable-storage cover.	108
Figure 4.33 Image of strut module prototype:.....	109
Figure 4.34 The physical PRM prototype version 1:	109
Figure 4.35 Physical restrictor mechanism (PRM) version 2:	110
Figure 4.36 The simple wiring diagram of the electronic control	110
Figure 4.37 Image of the electronic control system wiring:.....	112
Figure 5.1 Experimental setup of six LA-slider scaling.....	116
Figure 5.2 Pulse width modulation (PWM) signal	116
Figure 5.3 Example image to compare the LA-slider length data.....	117
Figure 5.4 The LA-slider scaling accuracy experiments:	118
Figure 5.5 Block diagram of the open-loop control experiment.	118
Figure 5.6 Step input response of the slider without payloads,	119
Figure 5.7 Relationship between duty cycle and the speed.....	119
Figure 5.8 Payload carrying experimental setup:	120
Figure 5.9 Experimental results of the LA-slider movements.....	121
Figure 5.10 The closed-loop control with the P-controller.....	121
Figure 5.11 The payload carrying experimental setup:	122
Figure 5.12 Closed-loop control with P-controller:.....	122
Figure 5.13 Multiple-step responses of the LA-slider.....	124
Figure 5.14 Relationship between the resistance force	126
Figure 5.15 Spring payload experimentations:	126
Figure 5.16 The multiple-target response of the LA-slider.....	127
Figure 5.17 Block diagram of the force sensor scaling.....	129
Figure 5.18 Experimental setup for the wall-press	130
Figure 5.19 Maximum and minimum distance for holding	131
Figure 5.20 Passive-compressive force of the end cap.....	132
Figure 5.21 Relationship between the control signal (duty cycle)	132
Figure 5.22 Maximum payload weight experimental setup.....	133
Figure 5.23 Experimental setup for the pressing force	134
Figure 5.24 Experimental setup for the cable length calibration.....	136
Figure 5.25 Experimental results of the cable length calibration	136
Figure 5.26 Experimental setup of cable-pulling force.....	137
Figure 5.27 Relationship between the cable-pulling force	137
Figure 5.28 The maximum braking force demonstration:	138

Figure 5.29 The experimental setup of the locking.....	139
Figure 5.30 Experimental results of the locking.....	140
Figure 6.1 Experimental setup of the 3-DOF structure.....	143
Figure 6.2 Video frames of the closed-loop LA-base.....	144
Figure 6.3 Experimental results of the 3-DOF system.....	145
Figure 6.4 Block diagram of the closed-loop LA-base	146
Figure 6.5 Left movement cycle of the LA-base;.....	147
Figure 6.6 Right movement cycle of the LA-base;.....	147
Figure 6.7 Experimental results of the LA-base.....	150
Figure 6.8 Experimental result of the closed-loop.....	151
Figure 6.9 Experimental setup of the angular control	153
Figure 6.10 Kinematic diagram of the LA-X1 angle:	153
Figure 6.11 Closed-loop control of the LA-X1 angle.....	154
Figure 6.12 Video frames of the 45° angular control	156
Figure 6.13 45° angular control experimental results:.....	156
Figure 6.14 Video frames of the 135° angular control	157
Figure 6.15 135° angular control experimental results:.....	157
Figure 6.16 5-DOF structure.....	159
Figure 6.17 Experimental setup of the kinematics equations.....	160
Figure 6.18 Sharp tip installation for pointing out	160
Figure 6.19 Example video frames of the kinematic equation	161
Figure 6.20 Movement behaviours of the end-effector.....	163
Figure 6.21 Block diagram of the closed-loop position control.....	164
Figure 6.22 Diagram of the end-effector target	165
Figure 6.23 Video frames of the end-effector position control	167
Figure 6.24 Experimental results of the end-effector.....	168
Figure 6.25 Control signal comparison of the three repetitive	169
Figure 6.26 Video frames of the end-effector position control	169
Figure 6.27 Experimental results of the end-effector	170
Figure 6.28 The control signal comparison of the three repetitive.....	171
Figure 6.29 Closed-loop position and angle control.....	172
Figure 6.30 Video frames of the end-effector position	174
Figure 6.31 The experimental results of the end-effector position.....	175
Figure 6.32 Control signal comparison of the three repetitive	176
Figure 6.33 Video frames of the end-effector	177
Figure 6.34 Experimental results of the end-effector position.....	178

Figure 6.35 Control signal comparison of the three repetitive	179
Figure 6.36 Cross-shaped tensegrity robots:.....	181
Figure 6.37 The structural configuration for swapping the structure .	182
Figure 6.38 Structural configuration to create a hard structure	182
Figure 6.39 Structural configuration to make a hard structure	183
Figure 6.40 The structural configuration to make a hard structure	184
Figure 6.41 Motion analysis of different cross-shaped	185
Figure 7.1 The basic crawling robot.....	188
Figure 7.2 Video frames of the crawling robot locomotion.....	190
Figure 7.3 The design of a compliant crawling robot	191
Figure 7.4 Robot configurations for inchworm locomotion.....	192
Figure 7.5 Robot configurations for turning its structure:.....	193
Figure 7.6 Example of robot configurations.....	193
Figure 7.7 Rapid prototype of the crawling robot	194
Figure 7.8 The forward movement cycle of the robot.....	195
Figure 7.9 The backward movement cycle	196
Figure 7.10 Turning motions for the forward and backward.....	197
Figure 7.11 Example images of the manual control motions.....	198
Figure 7.12 Cross-shape tensegrity structure.....	199
Figure 7.13 Cross-shape tensegrity structure.....	200
Figure 7.14 Multiple modules of a tensegrity structure.....	200
Figure 7.15 Cross-shape tensegrity structure using PRMs	201
Figure 7.16 Three modules of a tensegrity structure with PRMs.....	202
Figure 7.17 3D model of the proposed 3D robot	203
Figure 7.18 A physical tensegrity robot structure:	204
Figure 7.19 Demonstration of the soft structure:.....	205
Figure 7.20 Demonstration of hard structure:	205
Figure 7.21 Experimental setup for the structural stabilisation	206
Figure 7.22 X2 angular diagram.....	207
Figure 7.23 Experimental results of X2 angle stabilisation.....	207
Figure 7.24 Experimental results of X2 angle stabilisation:	208
Figure 7.25 X2 angle stabilisation control demonstrations.	209
Figure 7.26 Experimental results of the X2 angular control.....	210
Figure 7.27 Experimental results of the X2 angular control.....	210
Figure 7.28 Experimental results of the X2 angular control.....	211
Figure 7.29 Experimental results of the X2 angular control.....	211

Figure 7.30 Experimental results of the X2 angular control.....	212
Figure 7.31 Demonstration for moving the Z1 upward:	213
Figure 7.32 Demonstration of holding the Z1 in place:	214

List of Abbreviations

Abbreviation	Description
3D	Three Dimension
CAD	Computer-Aided Design
CCW	Counterclockwise
CNC	Computer Numerical Control
CO	Closed to Open
COF	Coefficient of Friction
COG	Centre of Gravity
COM	Centre of Mass
CPR	Count Per Revolution
CW	Clockwise
DL	Dorsal Longitudinal
DOF	Degree of Freedom
DT	Duty Cycle
DuCTT	Duct Climbing Tetrahedral Tensegrity
EMF	Electromotive Force
FSR	Force Sensitive Resistor
HLC	High-Level Control 101
IKCP	Inverse Kinematics Control Policy
IMU	Inertial Measurement Unit
LA	Linear Actuator
LED	Light Emitting Diode
LLC	Low-Level Control
MP	Maximum Percent Overshoot 228
NECTEC	National Electronics and Computer Technology Center
NTRT	NASA Tensegrity Robotics Toolkit
OC	Open to Closed
ODE	Open Dynamic Engine
PAMs	Pneumatic Artificial Muscles
PC-ABS	Polycarbonate Acrylonitrile Butadiene Styrene
P-controller	Proportional Controller
PKMs	Parallel Kinematic Mechanisms
PLA	Polylactic Acid
PPR	Pulse Per Revolution
PRM	Passive-Retractable Joint with a Cable Locking Mechanism

PRCS	Passive-Retractable-Cable Structure
PWM	Pulse Width Modulation
RC	Retractable Key Chain
ReCTeR	Reservoir Compliant Tensegrity Robot
RPM	Round Per Minute
SCL	Serial Clock
SDA	Serial Data
SE	Adjustable-Length Strut Element
SMA	Shape Memory Alloy
SPI	Serial Peripheral Interface
STD	Single-Step Distance
T12-R	Twelve-Strut Tensegrity Robot
TPSMA	Torsionally Prestrained Shape Memory Alloy
TR	Tensegrity Prism
TT	Six-Bar Tensegrity Robot
ULTRA	Underactuated Lightweight Tensegrity Robotic Assistive
VL	Ventral Longitudinal

List of Publications

Part of the research carried out for this thesis has been presented in international conferences, published in the following paper:

- A. Tantaworrasilp and R. Richardson, "Metamorphic Tensegrity Structure for Pipe Inspection", 2019 2nd International Conference on Advanced Control, Automation and Robotics (ICACAR 2019), 18-20 January 2019 [1].

Chapter 1 Introduction

1.1 Background

Tensegrity structures were initially explored in the 1960s by Buckminster Fuller [2] and artist Kenneth Snelson [3]. Tensegrity structures consist of discontinuous compressive elements, which are bars or struts and continuous networks of tensile elements, which are strings or cables. Despite the absence of rigid joints, tensegrity structures can maintain a stable volume in space [4]. These structures thus have advantageous properties compared with traditional structures, offering force distribution, lightweight mechanisms, and compliant capability [5].

These properties are of interest in robotics. Unlike normal structures with rigid joints, tensegrity structures are compliant, meaning they are able to absorb external impact forces by distributing the forces across their elements. Therefore, tensegrity structures could be employed to design a compliant-structural robot that can prevent damage to its mechanisms and payloads when high-external impact forces crash into it [6]. In addition, the force distribution property may make tensegrity robots safer than rigid robots when performing alongside a human [7]. The lightweight nature of this structure is important in developing a robot for exploration and inspection tasks. For example, a lightweight robot may move without getting stuck in soft terrains or climb inside a pipe with low traction forces while avoiding environmental surface damage. Tensegrity structures tend to be lighter than equivalent rigid structures because the compressive and tensile elements can be made from lightweight materials and connect to one another without rigid joints. Therefore, a robot designed with tensegrity structures could perform exploration and inspection tasks that require lightweight, compliant robots able to access various types of environments, such as soft surfaces, rough terrains, and pipelines.

Tensegrity robots can perform a range of locomotion modes, which is useful in accessing different geological areas. Fundamentally, tensegrity robot locomotion can be classified into four modes. The first mode, rolling locomotion, is achieved by changing the robot's centre of gravity (COG). The robot's COG can be adjusted by spooling outer cables to move each strut element, providing different robot configurations [8]. The robot's COG could also be adjusted by adjusting strut lengths to produce different cable tensions, making the robot structure unbalanced and letting it roll [9]. Manipulating the position control of the payload inside a robot structure to produce pushing force can also change the COG of

the robot, enabling rolling locomotion [10, 11]. The second mode is crawling locomotion, which can be achieved using frictional forces between robot legs and ground surfaces as well as pushing forces between strut elements [12, 13]. The third mode is climbing locomotion. A robot can climb inside a narrow environment such as a duct or pipe by using linear actuators that press against the pipe wall to maintain its position, or it can move up and down by actuating cables connected between the fixed and movable parts [14, 15]. Finally, the fourth mode is jumping locomotion, in which the robot is able to jump in both vertical and horizontal directions by applying heat to the Torsionally Prestrained Shape Memory Alloy (TPSMA) springs; the TPSMA springs are used to store and release energy mechanically to produce pushing forces between robot legs and the ground to perform jumping locomotion [16].

1.2 Motivation

The unique properties of tensegrity structures motivate this research of a new actuation method that could provide a compliant, lightweight, and low-energy design for inspection robotics. This new method would make a significant contribution to the field of robotics.

Tensegrity structures are of interest in the fields of engineering and architecture due to their effective combination of simplicity and rigidity [17]; these structures can be deformed by changing cable tension, allowing them to generate soft and hard bodies that could, in turn, lead to the developments of a robot for space applications [18]. A number of research teams have evaluated the force distribution properties of tensegrity structures to ensure tensegrity structures could be used to design and develop an exploration robot. Sunspiral et al. [6] introduced a six-strut tensegrity robot and demonstrated drop tests from heights of 7.5 m and 10 m. The experimental results found that the robot could still perform after landing and could be dropped again for other experiments. In 2014, a robot named DuCTT (Duct Climbing Tetrahedral Tensegrity) was introduced by Friesen et al. [15]. DuCTT was the first pipe robot based on tensegrity structures. DuCTT's actuation method was to use linear actuators that pushed against a wall pipe and rotary actuators that spooled cables to let the robot move up and rotate. DuCTT demonstrated a climbing concept along a straight-vertical pipe. However, a number of control and mechanical failures occurred, leading to the development of a new version named DuCTTv2 [14]. Tensegrity structures thus could be used to design a robot able to perform dangerous tasks or work in dangerous areas, such as in underground pipeline inspection.

However, a number of limitations should be considered in terms of actuation methods. Firstly, the structural configurations for tensegrity robots do not change quickly because existing actuated-cable mechanisms take a long time to spool cables; this system requires a high torque and low speed to sufficiently actuate the cables for robot configurations. Secondly, the power usage for locomotion is high, resulting in short operation when powered by batteries. Current actuated cable mechanisms are based on a high-torque and active actuator to spool cables for configurations. In order to make the robot move, the actuated-cable mechanism should be constantly supplied with energy while actuating cables. The energy demand is high, reducing operation time. Thirdly, the weight of the existing actuation mechanism of tensegrity robots is still too high, which inhibits climbing locomotion. Existing tensegrity robots require high-torque actuators to spool cables for robot configurations. High-torque actuators are high power, which increases the weight of the actuation mechanisms.

These limitations have motivated me to research the design of a new reconfigurable tensegrity robot that could change its shape quickly and conduct locomotion with minimal power. The design of a mechanism that could exert a large amount of force using less power to control cable lengths is also researched, as such a mechanism could reduce the overall weight of the proposed robot.

1.3 Aims and Objectives

The aim of this project is to design and develop a new actuation method for a reconfigurable tensegrity robot. The robot's individual elements would require less power to perform fast structural configuration, and it would operate using a lightweight mechanism. The individual elements consist of an adjustable-length strut element (SE) and multiple modules of passive-retractable joints with a cable locking mechanism (PRMs). The SEs and PRMs are connected using cables to form the tensegrity robot. All of the mechanisms of the tensegrity robot are designed to be manufactured and assembled. The objectives of this project are as follows:

- 1) Review the advantages of tensegrity structure properties used in different research areas and critically assess the literature on existing tensegrity robot types and locomotion classified by structure geometry. Based on the findings, investigate mechanical designs for compressive elements and actuated tensile elements that could be utilised to solve mechanical issues.

- 2) Investigate the locomotion types of existing tensegrity robots and the current limitations of their configurations to design and develop a new approach to overcome these limitations.
- 3) Design a new structural deformation concept and analyse the kinematics of the design.
- 4) Design and develop the SE and PRM prototypes based on the structural deformation concept.
- 5) Verify that the SE and PRM prototypes conform to the structural deformation concept by constructing, demonstrating, and evaluating the new structural deformation method and control.
- 6) Extend the proposed structural deformation method by developing physical robots based on the Class 1 tensegrity structure.

1.4 Contributions and Publication

1.4.1 Contributions

The contributions and originalities of this research are as follows:

- 1) *A new actuation method for a tensegrity robot.* Instead of using active actuators, including linear and rotary actuators, to spool cables or adjust strut lengths, the cooperation between an active actuator and passive-retractable joint to deform robot structures is introduced in this paper. The active actuator is an adjustable-length strut element (SE), and a passive-retractable joint that restricts and releases cable lengths is a passive-retractable joint with a cable locking mechanism (PRM). To deform the robot shape, the PRM is used to restrict and release cables while extending or retracting the SE length to generate varied cable tensions to move SE positions, resulting in a change in robot configurations. The proposed method would be beneficial for developing reconfigurable robots based on tensegrity structures. The method provides high-speed configurations, even when swapping from hard to soft structures to absorb internal and external impact forces by distributing the forces across the structure.
- 2) *A new design of the PRM.* The new design provides cable restriction in the locking stage and high speed for the spooling cable in the unlocking stage, improving performance of structural configurations. Both the locking and unlocking stages of the new design are different from the existing cable actuation methods of tensegrity robots, which currently have low speeds for spooling cable. In addition, the new design incorporates spring elements to exert cable forces and braking forces

passively, so less power is required to achieve the locking and unlocking stages leading to the possibility to give a tensegrity robot more locomotion efficiency than existing tensegrity robots. Moreover, for the first time in the field of tensegrity robotics, this new design could allow the PRM to carry out physically achievable locking and unlocking stages.

- 3) *New control rules for the proposed technique.* A concept of the new control rules consists of two phrases. The first phase involves finding the locking and unlocking stages of four PRMs by considering the cable-pulling forces generated by each PRM, interacting with SEs. These cable-pulling forces can be enabled and disabled by applying the unlocking and locking stages of the PRM, respectively. The unlocking and locking stages are defined, depending on the SE directions able to move the end-effector close to a target point. However, PRM alone will not be able to control the end-effector position. The push and pull forces of the SE must be applied to all PRMs by extending and retracting SE lengths, which is the second phase. The second phase involves determining to what extent SE-slider length should be extended. This phase can be achieved using the different displacement between a target point and a current point of a displacement error. The first and second phases are used to design control rules to enable and disable the cable-pulling force of the PRMs and calculate SE-slider length to control the end-effector positions. These new control rules were successfully implemented and applied to achieve position and angle controls for 3-DOF and 5-DOF systems.

1.4.2 Publication

A. Tantaworrasilp and R. Richardson, "Metamorphic Tensegrity Structure for Pipe Inspection", 2019 second International Conference on Advanced Control, Automation and Robotics (ICACAR 2019), 18-20 January 2019 [1].

1.5 Thesis Organisation

This thesis is divided into the following eight chapters.

Chapter 1 has introduced the background and motivation for the project and the aims and objectives regarding the development of a reconfigurable tensegrity robot based on the Class 1 tensegrity structure. The chapter has also outlined the scope and contributions of this research.

Chapter 2 reviews research on existing tensegrity robots focusing on the mechanical design of compressive and tensile elements used for the robot configurations for locomotion. Different geometries of tensegrity robots and control are studied to determine the limitations of the existing actuation methods for tensegrity robot configurations. Effective design techniques that have been used to solve mechanical problems in tensegrity robots are also reviewed in this chapter.

Chapter 3 focuses on existing tensegrity robot configurations for locomotion and current limitations. A new structural deformation technique to reduce the problem is then introduced. The basic concept of the tensegrity robot, including rolling and climbing movement behaviours, are described and discussed. Three- and five-degree-of-freedom structures are employed to describe the fundamental movement concepts of the proposed technique. The structural configurations, using a PRM in cooperation with an adjustable-length SE, are described and analysed. Kinematic equations for the proposed structures are derived to identify the end-effector positions used for a closed-loop control system.

Chapter 4 details the individual element design and implementations. The individual requirements of the SE and PRM, considering required forces to produce motions, are analysed and calculated to select electronic components. Then, the three-dimensional design, fabrication, and implementations of the SE and the PRM are detailed. The microcontroller control boards and other electronic boards used to control each SE and PRM and communication selection are also detailed in this chapter.

Chapter 5 shows individual element testing. To ensure that the developed SE and PRM meet requirements, SE-slider length, PRM-spooling force, and the PRM-braking force are scaled and tested experimentally. The open- and closed-loop control of the SE-slider length is demonstrated and evaluated to ensure that the SE sliders provide the required pressing forces to maintain their position in vertical directions.

Chapter 6 presents control and structural deformation validation. The 3-DOF and 5-DOF structures seen in Chapter 3 are implemented to evaluate the derived kinematic equations that identify end-effector positions. Control rules for locking and unlocking procedures of the PRM while changing the SE-slider lengths for the closed-loop position and angle controls of the end-effector are designed, implemented, and evaluated.

Chapter 7 discusses a case study of the employment of the proposed structural deformation method to design reconfigurable crawling and climbing robots based on Class 1 tensegrity structure. Initially, a conventional crawling robot is roughly

developed and demonstrated to illustrate how the robot moves using inchworm behaviour. The locomotion of the tensegrity crawling is then demonstrated with the same environmental conditions of the conventional crawling robot, and the tensegrity climbing robot locomotion is demonstrated considering the necessary functions of climbing robots. The demonstrations explore whether the proposed structural deformation method could be applied to the development of a reconfigurable robot able to move in both horizontal and vertical directions.

Chapter 8 summarises the completed paper and evaluates how well the aims and objectives have been achieved. The recommendations for future work are then presented.

Chapter 2 Literature Review

This chapter explores research on state-of-the-art tensegrity robots. Basic concepts of tensegrity structure and knowledge are first introduced. The chapter then analyses mechatronic designs and configurations of existing tensegrity robots. Following this analysis, actuation methods, the designs of strut elements and actuated cable mechanisms are reviewed to gain mechanical design knowledge beneficial for a new design of actuation method that is able to address existing issues.

2.1 Introduction

A tensegrity structure is a lightweight, compliant structure; it consists of compressive elements, namely struts or bars, surrounded by a network of tensile elements, namely strings or cables, to maintain a stable volume in space [4]. All of the struts are connected to the others using only cables without rigid joints, providing the compliant structure with multiple degrees of freedom at connecting points. The individual compressive elements can be made of different materials, such as wood, metal and aluminium, and the tensile elements can be made of elastic or inelastic materials, such as nylon rope or stainless wire. These materials allow the individual elements to be lightweight, resulting in the reduction in the weight of the structure. The tensegrity structure has been introduced in different aspects of biological systems, such as the cytoskeleton of individual cells [19, 20] and movements of human joints [21, 22]. The tensegrity structure was first invented by Snelson in 1948, as seen in Figure 2.1 (a), and formally patented by Buckminster Fuller in 1962 [2], who created the term “tensegrity”. which comes from the terms “tensile” and “integrity”.

The configurations of tensegrity structures can be classified based on the number of rigid bodies connecting at a contact point. According to the classification:

“A tensegrity configuration that has no contacts between its rigid bodies is a class 1 tensegrity system, and a tensegrity system with as many as k rigid bodies in contact is a class k tensegrity system[5].”

Examples of class 1, 2, and 3 tensegrity systems are presented in Figure 2.1 (b), (c), and (d), respectively.

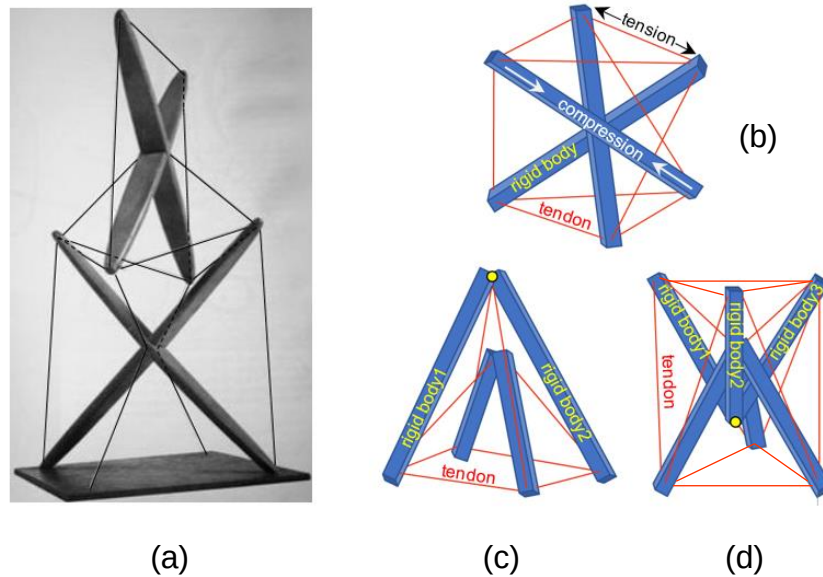


Figure 2.1 Tensegrity structure and class: (a) Snelson's X-piece constructed in 1948. Two rigid bodies connect with tensile elements creating a 3-dimensional stable structure [5], (b) Class 1 tensegrity system (no rigid body in contact), (c) Class 2 tensegrity system (2-rigid bodies in contact), and (d) Class 3 tensegrity system (3-rigid bodies in contact).

In its early stage, research on tensegrity structure focused on form-finding techniques related to the motion of endpoints or nodes inside of the structure, interacting with internal or external forces [23-26]. The design and analysis of static structures were introduced by [4, 25, 27]. In the mid-1990s, the varied controls of tensegrity structures were presented by initial efforts to formalise the dynamics of tensegrity structures [5, 28]. Sultan, et al. [29] investigated the linearised dynamics. Skelton and de Oliveira [5] proposed Lyapunov-function-based control techniques; however, this research appears to be practically limited to underactuated robotic platforms. The advantageous properties (multi-path load distribution, nonlinear dynamics, compliant structure, etc.) that cause tensegrities to interact with environments have also been presented to provide significant challenges to traditional control approaches. Without rigid joints connecting struts and cables, tensegrity structures provide useful properties that externally applied forces are distributed through individual elements to create system-level mechanical robustness [30, 31]. The tensegrity structure can fold and expand its structure by changing cable lengths and tensions [6], as shown in Figure 2.2.

Based on these advantageous properties, tensegrity structures are of interest in the fields of engineering, specifically civil engineering. Some applications constructed with tensegrity structures are Kurilpa Bridge in Brisbane, Australia, the needle in the United States, and the roof structure of the sports stadium at La Plata in Argentina [32], as presented in Figure 2.3.

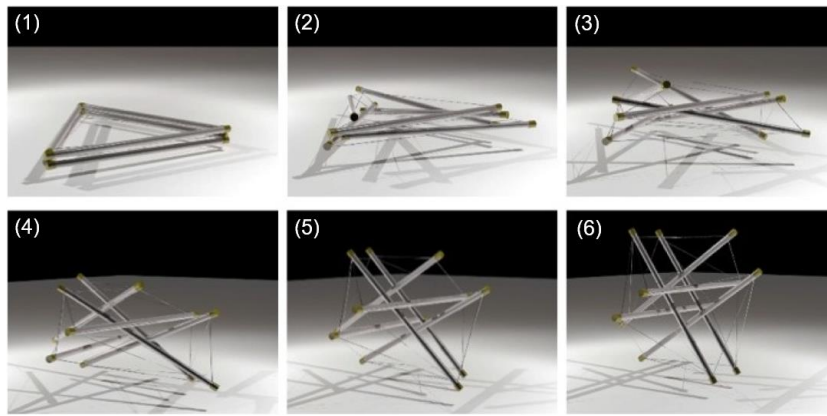


Figure 2.2 The fold and expand capabilities of class 1 tensegrity structure: (1) completely folded structure to (6) fully expanded structure [6] There are many different possibilities for configuring tensegrity structures, such as polygon, hexagon, and octagon [4].

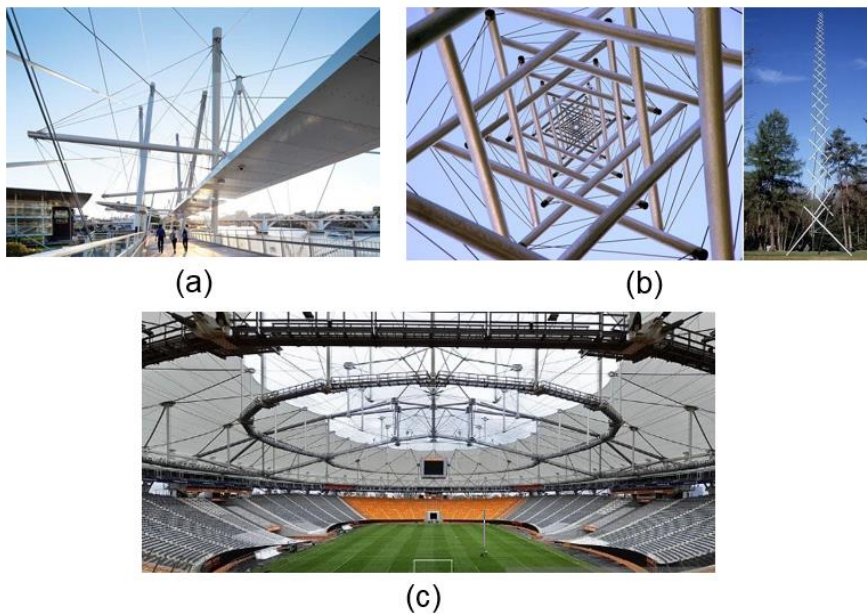


Figure 2.3 Example of tensegrity structures used in civil engineering [32]: (a) Kurilpa Bridge in Brisbane, Australia, (b) the needle in the USA, and (c) the roof structure of the sports stadium in La Plata, Argentina.

2.2 Tensegrity Robotics

Tensegrity structures are of interest in soft robotics because of their flexible, robust nature [8]. These structures are able to distribute external forces to each element. Therefore, tensegrity robots are soft machines that can absorb forces and interact with both structured and unstructured environments [31]. Tensegrity structures can be used as a platform for soft robotic designs, which ensure that they are not harmful to humans, which has led to their increasing popularity in soft robotics [8].

The properties of tensegrity structures have also received academic attention from a new generation of robotic landers and rovers for space exploration. The ability to land a low-cost rover without damage and move to another unstructured terrain is desirable for successful space exploration [6]. A robot can deform its structure following unexpected and undesirable interactions with the environment, such as collisions with obstacles while moving. In addition, the efficient movement of tensegrity robots is possible, though they are constructed using elastic cable and struts to produce dynamical legs because lightweight structures require less power for configurations than heavyweight structures. Aside from these properties, tensegrity structures have more advantageous features that are beneficial for robotics [6, 30, 33-35], including the following:

Lightweight: The mechanism of the tensegrity structure is generally made of lightweight materials such as aluminium tubes and elastic cables;

Robust to failures: Tensegrities are distributed systems as they have many actuators that drive a robot and lightweight mechanisms. Therefore, tensegrities can still operate in the presence of an actuator failure;

Capable of unique modes of locomotion: The locomotion of the tensegrities structure can be achieved by methods such as rolling, crawling, galloping, swimming, and flapping wings, depending on the purpose of applications;

High strength-to-weight ratio: The size of each actuator inside the struts is low relative to the number of degrees of freedom and leads to the possibility of reducing the weight of the struts; and

A high degree of modularity: Each strut is constructed with identical sensors and actuators. Therefore, to create a tensegrity structure with ten struts is the same design effort as one with three struts.

Although the advantageous properties of tensegrity structures are worth exploring, their use in robotics is still being researched to investigate how to employ these structures to develop a robot that provides effective functions in a way that traditional robots do not. Therefore, different research areas in tensegrity robots have been being explored for decades, such as kinematics and dynamics, controls, locomotion efficiency, and mechanical designs.

Paul et al. [36] were the first to link tensegrity structures to structural configurations for robot locomotion. The authors introduced tensegrity prisms with three and four struts called TR3 and TR4, respectively and developed controllers to produce static and dynamic legs for both robots. Sunspiral, et al. [6] used Euler-Lagrange to solve the dynamic equation of a six-strut tensegrity robot,

allowing it interacting with an environment. The simulation results were compared with Skelton's dynamic equations [5]; The Lagrange approach was used as well as Skelton's constrained class 1 structure. Friesen et al. [15] employed the force density method to solve the inverse kinematics of a climbing robot based on a class 3 tensegrity structure. The research on tensegrity robot locomotion was also initiated by Pual [33, 36], and the challenges of controlling tensegrity robots was inspired by biological sciences, using evolutionary algorithms [33, 34, 36-40], neuroscience-inspired central pattern generators (CPGs) [41-44], biomimetic motions of animals such as caterpillars [38, 45, 46], and Ray's wing [47].

A smaller number of studies have been conducted on locomotion efficiency. Kim, et al. [48] introduced the use of thrusters to make a six-strut tensegrity robot that hops and rolls on rough terrains. The authors implemented an A-star algorithm to find a feasible path for the robot to hope and roll from its initial to the target locations, minimising energy consumption, though the energy consumption has not yet been physically tested. Therefore, locomotion efficiency research needs to be further explored in order to design individual elements that require less energy for robot configurations and locomotion.

This research focuses on the mechanical design of individual elements and structural configurations methods to address limitations in the field of tensegrity robotics. Therefore, the mechanical design, locomotion, and actuation methods of the existing tensegrity robots are reviewed to respond to the research questions.

2.3 Tensegrity Robot Structures and Mechanical Designs

This section introduces tensegrity structures that have been adopted in the field of robotics and describes the mechanical design of tensegrity robots. Most studies have attempted to find novel forms of a robot based on tensegrity structures to access complex environments where existing robots cannot perform. There are several tensegrity structures introduced in the field of robotics, as presented in the following subsections.

2.3.1 Triangular Tensegrity Prism

The triangular tensegrity prism (TR-3) constructed with three struts was proposed in [36, 37]. The researchers proposed the concept of a legged robot constructed based on a tensegrity structure and demonstrated locomotion. The open dynamics engine (ODE) was used to simulate the movement of the robots, as presented in Figure 2.4 (a). The physical TR-3 was developed to test controller

performance. A genetic algorithm was used to converge on periodical control patterns to be applied to the robot configurations for locomotion.



Figure 2.4 TR-3 design [36]: (a) TR-3 simulation model; and (b) TR-3 prototype.

The TR-3 mechanism comprised of three struts made from aluminium tubes. Each strut was connected to another using nylon-covered rubber elastic cables. The Hitec HS-625MG servomotors mounted on the struts to spool the cables produced traction forces between contact points and the ground. At the end of each strut, a nylon cable was mounted with a nut, bolt, washer fitting, and a heavy-duty fishing cable. Each servomotor was controlled to alternate position control between maximum and minimum cable lengths, providing an approximate 2 cm change in the length of the cable. The experiment results suggest that the robot could move horizontally at a speed of 60 cm per minute but could not move in a straight line because the controller was unable to generate the control signal for the straight motion due to a lack of position feedback and the structure of TR-3 was not symmetrical. The TR-3 prototype was inapplicable for high precision movements because the robot structure generated vibrations when moving under lower-pre-stress conditions. The researcher found that high bandwidth control may be used to reduce the vibrations. The TR-3 mechanism is presented in Figure 2.4 (b).

Rieffel, et al. [34] developed a three-bar tensegrity robot. The actuator system of this robot was different from TR-3; the ends of each strut were integrated with a tension sensor used to measure the tension of the nylon cable, and AX-12 servo motors were employed to pull the nylon cable. The servomotor used a continuous rotation integrated with a load sensor. A controller module was integrated into each strut and communicated through a wireless communication module. Evolutionary optimisation was employed to produce leg movement patterns for locomotion. Each module's controller comprised of a simple two-layer neural network. The inputs of the neural network were forces measured by a load sensor, and the outputs of the neural network were of the desired length for each

nylon cable. An ODE was employed to evaluate the proposed controller. However, this research did not show simulation results; instead, the concept of the decentralised control illustrated a robust failure capability. Each of the three struts of the robot contained a controller module that communicated with the others to send motion commands to actuator drives. If one of the controllers failed, the remaining controller could still send motion commands to ensure that the robot moved. In contrast, if the robot had only one controller or centralised control, the robot would completely stop if the controller failed.

In 2010, Tur [49] introduced the idea of the strut actuation method for locomotion using the extension and retraction of strut length. The mechanisms of each strut were comprised of three struts made of aluminium tubes, which were built using two different diameter tubes. The first tube (13 mm diameter x 10.5 mm length) was inserted inside the second tube (18mm diameter x 15 mm diameter), allowing its length to vary between 55 and 92 cm. The second tube could be extended and retracted using transmission mechanisms that consisted of a DC motor (Faulhaber Series 2342) together with a metal gear head (14:1) and a rotary encoder (16 pulses per revolution (PPR)) mounted on the bottom of the DC motor. The robot had two types of joints. The lower joint was a spherical joint that allows the strut to move in any direction and was connected to a spring. The upper joint connected three springs to hold each strut in the vertical position. However, each upper joint of the robot was mounted on a fixed platform that did not allow the robot to move. The prototype structure and mechanical parts are presented in Figure 2.5. Although the robot structure could not be moved, the design concept of the strut mechanism was novel as the struts could adjust the lengths to change the structure shape instead of pulling cables connected to each strut end.

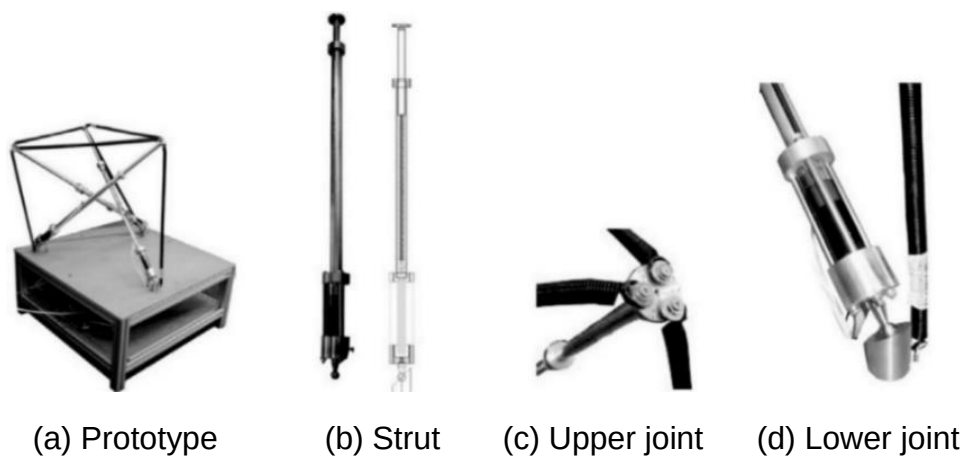
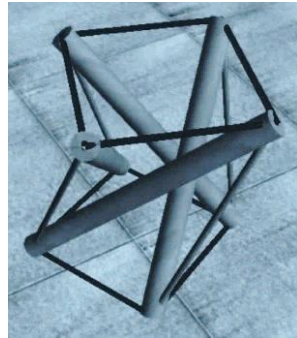


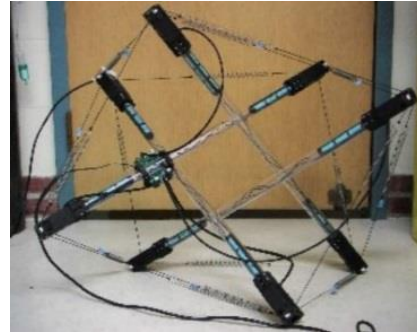
Figure 2.5 The prototype structure and mechanical parts [49].

2.3.2 Quadrilateral Tensegrity Prism

Paul, et al. [33] introduced the quadrilateral tensegrity prism TR-4 constructed with four struts. This prism was designed to compare the performance of the evolutionary optimisations applied to both TR-4 and TR-3 in the software simulation. 10 cycles of the simulations were then performed. All of the simulations of the TR-4 were achieved with the highest possible fitness, which was successful locomotion.



(a)



(b)

Figure 2.6 The TR-4 design: (a) the TR-4 model designed by Paul, et al. [33]; and (b) a prototype of a four-bar tensegrity robot developed by Rieffel, et al. [38].

TR-4 was optimised for a crawling motion based on the strut end, as shown in Figure 2.6(a). Additionally, fault-tolerance experiments were introduced to guarantee that the robot moved even when one or two actuators failed. The experimental results found that the robot could achieve fitness ranging between 1.99 and 3.58m when one actuator failed. In addition, the robot could still move at a slower speed to achieve fitness ranging between 1.21 and 2.82 m when two actuators failed.

In 2008, Rieffel, et al. [38] developed a tensegrity robot comprised of four strut modules and 12 tensile cables, as presented in Figure 2.6 (b). This robot was developed to explore control algorithms that could be exploited to control the movement of a soft robot, leading to the design and simulation of a complex, highly dynamically coupled 15-bar tensegrity structure.

2.3.3 Icosahedron Tensegrity Prism

An icosahedron tensegrity prism consisting of six struts is the most popular shape due to the spherical geometrical structure that contains the minimum number of struts to achieve rolling locomotion [50, 51]. There has been a significant body of research on the icosahedron tensegrity robot.

Shibata, et al. [50] introduced an icosahedron tensegrity robot with a six-strut actuated by Shape Memory Alloy (SMA). A prototype of this robot is presented in Figure 2.7 (a). The mechanism of the robot comprises six struts made of acrylic pipes and 24 strings made of rubber bands with a coefficient of rigidity of 13.1N/m. The rubber bands were used to connect between each strut at the end of the struts to create an equilibrium structure. The BMX150 SMA actuators were adopted for the deformation process; the robot could deform its shape by applying sufficient voltage and current to the SMA. However, the robot only demonstrated this new concept to deform the tensegrity robot structure for locomotion and required external electronic control modules and batteries via electric wires.

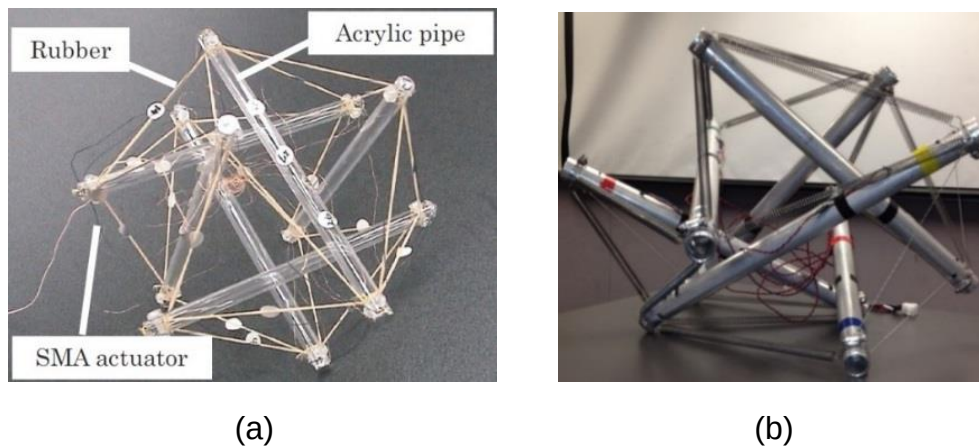


Figure 2.7 Icosahedron tensegrity prism: (a) six-strut tensegrity robot developed by Shibata, et al. [50] and (b) Icosahedron tensegrity robot constructed by SunSpiral, et al. [6].

The important evaluation of the icosahedron tensegrity robot was introduced by SunSpiral, et al. [6]. This research aimed to design and develop a tensegrity robot able to distribute impact force for landing at Titan. The robot prototype is shown in Figure 2.7 (b); it consisted of six struts made of aluminium tubes with an outer diameter of 1-3/8 inches with 1/8-inch thickness and a length of 20 inches. The motor and controller were integrated inside each strut to prevent unexpected damage that might occur during landing. The robot structure could be balanced by six actuated strings and 18 outer springs to generate tensile forces and compression forces. In order to deform its shape, the six strings were spooled by motors mounted at the end of each strut.

In the landing demonstration, the drop tests were from a height of 7.5m and 10m. A speed of 11m/s was achieved during landing; and the experimental results show that the robot still performed after landing and could be dropped again for other experiments. Figure 2.8 shows the robot bounding and rotating forward with approximately double distances of its diameter.

An interesting anomaly occurred during a drop test. The motors were rotated backwards around 2-3 cm during landing. Therefore, the researchers suggest that the motors should be locked during landing by integrating a braking mechanism.

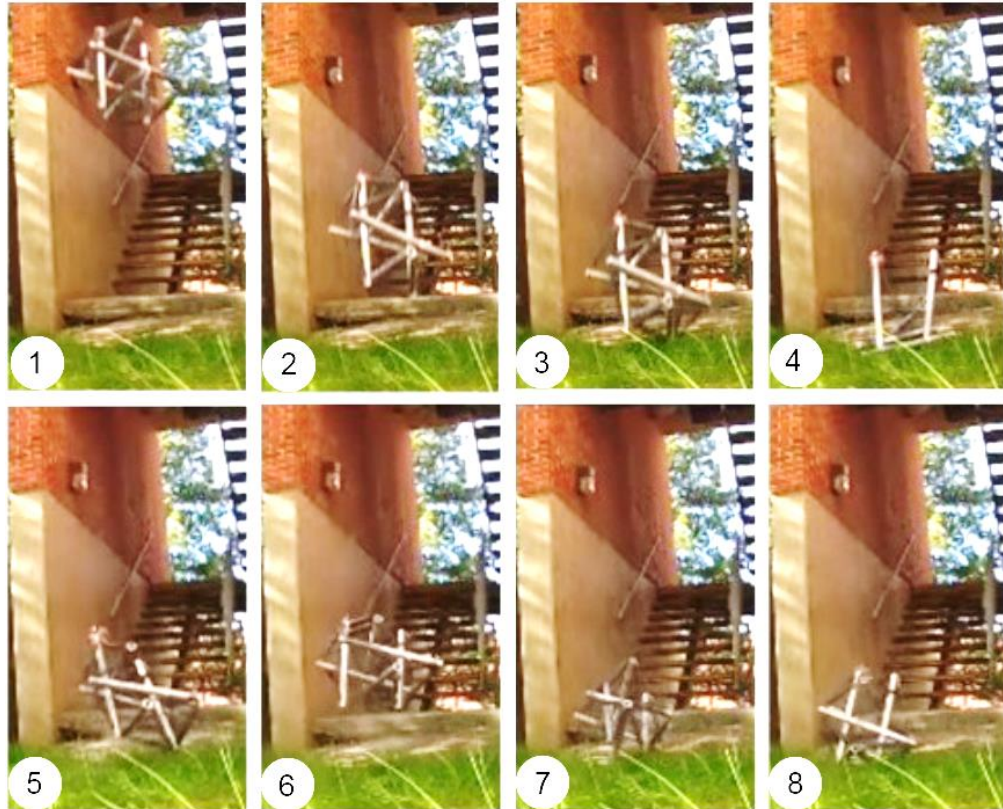


Figure 2.8 The experiment of 10m (30') drop test [6]

Another research team proposed the six-strut tensegrity robot actuated by pneumatic actuators [52, 53], as presented in Figure 2.9. The mechanical and electrical components of the robot comprised of six aluminium struts of 750 mm in length, 24 pneumatic McKibben actuators actuated by air pressure from the external compressor via hoses, and two rigid balls of 45 mm diameter connected to both ends of each strut.

The research attempted to employ other actuators that would be able to produce larger forces than SMA actuators and determine how many actuators could make a robot rolling to minimise power usage and design a simple control. The experiment found that, although the pneumatic McKibben actuator could produce 800 N force while applying 0.5 Mpa air pressure, the tensegrity robot could not roll the body with one actuator. The robot could be rolled by using two McKibben actuators driven by the air pressure of 0.15 MPa while the robot changed the direction from planar symmetric contact to another planar symmetric contact, and six McKibben actuators were driven by the air pressure of 0.4 Mpa when the robot changes direction from axial symmetric contact to a planar symmetric contact.



Figure 2.9 The prototype of a six-strut tensegrity robot [52, 53].

Although the pneumatic actuator provided a high torque use for rolling the robot, the rolling motion of the robot is limited due to the lack of any sensor, such as force, tension, and position sensors to measure current position. The controller and air pressure supply were not installed inside the robot, requiring the robot to use an external air pressure supply. This limitation was one of the disadvantages of the existing icosahedron tensegrity robots at the time.

This limitation was overcome between 2013 and 2018. The development of an icosahedron tensegrity robot called ReCTeR (Reservoir Compliant Tensegrity Robot) and a series of SUPERball was introduced [11, 31, 51, 54-56]. Both robots were constructed containing controllers, drivers, sensors, and actuators. ReCTeR was a compliant robot able to fold and unfold structures effectively and had a lightweight structure of 1.1 kg, including batteries, due to the use of carbon fibre for six struts (8 mm outer diameter). ReCTeR prototype and configurations are presented in Figure 2.10.

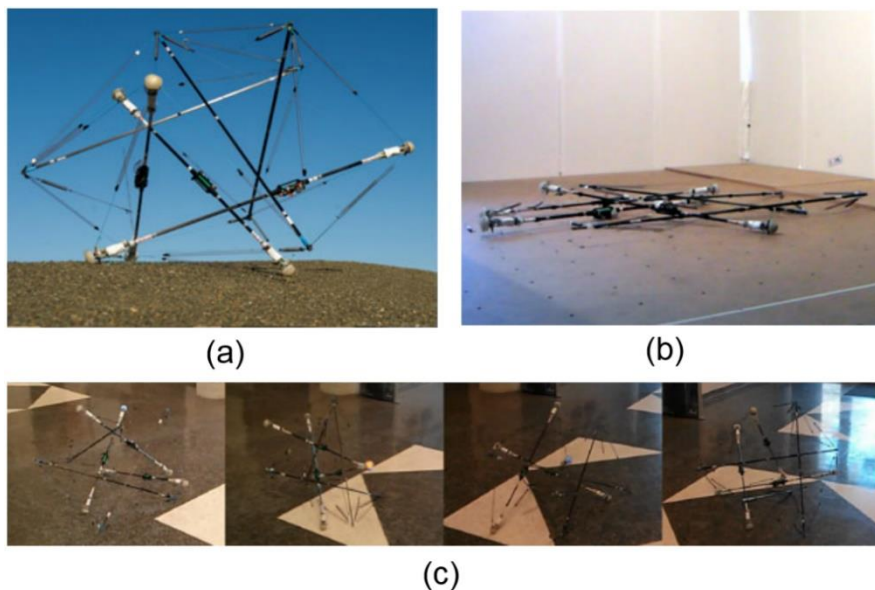


Figure 2.10 The prototype of ReCTeR [31]: (a) deployed robot, (b) active folding, (c) ReCTeR rolling from right to left.

The mechanical design of the ReCTeR is unique. Two groups of strut elements were designed differently. The first group consisted of three actuated struts, and each strut comprised of two sets of an actuator and electronic module, mounting on both ends of the strut to actuate cables. The second group consisted of three struts, which each strut comprising only a compressive spring. 24 cables were used to connect struts. Six-actuated cables were spooled through all actuated struts by DC motors with a gearbox (ratio 4.4:1) mounted at the end of the actuated struts. The six-actuated cables were attached to actuated spring (81 Nm^{-1}) and passive spring (28.4 Nm^{-1}) mechanisms called “end caps”, as illustrated in Figure 2.11. Each actuated spring passed through the strut and connected a non-parallel strut to allow the robot to balance. The design technique allowed for low motor energy consumption to adjust the robot’s stiffness.

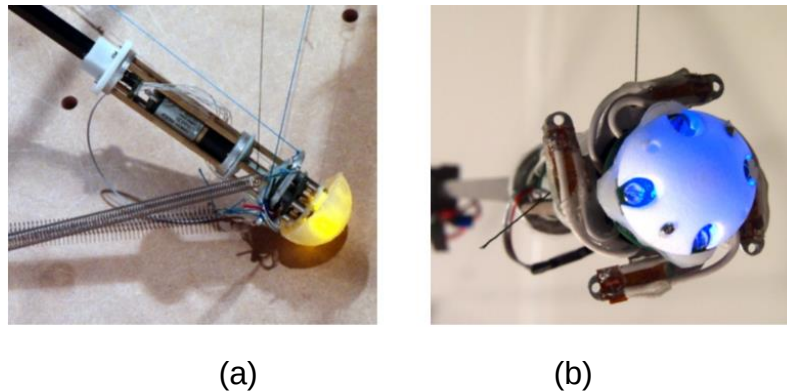


Figure 2.11 The ReCTeR end cap mechanism [31]: (a) end cap design with the cover motor removed and (b) zooming in end cap design and four tension sensors, attached to each end cap, without silicone protection.

To effectively accomplish deformation and rolling, feedback sensors were used to measure ground impact forces, spring tension, and the robot’s position. Each end cap included four tension sensors using strain gauges, a ground impact force sensor, and a 6-DOF position sensor attached to the middle of the strut. The controller modules and power batteries were designed and installed in the middle of each actuated strut. This robot structure was tested with a drop test of 0.5m. After experimenting, all struts were performed without any damage to confirm that the tensegrity structure could distribute impact force to member elements [6]. However, the robot could not be used as a general tensegrity robot platform due to a number of restrictions. Firstly, the lightweight mechanical design could not carry any payload, which was a crucial property of any terrain exploration tasks. Secondly, the design of the spring to prevent the robot structure damage was a key factor that would increase the weight of the robot. It was difficult to restrict the maximum spring extension to protect it from unexpected deformations.

Therefore, the development of an icosahedron tensegrity structure SUPERball was introduced to address these issues.

SUPERball consisted of 12 geared motors mounted at the end of six struts. Each strut consisted of two end caps, which included both electrical and mechanical elements. Both of the end caps were connected by the aluminium tube, which was used to support the structure. The design of the end cap was simple to assemble and remove and consisted of five parts: spring holder; battery holder; motor and electronic component; cable actuation component; and a ground impact component, as illustrated in Figure 2.12.

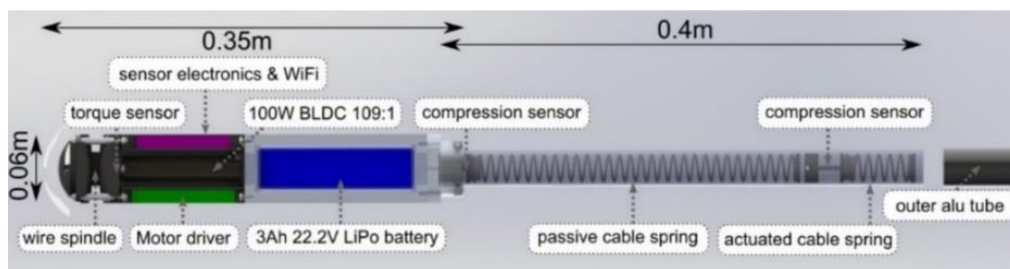


Figure 2.12 SUPERball end cap components [31].

The design of the compression spring was safer than the extension spring; this design allowed for integrating two compression sensors, which were independent of the cables. The longer compression spring, which was connected to a cable, was not actuated, whereas the short, stiffer spring was attached to an actuated cable from another end cap. The aluminium tube was used to cover both actuated and passive springs and connected between the two end caps of the strut.

ReCTeR may encounter a number of problems; for example, the exposed springs may get caught on objects. An enclosed compression spring was integrated to reduce this issue in the end cap design of the SUPERball. During any unexpected impact, the compression springs are not easily deformed.

For the electrical and sensor design, each end cap contained two electronic control boards, a motor drive board, sensor interface, and wireless communication board. Each control board consisted of a microcontroller and sensor interface board, including an analogue to digital converter and 9-DOF for the motion sensor. The torque sensor, compression sensors, and current sensors were utilised in each strut, allowing them to demonstrate advanced control schemes. However, the research did not mention SUPERball implementation, instead proposing a new method for learning locomotion with software simulation [31].

In 2015, Sabelhaus, et al. [51] enhanced the performance of SUPERball to meet the requirements of the project aimed at NASA Ames Research Centre

Roverscape. Overall, the features of the electronic components, including sensors and control boards of SUPERball 2015, were similar to the previous version, though some mechanical parts and material specifications were different. The novelty of mechanical design of SUPERball end caps comprised three components: spring-cable system; electronics components; and actuation system, as shown in Figure 2.14.

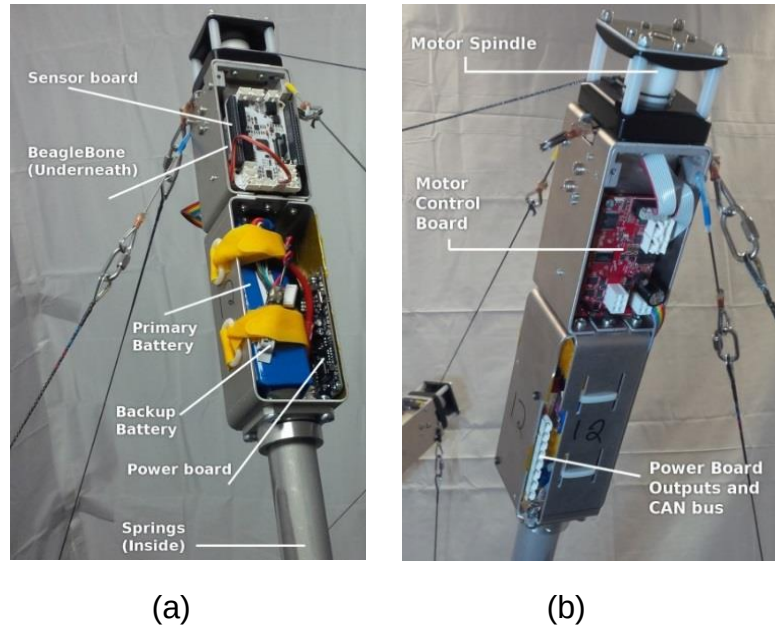


Figure 2.13 The new mechanical design of SUPERball end cap [51] - (a) front view of the end cap and (b) the back view of the end cap.

For the simple locomotion, SUPERball could change its body using feedback control. The robot movements used the basic motion for spherical tensegrity structure, rolling from one triangle face to another triangle face. This method could be employed for SUPERball locomotion successfully. The locomotion result of rolling outdoor experiments is presented in Figure 2.14.

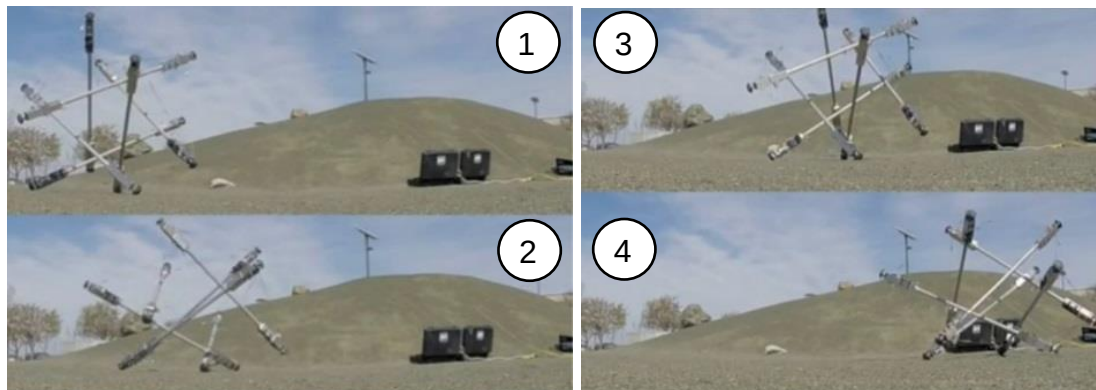
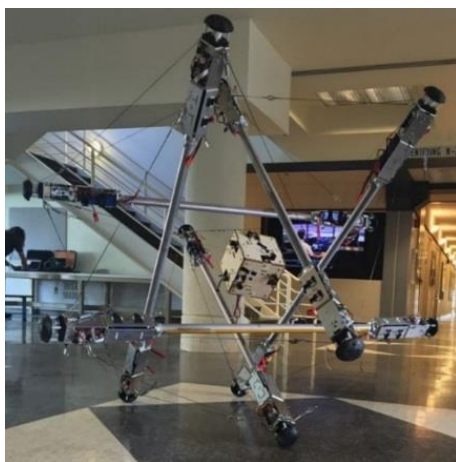
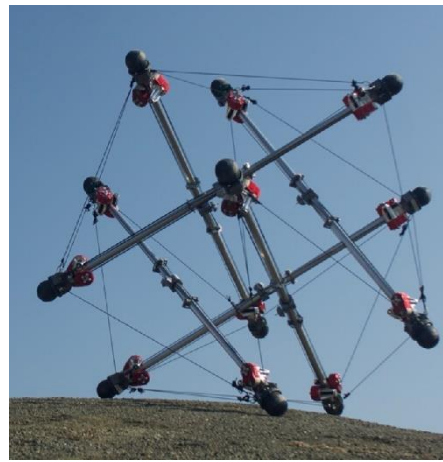


Figure 2.14 Outdoor experiment of SUPERball locomotion [11].

A new concept for tensegrity robot locomotion was also proposed in this research. The idea was to move the payload for adjustment of the robot's centre of gravity. The prototype of the actuated payload was developed by engineering students at the University of Idaho. The payload was installed in the middle of SUPERball using 12 Vactran cables, developed by NAZA, connecting the payload and end caps, as shown in Figure 2.15 (left). The lengths of the Vactran cables were adjusted by brushed DC motors, which were integrated inside the payload structure. The cable length was measured with 12 geared potentiometers attached to 12 brushed DC motors. The experiment was successful in demonstrating the robot's ability to roll a SUPERball by adjusting the payload to change the robot's centre of mass.



(a)

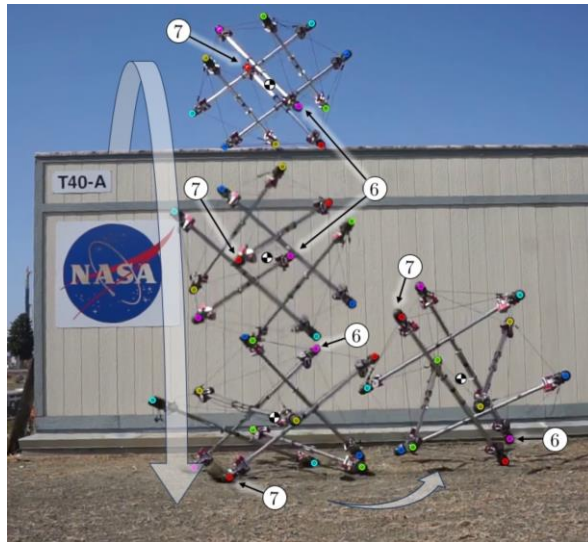


(b)

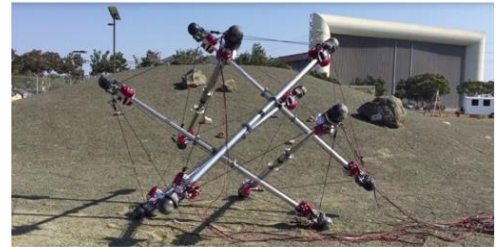
Figure 2.15 A series of the SUPERball: (a) SUPERball 2015 containing the actuated payload [11] and (b) an image of SUPERball v2 [56].

In 2017, SUPERball v2 [56] was presented to continuously enhance the previous SUPERball versions, as illustrated in Figure 2.15 (right). A new design of strut element to absorb large impacts, fold and unfold structure, and make the robot more robust, was described. A MATLAB-based tensegrity simulator was used to simulate the dynamics force during impact scenarios to demonstrate the mechanical design concept. The use of nylon cables instead of metal springs as a source of the soft body, together with the specific materials, cable routing, and actuators provided a lightweight robot able to withstand high-speed landings. The drop test of 3.4 meters from a rooftop with 8m/s falling speed before touching the ground was demonstrated, as shown in Figure 2.16 (a). All mechanical parts and sensors still worked following the experiments. Additionally, the preliminary tests of the unpacking and packing robot were demonstrated successfully to decrease the package for delivery, as illustrated in Figure 2.16 (b) and (c), respectively.

The SUPERball series provided a range of knowledge on the design technique of a tensegrity robot. The novel mechanism of the end cap was beneficial for the development of other forms of tensegrity robots. The passive and actuated cables were separately designed and connected with tension sensors to prevent motor overload and cable damage.



(a)



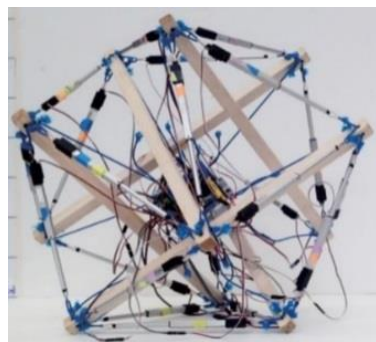
(b)



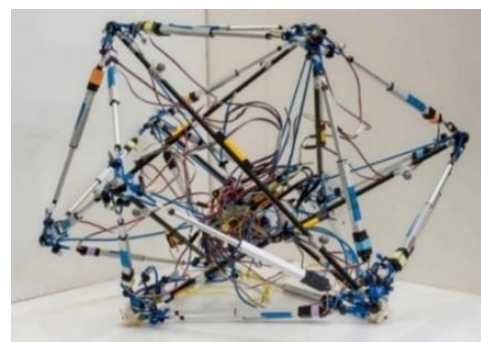
(c)

Figure 2.16 SUPERball demonstrations [56]: (a) the full structure drop test from 3.4 meter rooftop, (b) unpacking structure, and (c) packing structure.

Another research in icosahedron tensegrity robots was on the development of TT-2 and TT-3 tensegrity robots constructed at UC Berkeley, in collaboration with NASA Ames [8]. TT-2 was developed with the concept of building the rapid prototype tensegrity robot for research groups interested in the tensegrity robot. This research also found the possibility of designing the robot-based tensegrity structures, which were useful and appropriate for performing a variety of tasks with human [7]. The rapid prototype of the icosahedron tensegrity robot is presented in Figure 2.17.



(a)



(b)

Figure 2.17 The rapid prototype of an icosahedron tensegrity robot TT-2: (a) version 1 [7] and (b) version 2 [8].

Some of the elements of TT-2 were different from previous icosahedron tensegrity robots, particularly the actuation system. The 24-prismatic actuators were mounted in the middle of each outer cable to deform the robot shape instead of the use of actuators mounted on each strut. The prismatic actuator had a strain of 10, providing force up to 45 N and a maximum speed of 5 mm/s. Spring snaps were mounted between these actuators to connect actuators to the outer cable. The payload of TT-2 consisted of a controller brick, including LEGO Mindstorms EV3, Li-Ion batteries, and a servo controller to control prismatic actuators, which was attached to the middle of the robot by 12 inner cables of 35 cm length.

The researchers defined three different types of locomotion steps of the triangular base, as described in [52, 53]. The actuation policy was designed for the three steps using a greedy search algorithm. The TT-2 locomotion was successfully demonstrated. However, TT-2 had a limitation in its deformation because the retraction of the outer cable length was restricted by the slight strain of the prismatic actuator. Therefore, to achieve TT-2 requirements, a soft spherical tensegrity robot called TT-3 was developed using rod-centred actuation and control.

TT-3 was a spherical tensegrity robot with a lightweight structure, low cost, and fast assembly. The new mechanical design of TT-3 was the actuation module mounted in the middle of each strut. The actuation module consisted of four geared motors, two driver boards, a power module, a microcontroller, and a wireless communication module for sending and receiving a command signal. In this design, no signal wire linked between struts. The actuation modules are shown in Figure 2.18 (a). Figure 2.18 (b) illustrates how the actuated cables are routed by motors connected to an adjacent strut.

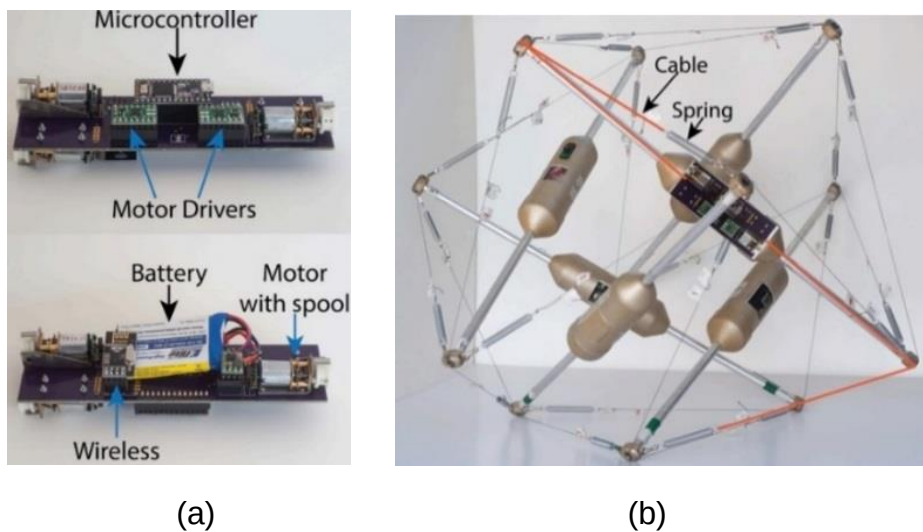


Figure 2.18 TT-3 control module and structure [8]: (a) the components of the control module and (b) the six-bar tensegrity robot and route of the cables connected from the control module.

The locomotion experiments were demonstrated to observe the robot behaviour. The first experiment was to roll its body in a circular pattern on flat ground with a straight line, as shown in Figure 2.19 (a). The second experiment was to roll its body while carrying a payload placed in the middle of the robot. This experiment allowed the researcher to visualise the payload interaction with the robot during locomotion, as shown in Figure 2.19 (b). The third experiment involved rolling the body of the device with a straight line on an unstructured outdoor terrain, as shown in Figure 2.19 (c). The experimental results suggest that the robot could be moved following a straight-line trajectory command. However, the movement behaviour of the robot did not move straight physically. The robot moved with a zigzag motion because the robot could not change its shape to roll straight forward like a wheeled robot.

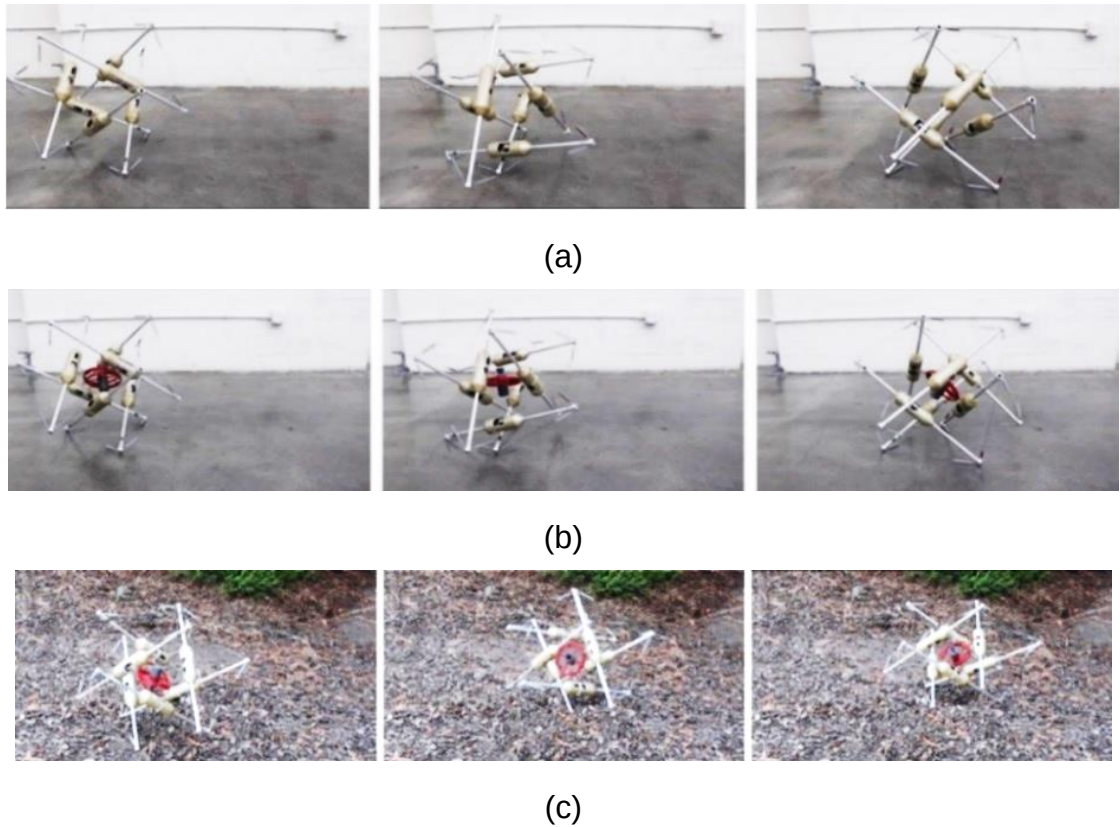


Figure 2.19 The three experiments of TT-3 locomotion [8]: (a) the rolling movement with a straight line on flat ground, (b) the rolling movement by carrying a payload, and (c) the rolling movement with a straight line on an unconstructed outdoor terrain.

2.3.4 Rhombicuboctahedron Tensegrity Structure

In 2017, a 12-strut tensegrity robot called T12-R was presented [57], as illustrated in Figure 2.20 (a). The researcher claimed that this structure allowed for rapid rolling because the robot can roll in a straight path to a target point (see Figure 2.20 (b)) rather than a zig-zag path (see Figure 2.20 (c)) in the same way as six-

strut tensegrity robots. The T12-R could deform the structure for rolling locomotion with cable-driven modules (see Figure 2.20 (d)) to actuate cables attached to each strut end. Two control methods were used to generate motion patterns. The numerical method called dynamic relaxation was used to predict structural deformations of the T12-R when cable tensions were given, and a multi-generation Monte Carlo was used to find a good set of cable tensions that will generate desirable shapes of the T12-R for movement steps. In the software simulation, 100 samples of the Monte Carlo were obtained per generation, and a total of 10 generations were performed in order to find the most-deformed shapes of the T12-R. The results showed that the T12-R could deform the structure and rolling to target points effectively. However, the physical demonstration of the T12-R locomotion was undertaken.

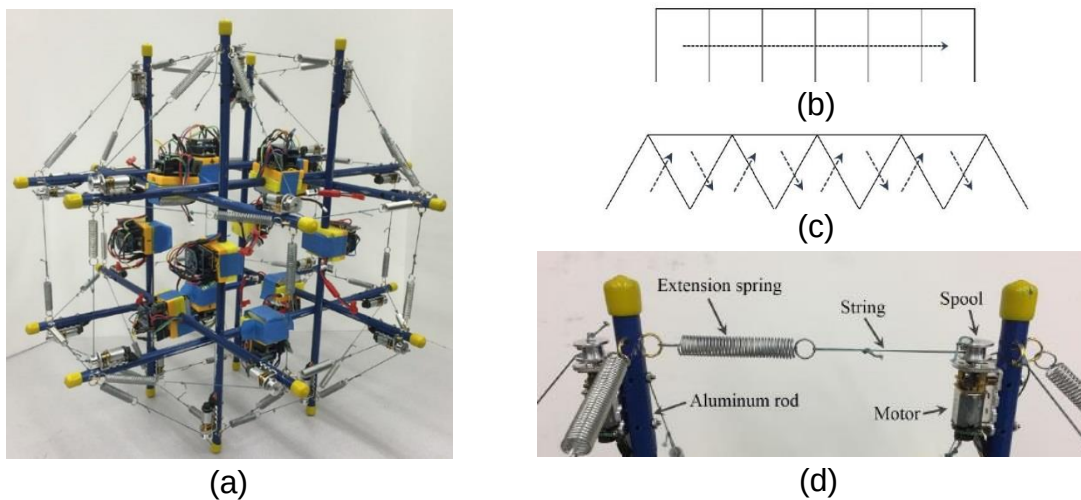


Figure 2.20 The T12-R tensegrity robot [57]: (a) T12-R prototype, (b) straight movement, (c) zig-zag movement, and (d) cable driven components.

2.3.5 Tetrahedron and Bio-Inspired Tensegrity Structure

The tensegrity structure can be explained at various scales of life, such as the cellular cytoskeleton [20, 58], the protein structure [59], and the tendon network of the human joint [60]. All scales comprise complex mechanisms and dynamics, which are avoided in engineering design. However, these linkages may be advantageous in some cases. Therefore, [39] proposed how a complex mechanical system is able to employ mechanical and dynamical connections as an advantage. The researcher designed a complex tensegrity structure, which was comprised of 15 struts and 78 cables (see Figure 2.21) and described the possible designs of 20, 30 and 50 struts. Each strut had an individual control module that could communicate with others to provide the ability to adjust the complex shape of tensegrity structures, leading to the development of novel

morphological communication to allow for the decentralised control of large, coupled, and modular systems.



Figure 2.21 The 15-strut tensegrity structure model included high degrees of dynamic linkages[38, 39].

To enhance robot mobility, an Assur tensegrity structure inspired by a biological caterpillar was introduced in Orki [45], Orki, et al. [46]. The researcher explained that the biology of caterpillar was complex, including approximately 70 discrete muscles. The main muscles of each segment contained the Ventral Longitudinal muscle (VL) and Dorsal Longitudinal muscle (DL), as shown in Figure 2.22. Each VL1 muscle was controlled individually and could extend in the same way as DL1 muscle. The VL1 muscle was connected to the sternal antecosta, and the DL1 muscle was connected to the Tergal antecosta. This research explained how the caterpillar uses its muscles to crawl on dorsal and ventral surfaces.

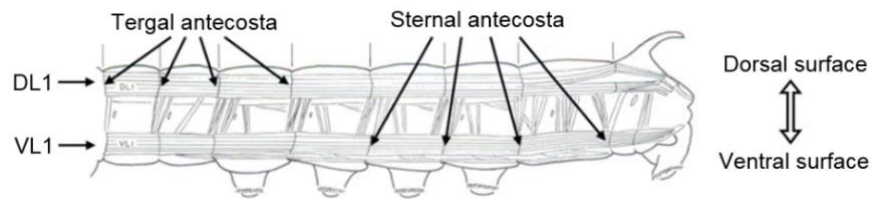


Figure 2.22 Caterpillar body and muscles [46].

A model of the caterpillar represented by a planar tensegrity structure was also introduced. The model comprised of three main elements, including two tensile elements (cables), a strut, and two bars, as illustrated in Figure 2.23.

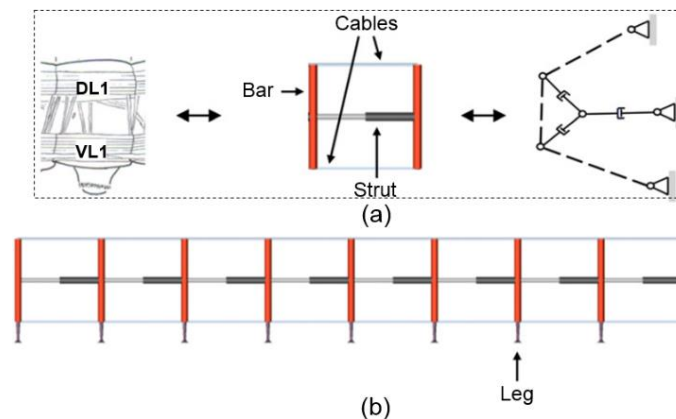


Figure 2.23 The model of Caterpillar mechanism [46]: (a) to compare the caterpillar biology segment, the caterpillar 2D model and the Assur tensegrity triad and (b) the proposed model for the Caterpillar mechanism.

For movement control, two levels of controllers were designed, comprising of low- and high-level control. Low-level control was designed based on caterpillar characteristics and consisted of individual controllers based on impedance control [61] for each strut, cable, and leg component. The strut, cable, and leg controllers were used to control the pressure of its structure, the elastic muscle behaviour, and leg behaviour, respectively. High-level control was employed to control the nervous system. The primary purpose of the high-level control was to control timing motions and drive the cable and leg elements. This high-level control also consisted of two sub-levels. The first sub-level was the central control component to generate the caterpillar's central pattern generator (CPG) signals for robot motions, and the second sub-level was a localised control used for producing control signals for each robot segment. This level also connected the control signals to the low-level control of leg, cable, and strut controllers. Impedance control was employed for low-level control. The control structure of the proposed controllers is presented in Figure 2.24.

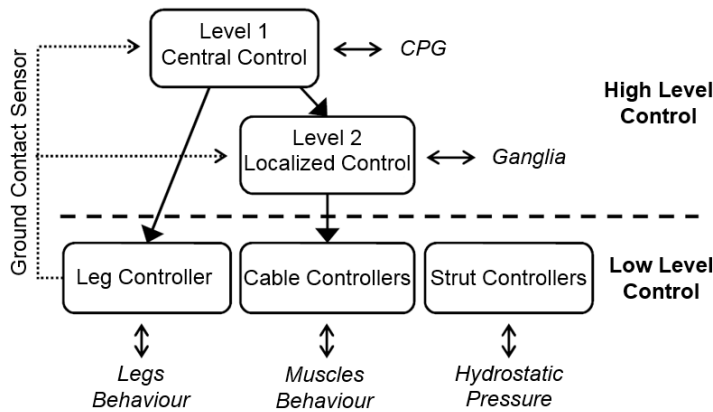


Figure 2.24 The diagram of high and low-level control [46].

The simulation result of the caterpillar model locomotion on different terrains is presented in Figure 2.25. The control algorithm in this research could be used to control the model climbing on a high slope terrain due to its legs gripping the ground surface. Furthermore, the model could also crawl both vertical and horizontal terrains without adjusting control strategies. Impedance control of the caterpillar model provided adequate control of the robot locomotion [39].

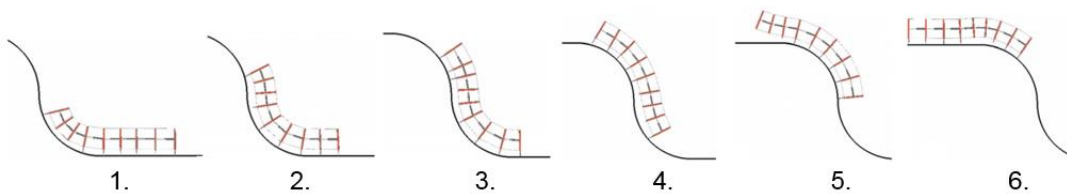


Figure 2.25 The model locomotion with high slope terrain [46].

In 2013, Tietz, et al. [41] introduced a tensegrity robot motivated by spine named Tetraspine. The purpose of this project was to create a new method of robotic locomotion and learn how vertebrates move by changing their compliant spines. Figure 2.26 (a) presents a comparison of the spine tensegrity model created by Flemons [62] and Figure 2.26 (b) Tetraspine tensegrity model.

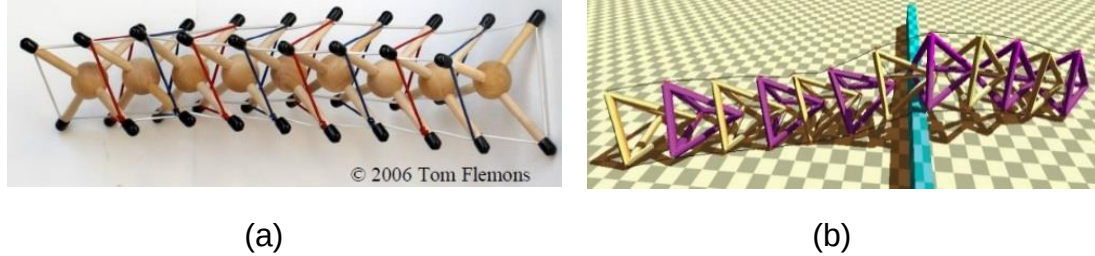


Figure 2.26 The spine tensegrity model [41]: (a) the spine tensegrity model and (b) Tetraspine tensegrity model.

The researcher modified the original Flemons model of spine tensegrity structure to tetrahedral structure because it was more accurate for ground contact surface and the integration of actuators, controllers, and sensors. Tetraspine was a class three tensegrity structure comprised of rigid tetrahedron-shaped modules. Each module connected to another with six cables, three on the outside and three on the inside. The outside cables connected the tips of each module's base triangle to the one in front of and behind it, and the inside cables connected from the tip of a module to the base tips of the one in front of it.

The Tetraspine control method consisted of two controller levels. The first level was local control. The impedance control was employed on this level due to the locomotion control performance of complex robot structures [45, 46]. The impedance control was used to control the actuated cable lengths of each tetrahedral module. The second level was CPGs, using the phase coupled oscillator method [63]. The CPG was utilised to produce a movement pattern for Tetraspine. The output signals of CPG were sent to the input signals for each local control to generate movement patterns for Tetraspine's locomotion. The control method was demonstrated using a Bullet environment. The results demonstrated that the robot could move on rough surface areas and flat terrain with 7.5-degree ramp and bumpy terrain, as illustrated in Figure 2.27(a), (b), and (c), respectively.

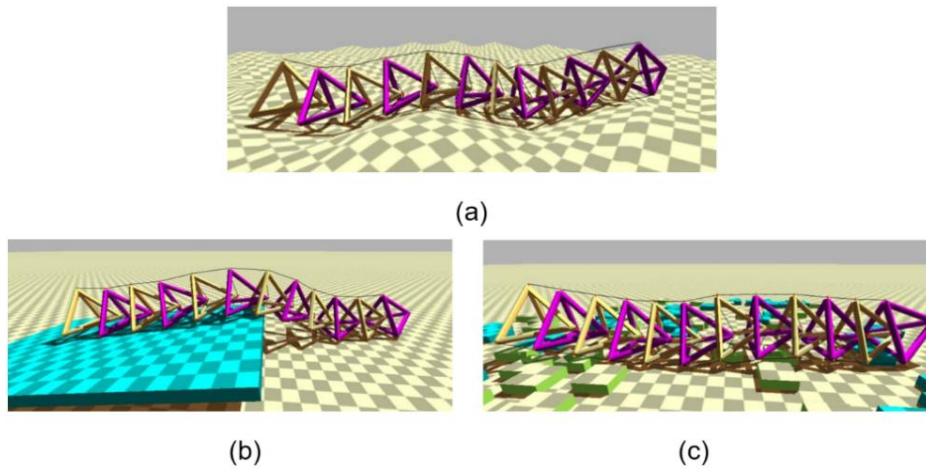


Figure 2.27 The simulation results of Tetraspine's locomotion [41]: (a) multiple-high hills, (b) 7.5-degree ramp, and (c) different high blocks.

A prototype of a six-module Tetraspine was also developed to verify simulation results, but only two modules were constructed, as illustrated in Figure 2.28 (a). Each module of the prototype was comprised of carbon fibre struts. The length of each strut was 28 cm. The modules were linked with cables that were rolled and unrolled by DC-gear motor together with rotary encoders. All components were attached to the carbon fibre frames. Arduino microcontrollers were employed for the control module of the robot. Knit stretch sensors were used to measure the cable tension and were attached to the middle of each cable.

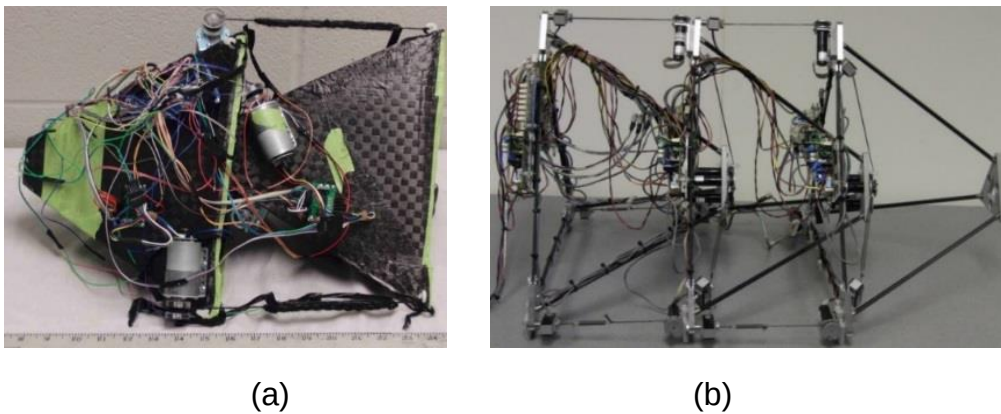


Figure 2.28 The series of Tetraspine prototypes [11]: (a) the two modules of Tetraspine developed by Tietz, et al. [41], and (b) the Tetraspine3 prototype developed by Mirletz, et al. [12].

The research explored the CPG-driven compliant control system that could be used to control the complex mechanisms of the tensegrity robot locomotion. Additionally, the researchers developed and tested a tensegrity software simulator implemented in a real-time opensource Bullet physics engine [64] to test the control algorithms, leading to the discovery of a new control strategy for more compliant robots that can move in extreme terrains.

In order to enhance the potential of a software simulator for other forms of tensegrity robots, the development of a compliant spine-like tensegrity robot named Tetraspine3 was introduced [12]. The aim of this study was to evaluate the performance and accuracy of the NASA Tensegrity Robotics Toolkit (NTRT) software simulator. Tetraspine3 had been improved from the previous version Tetraspine, which encountered problems in tension sensors that were too difficult to calibrate. Tetraspine2, on the other hand, only performed position control, leading to movement limitations. The Tetraspine3 is the completed version that meets the actuation requirement of corresponding with software simulators.

The Tetraspine3 mechanisms consisted of 12 DC motors, 12 inelastic cables, and 12 tension sensors (load cell). The strut length of Tetraspine3 was approximately 38 cm with a 0.64 cm diameter, as shown in Figure 2.28 (b). One end side of the cable was connected to a DC motor used for spooling an actuated cable. The other end side of the cable was mounted to a tension and compression sensor to measure the cable's tension. Eight 227 N/m springs were connected between cable and load cell to make the robot more compliant. Other top-four cables did not attach springs because they were employed to support the weight of each module.

Carbon fibre was used to construct all inner and outer struts to reduce the weight of each module. The three motors were placed at the front tip of the tetrahedron to control the length of the inner cables. 3D printing materials were created to mount three motors as a result of robot weight optimisation.

Tetraspine3 was suitable for comparing forces produced by the real robot and the simulation model. The researchers focused on forces because it was the output signal of the impedance controllers that provided a suitable test of the control system, which was a crucial factor in designing a new structure and actuator selection. Furthermore, the researcher expected that the forces generated by the simulator were similar to the physical forces, leading to the use of their software simulator to design other tensegrity robots in the future.

In the experiment, the researcher found that the forces generated by NTRT were within expected errors for robotics design. The accuracy of the simulator led to the development of a complex robot structure actuated by multi-actuators. This research also demonstrated that the distributed impedance control could effectively control tensegrity robot legs for locomotion.

In 2016, the design of a novel mechanism and simulation of the Underactuated Lightweight Tensegrity Robotic Assistive Spine (ULTRA Spine) based on cable-driven locomotion was presented by Sabelhaus, et al. [65]. ULTRA Spine was designed considering the specification of performance, which was different from

Tetraspine. ULTRA Spine's mechanisms, actuators, and structure materials were designed for specific movements. Moreover, ULTRA Spine introduced innovative designs for parallel under actuation in a cable-driven system. The design of the ULTRA Spine prototype is presented in Figure 2.29.

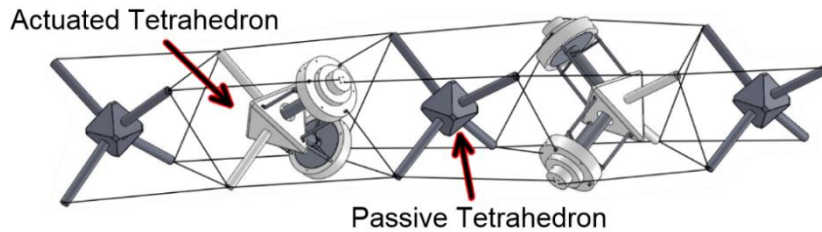


Figure 2.29 The design of ULTRA Spine with cable linkages [65].

ULTRA Spine consisted of two main elements, namely actuated tetrahedron and passive tetrahedron. The core of the spine link tetrahedron was mounted with both passive and active elements, including an actuator and internal spring mechanism. These mechanisms could easily integrate with four rods of a single tetrahedron, as well as a multi-output spindle dimension mounted on the motor shaft. The spindle was used to adjust motor force, which was similar to a gearbox. A locking mechanism was designed to attach the passive elements to the link core. For the passive spring-cable mechanism, both red and blue springs were separately connected to swaged nuts. The springs inside the tubes were constrained to perform linear movement and prevent permanent distortion of their shape. 3 mm Vactran cables were employed to connect the individual tetrahedron and drive the robot because of the high elasticity, durability, and high strength-to-weight property.

Although the physical prototype of the ULTRA Spine had not been constructed, the concept of underactuated motion in the tensegrity robot was beneficial in extending the new mechanism designs of tensegrity robots for locomotion.

Based on the many advantages of the tensegrity structures, some research teams have attempted to develop a tensegrity robot for real-world applications. Friesen, et al. [15] introduced a new form of tensegrity robot for duct system exploration called DuCTT. Existing robots used wheels that pushed against duct walls during locomotion. Although these wheels ensured fast movement, it was difficult to overcome small-angle corners or rough surfaces. Other robots could overcome these challenges by integrating limb mechanisms, though these leg mechanisms usually required high power, leading to the use of heavy actuators to be able to climb vertically in duct or pipe systems [66, 67]. To address this issue, the design and development of DuCTT were proposed, as shown in Figure 2.30 (a). The inspiration for developing the DuCTT structure is the vertebrate spine model of Flemons [62]. The advantage of this structure is that it is able to

unblock liquid or gas flow during performing inside a pipe due to the slim shape of the robot, as shown in Figure 2.30 (b).

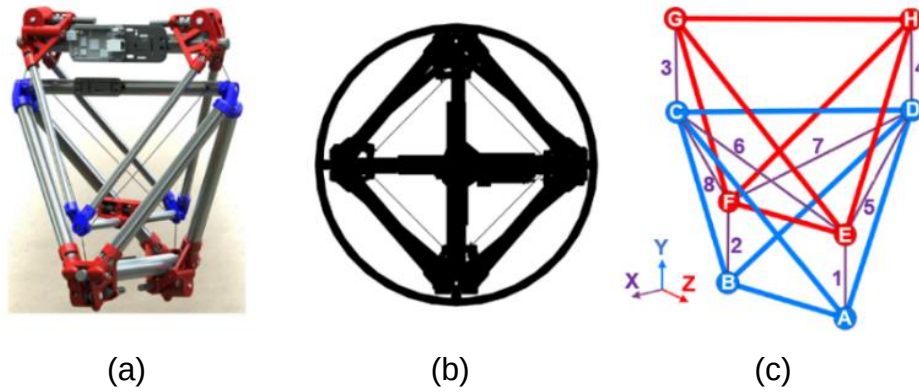


Figure 2.30 The prototype of DuCTT [15]: (a) DuCTT structure, (b) top view of DuCTT inside a duct, and (c) diagram of nodes and cables.

DuCTT consisted of two tetrahedral modules with six rigid elements connected by hinge joints. One prismatic actuator was mounted between node-A and -B, and another between node-H and -G, as presented in Figure 2.30 (c). The prismatic actuators could extend lengths from 31.5cm to 41.5cm, which would cause the angle of the tetrahedron opposite to the prismatic actuator to increase. A red tetrahedron could lift a blue tetrahedron by spooling cables 1 to 4, and a blue tetrahedron could lift the red tetrahedron by spooling cables 5 to 8. Therefore, the DuCTT prototype may be controlled to move in four-degree-of-freedom.

Before implementation, NTRT was used to simulate the control algorithm for climbing motion. All of the actuators were controlled by defining rest lengths specified by the inverse kinematics control policy (IKCP) to the controller. The experimental results are shown in Figure 2.31.

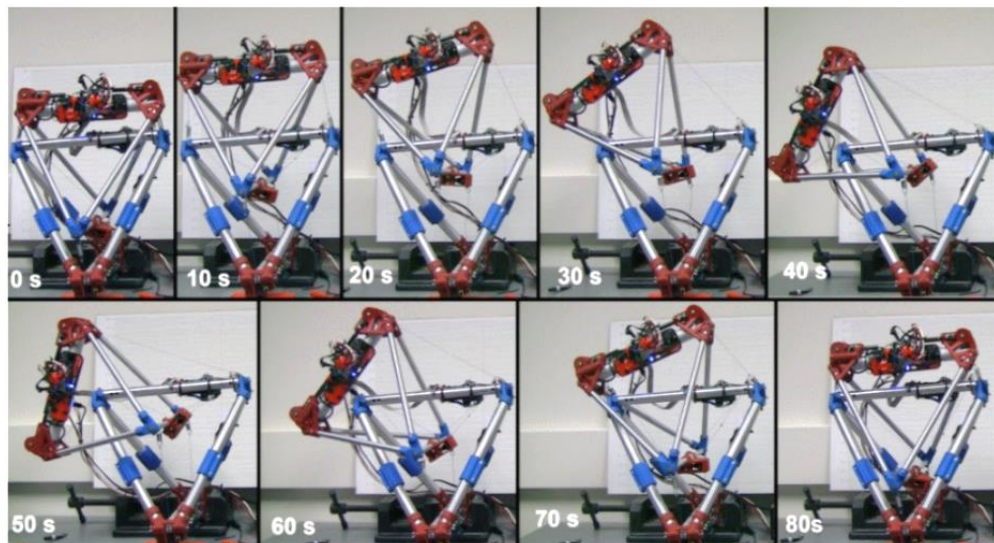


Figure 2.31 The preliminary test of DuCTT [15].

The preliminary experiment showed that the DuCTT could move inside duct systems and that the IKCP could control the robot. However, mechanical and electrical failures were encountered during demonstrations, resulting in system inconsistency. Therefore, DuCTTv2 [14] was developed to deal with the problems.

DuCTTv2 was a wholly re-engineered tensegrity pipe-exploration robot that implemented robust solutions that small cable-driven robots were unable to. The design of the robot was the same fundamental topography of the DuCTT prototype, but the development of a control method and mechanisms were improved, and the robot had a lightweight system with an eased mechanical design, leading to higher reliability and more effective navigation in unexpected environments.

DuCTTv2 consisted of two tetrahedral modules connected via eight actuated cables, remaining unchanged, as shown in Figure 2.32 (a). Eight cables were individually actuated, providing six degrees of freedom motion. A prismatic actuator was mounted to each tetrahedral module, which was used to produce frictions against a pipe wall to maintain robot positions and locomotion. The prismatic actuators could change length between 35 and 45 cm, which was the possible range for navigated pipe diameters. The overall size of the robot when fully contracted was approximately 40 cm.

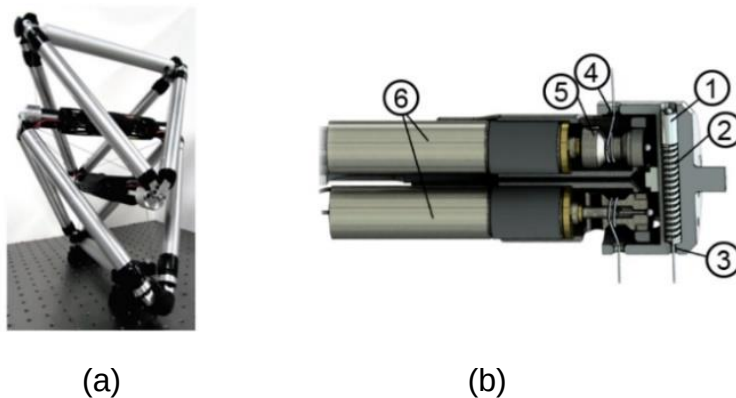


Figure 2.32 DuCTTv2 prototype [14]: (a) DuCTTv2 prototype and (b) close-up actuated cable module.

The total weight of the robot, including eight brushless DC motors, was 3.75 kg. A 17:1 gear ratio was used across four actuators to spool four vertical cables, reaching a maximum tension of 112 N, whereas a 67:1 gear ratio was used in the saddle cables to enable a maximum tension of 443 N. Each tetrahedron contains eight batteries, which provided a 14.8 volt 6 amp-hour, meaning that DuCTTv2 could continuously perform for approximately six hours per full charge.

Linear compression springs were used to deform the robot's shape. The value of spring stiffness was 4.5 kN/m, which could fully compress without distortion.

Figure 2.32 (b) presents the cross-section of the centre bar endcap. Four endcaps of two bars contained two Maxon DC motors (6) connected to the pulley (5) for spooling cables through the routing hole (4). A cylindrical metal piston (1) was used to hold high-modulus polyethylene cables, which ran down the middle of the compression spring (2) and out the shaft (3) to be wired into the other tetrahedron's endcap. These simplified, efficient mechanisms enhanced the robot's cable routing performance. Planetary gearboxes were used to reduce mechanical frictions.

Two main experiments were conducted to evaluate the robot's performance. The first experiment involved replicating a previous test of DuCTT. The base of the tetrahedron was first fixed on a table, and open-loop control signals for vertical movement and rotation were commanded. The positions of the robot were measured with 2D motion tracking. The experimental video was presented in [68]. DuCTTv2 could significantly improve the speed of the motion; it took nine seconds to complete a target point, whereas the previous prototype (DuCTT) took 80 seconds.

The second experiment involved using climbing ability to move the robot inside a straight vertical pipe, with a diameter of 36 cm and a height of 76 cm. In this experiment, locomotion speed was not optimised. The results suggest that the robot could climb with an average speed of 1.4 cm/s. This speed could be improved using the high speed of the prismatic actuators related to the climbing speed of the robot. The climbing test video is shown in [69]. Further research in the field may involve constructing a pipe test structure to test the robot's capability to move in the right angles and T-junctions of the pipe system. Additionally, the accurate evaluation of the DuCTTv2 simulation model and the real hardware is demonstrated to ensure that the simulation model is sufficient. This approach will be useful for control strategy design, both through machine learning and analytic methods.

The development of DuCTT and DuCTTv2 are useful research tools in determining that tensegrity structure could be potentially used in the field of inspection robotics, making it close to achieving real-world applications.

2.3.6 Other Forms of Tensegrity Robots

Other fascinating forms and mechatronics designs of tensegrity robots have been found. The development of a spherical mobile robot based on a tensegrity structure was introduced by Bohm, et al. [10]. In this research, the robot's structure was different from many existing tensegrity robots; it consisted of two curved compressed members that connected to one another via springs and

metal cables, as shown in Figure 2.33 (a). Each curved compressed member consisted of one curved strut and one drive unit compliantly constructed with twelve passive-spring cables.

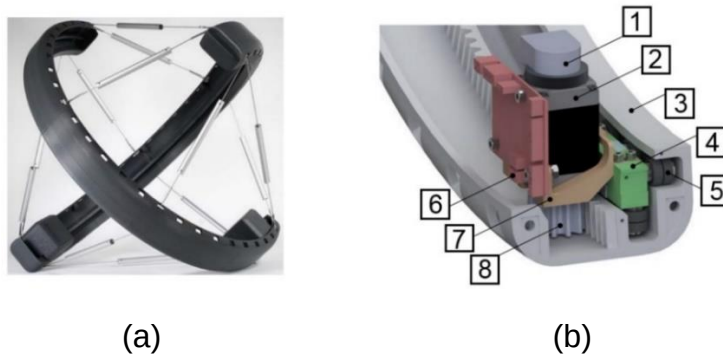


Figure 2.33 Spherical mobile robot prototype [10]: (a) robot structure and (b) CAD model of curved strut essential parts including (1) encoder, (2) stepper motor, (3) curved strut, (4) slide component, (5) follower, (6) motor controller, (7) motor mount and (8) geared moving system.

The curved strut had an outer diameter of 70 cm and an arc angle of 200 degrees. Each curved strut contained a guide for a drive unit, including a geared moving system, a motor, electronics, and a battery. The 3D model of the curved strut and other components are shown in Figure 2.33 (b). The twelve spring cables of the 1st-curved strut and second-curved strut allowed a pre-stress-level and length adjustments. The connections of the spring cables between curved struts were duplicated for a more effective distribution of the load. The spring cables could adjust their length up to 20 mm, and an adjustment of the pre-stress level between 6N and 22N was possible. All of the spring cables could be quickly assembled and disassembled.

This robot's locomotion adjusted the centre of mass by moving the drive unit along the curved struts with a position control mode. The positions of the drive unit were measured with a rotary encoder attached to a stepper motor. In the experiment, the robot was able to roll its structure on the flat ground with a speed of 0.5 m/s; it could continuously perform for several hours using two 850 mAh batteries and also carried a payload with the compliant passive structure.

Another research relating to tensegrity structures was a concept for parallel kinematic mechanisms (PKMs), which were actuated by fluid actuation [70]. The researcher stated that the PKMs are widely used for high-performance multi-axis motion systems due to their high stiffness and low mass. The authors discussed PKMs constructed with multiple bodies, including pre-stressed actuator networks, which could be alternatively employed to morph aircraft wings due to the lightweight structure. The PKMs were suitable for applications that required an efficient dynamic response. Hydraulic actuators were effectively used for these

applications because of the high power-to-weight ratio. Most PKM configurations were built with rigid bodies respected to the ground. The form-finding of equilibrium node positions of an example tensegrity structure and the calculation of the stiffness matrix of each node were derived. Additionally, an example tensegrity structure was also introduced and described how the proposed structure could change its shape by retracting and extending cable length. The proposed tensegrity structure model comprised of 13 struts, 20 cables, and 12 nodes linked as a network is present in Figure 2.34. The small red circles surrounding each node are the pin joints.

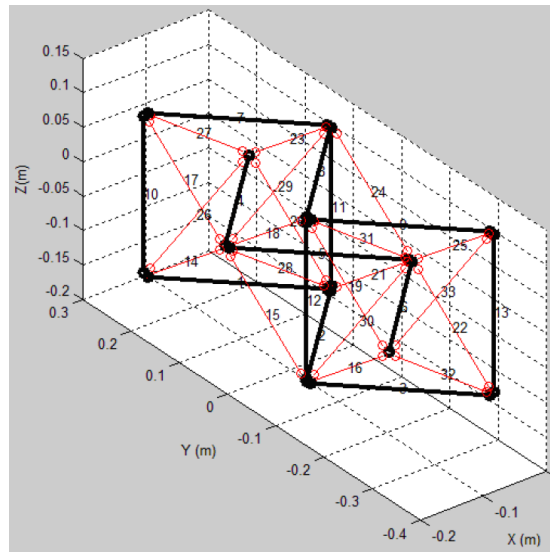


Figure 2.34 Isometric view of the tensegrity structure [70].

To clarify the shape deformation concept, three demonstrations were presented. Considering the isometric view, firstly, a bend motion in the X-Y plane occurred when central cables 15 and 18 were retracted by 15% and cables 21 and 24 were extended by 20% (see Figure 2.35 (a)). Secondly, a shear motion in the Y-Z plane occurred when cables 15 and 24 were retracted and cables 18 and 21 were extended (see Figure 2.35 (b)). Finally, a twist motion in Z-X plane occurred when cables 18 and 24 were retracted (or extended) whereas cable 15 and 21 were extended or retracted, as shown in Figure 2.35 (c).

From the simulation results, it appears that tensegrity structures could be designed with actuated cables and practical nodes of finite dimension to provide shape deformation. However, a new concept was proposed and tested in the simulation. Lai, et al. [71] introduced a new concept of the PKMs based on the tensegrity mechanism actuated by pneumatic artificial muscles (PAMs). The paper described the use of an interactive approach to calculate the form-finding for an actuated three-unit-cell tensegrity structure. The form-finding method and the structure were similar to the tensegrity structure of Plummer and Lai [70], but

the improvement in this research involved establishing a unit test process to demonstrate the concept.

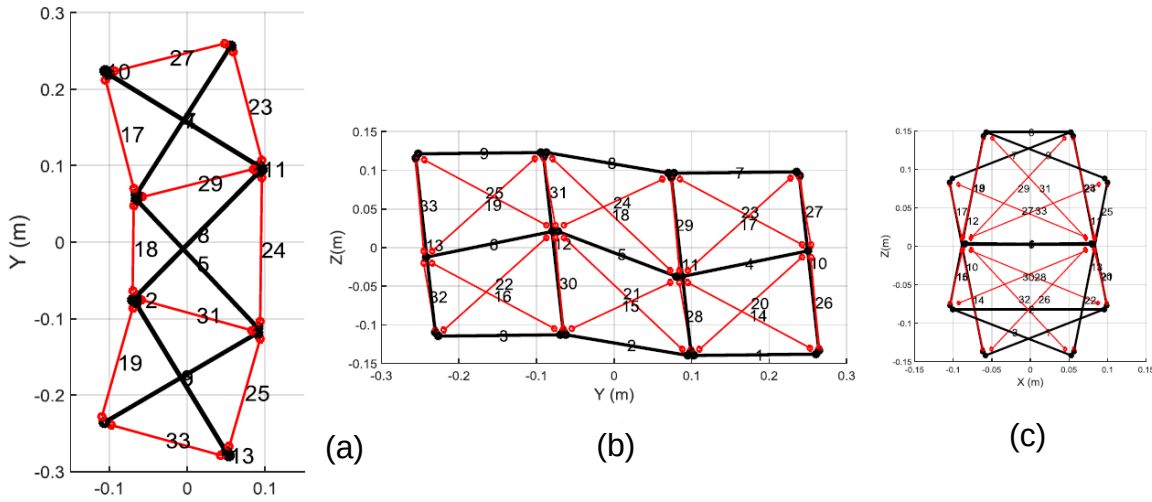


Figure 2.35 Example of a tensegrity structure [70, 71]: (a) bending displacements (retracting 15 and 18, extending 21 and 24), (b) shear displacements (retracting 15 and 24, extending 18 and 21), and (c) twist motion

Figure 2.36 presents the experimental setup. The proposed tensegrity structure consisted of four PAMs (290N) mounted between each strut to deform the structure. Each PAM was controlled by two solenoid valves. One solenoid valve was linked to a pressure source of six bars, whereas the other solenoid valve was connected to the atmosphere. The compressed air was applied to PAMs when both valves were switched off. To measure muscle pressure, a 0-10 bar pressure transducer was utilised. A rotary encoder with a roll-wire mechanism was used to measure the displacement of the rest cable. The measured data from both sensor devices were sent to a host PC using a microcontroller board, which was coordinated with the Simulink model in a real-time system.

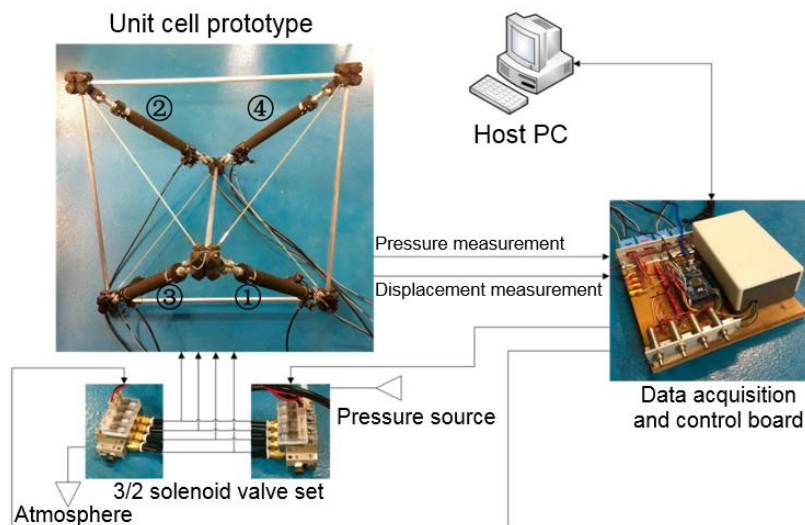


Figure 2.36 Experimental setup for the tensegrity structure [71].

The researcher presented a method to calculate the mathematical model and control strategy of the system. A bang-bang, or on-off, controller with position and force control were employed to control the tensegrity structure. To evaluate the control strategies and the accuracy of the mathematical model, a control system simulation was demonstrated using SimMechanics software simulator. Eventually, the physical experiments, which involved the same steps as the simulation, were implemented.

The implementation found that the bang-bang controller could control the position of the tensegrity structure during pre-load need, though different results occurred when compared to the simulation results because the simulation model did not include the friction of each joint, which is significant for the structure movement. In future research, a full non-linear model could be used with the addition of another two-unit cell to the current prototype to accomplish bending, shear, and twisting motion of the structure. This method will ensure that the tensegrity structures are a practical concept of lightweight, high stiffness-to-weight ratio with an actively controllable shape.

2.4 Tensegrity Robot Locomotion

Based on the review of existing tensegrity robots, it appears that locomotion of tensegrity robots can be divided into four types: rolling; crawling; climbing; and jumping, depending on structural geometry and actuation methods.

2.4.1 Rolling locomotion

The rolling locomotion concept involves changing the centre of mass (COM) of the robot to make a robot unbalanced. This disequilibrium can be achieved by changing cable lengths to create different cable tensions that connect to each strut end. Different cable tensions can move strut elements to deform the robot shape, resulting in a rolling motion.

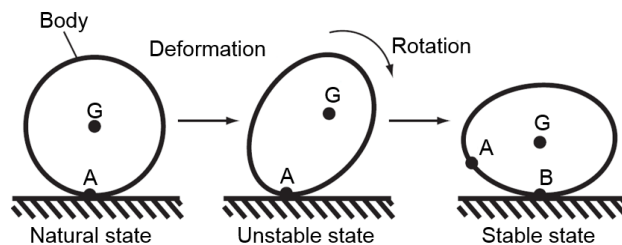


Figure 2.37 Basic locomotion by body deformation [50].

For simplicity, the robot body is built as a single material (see Figure 2.37). In its natural state, point A is a contact point between a robot and the ground, and point G is the COG of the robot with the minimum-gravitational potential energy. If the

gravitational potential energy is changed due to robot body deformation, it produces a moment of gravitational force around the contact area to push the robot to change point G, making it unstable (see Figure 2.37 (Unstable state)). Following this process, the robot rotates clockwise and moves on the right-hand side. Then, the gravitational potential energy reduces to a minimum value at the new contact area B, where point G is in the middle of the robot. In this stage, the robot is stable.

There are two methods to deform robot structure to change the COG of the robot for rolling locomotion. Firstly, the use of rotary actuators to roll and unroll cables connect between strut ends generate high-tension forces to push and pull strut elements, resulting in the change of COG of the robot to produce rolling locomotion [7, 8, 48, 51-53, 56, 57].

Figure 2.38 shows the example of one step rolling motion of a six-bar tensegrity robot named SUPERball [11] developed by NASA. For the initial stage, the robot was a balanced structure, where three endcaps of the red triangle always touched the ground, indicated by green circles. One of the endcaps was also a part of the blue triangle that was the target triangle surface. Following this process, the yellow-highlighted cable on the red triangle was retracted to move the strut position until the robot became unbalanced and started to flip the structure, as shown in the halfway stage (middle image), where only two endcaps touched the ground. Finally, the robot rolled to the large triangle surface, where the three endcaps touched the ground to make the robot stable.

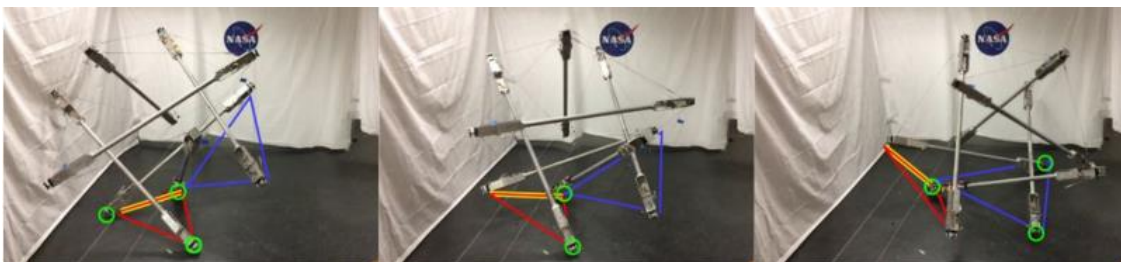


Figure 2.38 SUPERball performing a single roll or face-change movement [11]: (left) initial stage, (middle) halfway stage and (right) final stage.

The control algorithms to adjust each actuated cable were different depending on the current triangle and target triangle base, as described by Kim et. al. [7]. For instance, if the current triangle base has a small area, where the robot is easy to unbalance, called open base triangle, the rolling stage may be achieved by actuating only one cable (see red-dotted line in Figure 2.39 (a) and (b)), rolling to the adjacent closed-triangle base sides, where the triangle base has large areas that make the robot more stable. If the current triangle base is at the closed base triangle, the rolling stage can be achieved by retracting three actuated cables to

roll to the adjacent open-triangle base sides, as shown in the red-dotted line in Figure 2.40 (a) and (b).

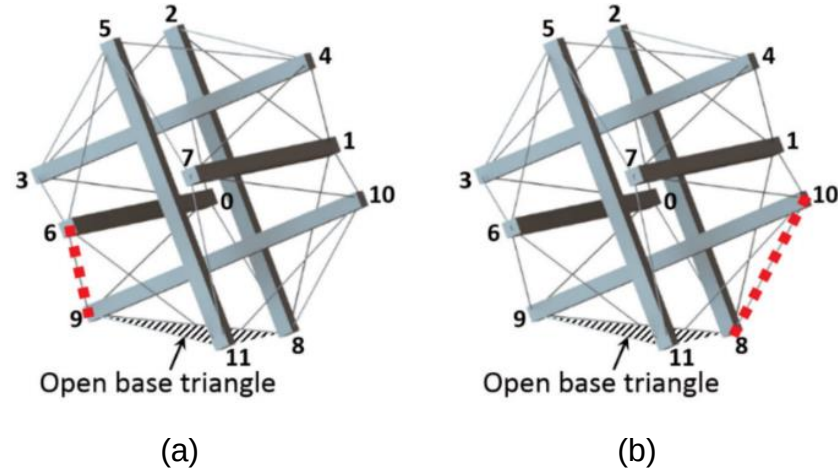


Figure 2.39 Open to closed (OC) step policies for rolling the robot [7]: (a) OC-Policy1 and (b) OC-Policy2. The Hashed triangles and thick dotted lines represent open base triangles and actuated cables, respectively. The endcap numbers or nodes of each strut are also shown in Table 2.1.

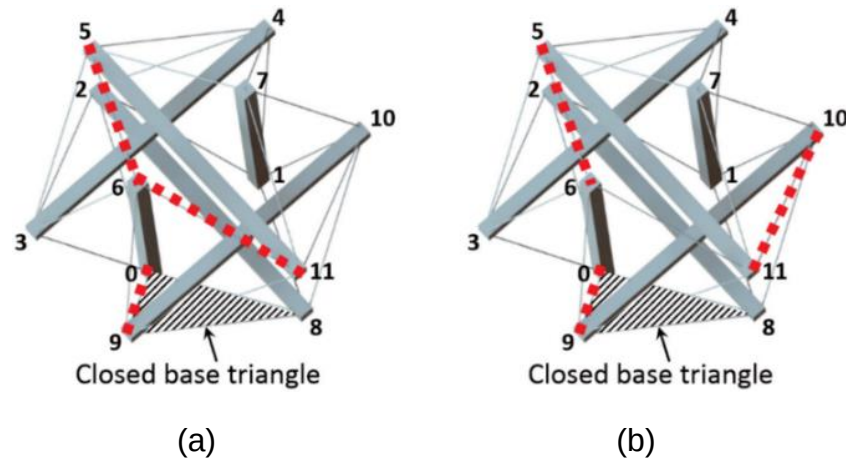


Figure 2.40 Closed to open (CO) step policies to roll the robot [7]: (a) CO-Policy1 and (b) CO-Policy2. The hashed triangles and thick dotted lines represent closed base triangles and actuated cables, respectively. The endcap numbers or nodes of each strut are presented in Table 2.1.

Table 2.1 Actuated cables policies for rolling motion (see Figure 2.39 and Figure 2.40) [7].

Type of step	Starting triangle	Landing triangle	Actuation policy
CO-step	(0,8,9)	(6,9,11)	(0,9), (5,6), (6,11)
CO-step	(0,8,9)	(6,9,11)	(0,9), (5,6), (10,11)
OC-step	(8,9,11)	(0,8,9)	(6,9)
OC-step	(8,9,11)	(0,8,9)	(8,10)
OO-step	(8,9,11)	(8,10,11)	(8,9), (9,11), (7,10), (1,10), (6,11), (0,8), (1,8), (0,3)

3-tuple: triangle formed by nodes

2-tuple: actuated cable between two nodes

Therefore, the numbers of actuated cables vary depending on the current triangle base areas. The COM of the robot change easily if the triangle base area is small (open base triangle). Therefore, the robot can roll by actuating only one cable. In contrast, the COM of the robot can change if the triangle base area is large (closed base triangle), requiring three-actuated cables to cause rolling locomotion.

Second, rolling locomotion can also be achieved by adjusting strut lengths to exert different cable tensions [9, 50, 72]. With this method, elastic cables are used to connect all strut ends, allowing the tensile elements to form a robot structure. However, the robot configuration concept is similar to the actuated cable method by defining the robot's COM targets and finding the open and closed base triangles to adjust each strut length for the rolling locomotion [72].

2.4.2 Crawling locomotion

The concept of crawling locomotion involves adjusting cable length to produce different cable forces capable of moving strut ends to change the COM of the robot. The change of the COM may cause different frictions at ground contact points to generate crawling locomotion [12, 13, 41, 65].

For example, the three-prism tensegrity robot called TR-3 [33] can produce a motion pattern of its legs for crawling locomotion by actuating three horizontal cables connected between strut ends to generate cable forces to change robot configurations. This motion pattern could be applied as a repeated loop through a sequence of binary states $[S_1, S_2, S_3]$, where S_i was a binary value (0 and 1) corresponding to the state of actuator i . Logic 0 represented the actuator being relaxed, and logic 1 represented the actuator being activated (contracted). The loop pattern of the robot legs were defined as $[1,1,1]$, $[0,1,1]$, $[1,1,1]$, $[1,0,0]$, $[1,0,1]$ to produce cable forces and robot configurations, as presented in Figure 2.41.

At the bottom of Figure 2.41, TR-3 is able to move using the alternation of the robot configurations between A and C, where top cable C_9 can be contracted. This alternation leads to forward motion, as presented in the video frames of a software simulation in Figure 2.42.

During the robot configurations that involve changing leg positions, the COM of the robot is changed, as presented in Figure 2.43. The robot motion trajectory has not a straight path; however, the speed is high, achieving a rate of 0.45 m/s.

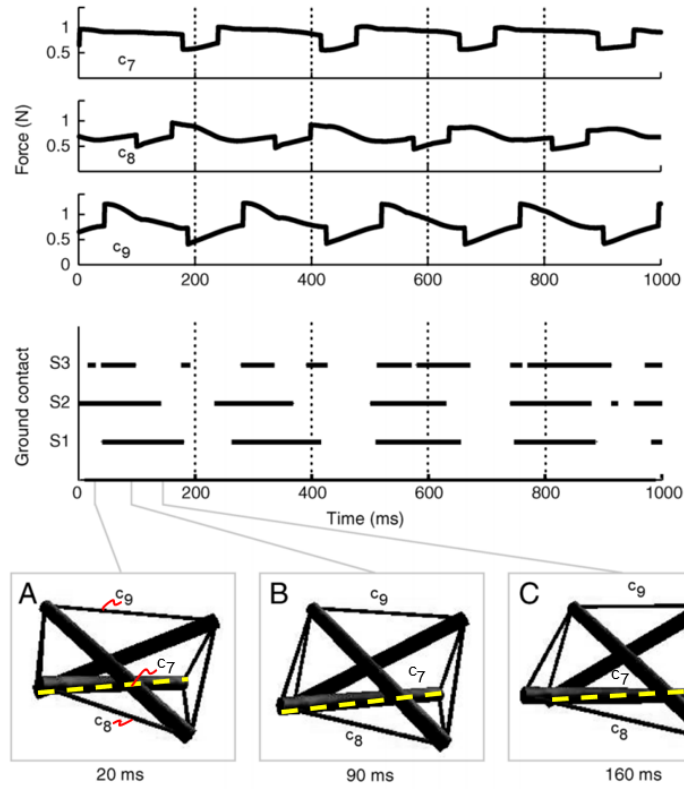


Figure 2.41 TR-3 crawling simulation [33]: (Top) cable forces of the three actuated cables (c_7 , c_8 and c_9), (Middle) ground contact information plotted for strut S_1 , S_2 and S_3 ; dark lines are the contact point between strut ends and the ground, whereas the white lines are the absence of ground contacts. (Bottom) configurations of the robot in three different phases of the leg cycle

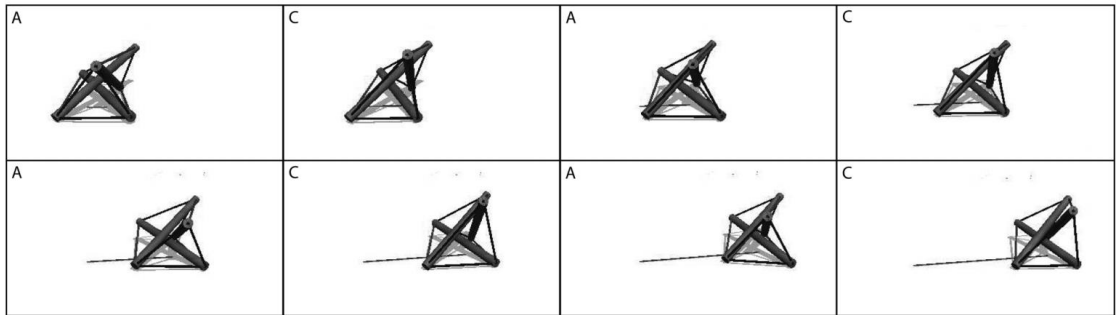


Figure 2.42 The captured images of the crawling locomotion of the TR-3 robot [33]; the robot moves by alternating between configurations A and C, as depicted in Figure 2.41.

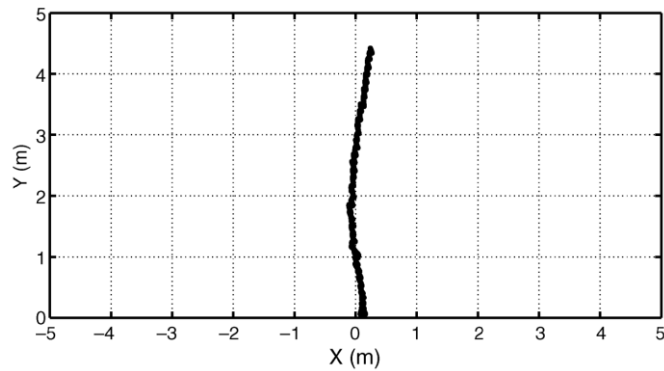


Figure 2.43 Trajectory of the COM of the TR-3 robot, plotted for 10 s of operation time [33].

2.4.3 Climbing locomotion

The concept of climbing locomotion for existing tensegrity robots involves producing pulling and pushing forces that provide climbing ability, accessing both horizontal and vertical environments such as pipeline systems. The pulling and pushing forces can be generated using a combination of the cable and strut length adjustment.

DuCTT was the first climbing robot based on a class 3 tensegrity structure able to climb a straight vertical pipe [14, 15, 69, 73] using a combination of cable and strut length adjustment method. DuCTT consisted of two modules of a tetrahedron. Each module contained a rotary and linear actuator to actuate cable and strut lengths. These actuators were connected to one another using actuated cables to produce pulling forces. The linear actuators were used to produce pressing force against a pipe wall. The climbing locomotion was achieved by defining the climbing motion procedures, which consisted of six steps, as shown in Figure 2.44.

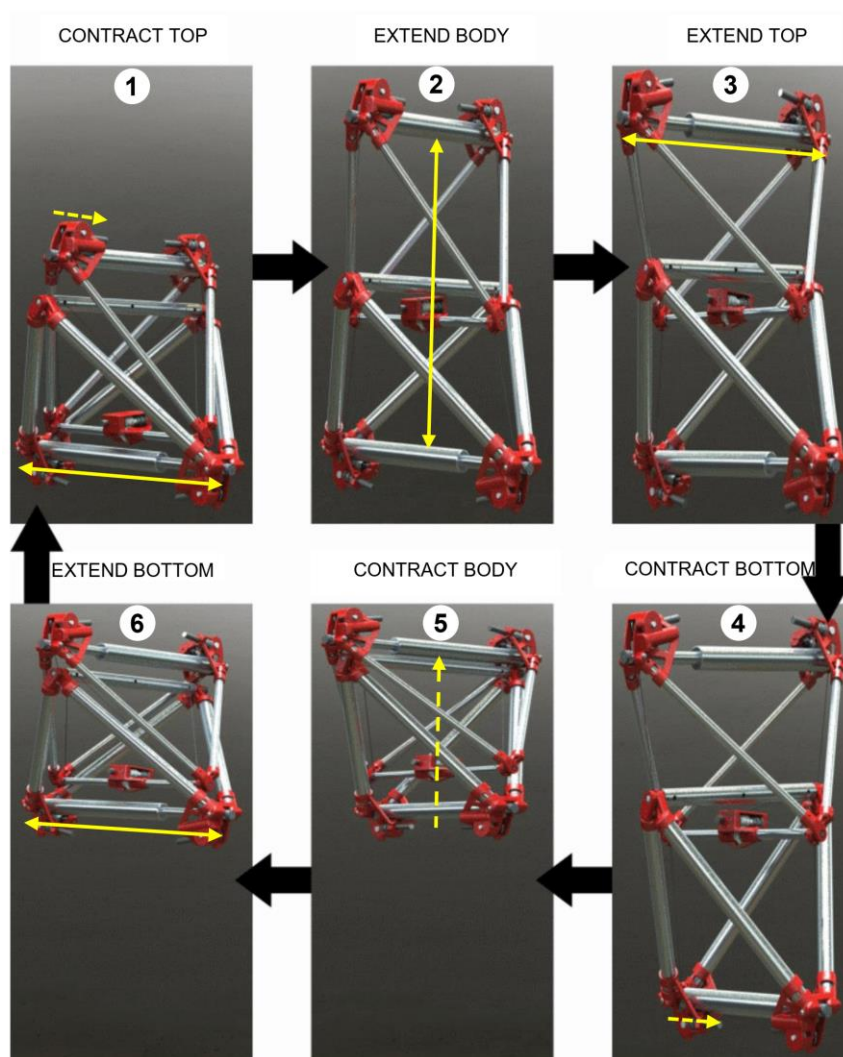


Figure 2.44 Climbing motion procedures for DuCTT [14].

2.4.4 Jumping locomotion

The jumping locomotion concept involves using elastic elements or spring mechanisms to store and release energy. For example, a jumping tensegrity robot with torsionally prestrained shape memory alloy springs (TPSMA) was introduced by Chung et al. [16]. This robot is a six-strut tensegrity robot with a height of 12.5cm. Each strut was connected with elastics to form the robot's structure. TPSMA springs were employed to attach between the tips of different struts in parallel with the elastics. A high current of 5.2A for 0.3 seconds was applied for TPSMA to change the robot shape, with a resting time of 3.6 s for recovering its shape to make the robot jumping, as presented in Figure 2.45.

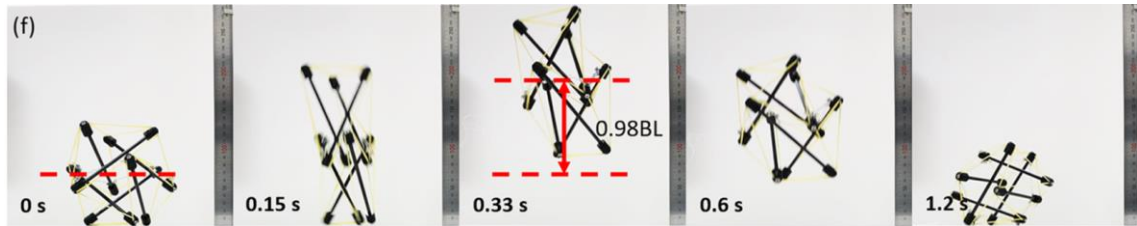


Figure 2.45 Jumping robot based on six-strut tensegrity structure, driving by TPSMA [16]; the current of 5.2 A was applied with 0.3 seconds for each jumping cycle.

2.5 The Actuation Method of Tensegrity Robots

The existing actuation methods of tensegrity robots are categorised into four types, namely cable actuation, strut actuation, payload actuation, and vibrating actuation (see Table 2.3). However, effective actuation methods for tensegrity robots to exert forces for locomotion are the cable actuation and strut actuation methods that produce sufficient forces for robot configurations.

2.5.1 Cable Actuation Method

Cable actuation methods can be achieved by adjusting cable length to exert pulling and pushing forces between strut elements. An example of a class 2 tensegrity robot, including two rigid bodies and two actuated cables, is presented in Figure 2.46.

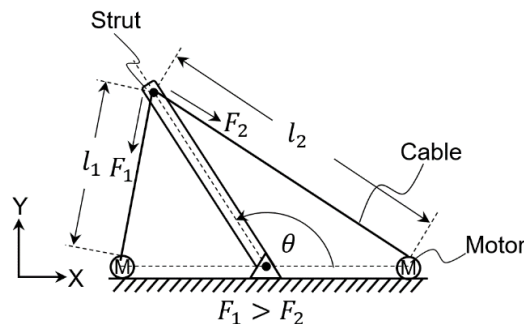


Figure 2.46 Class 2 tensegrity robot driven by the cable actuation method.

In this structure, the structural configurations can be achieved by controlling spooling forces (F_1 and F_2) related to the motor torque to spool cable lengths on both sides (l_1 and l_2) of the strut. Furthermore, the strut angle (θ) can be controlled using inverse kinematic equations [74] to calculate the target length of the cables l_1 and l_2 . This basic concept of cable actuation is employed to actuate cables attached to each strut end of tensegrity robots to produce different cable tensions, resulting in the movement of strut elements to deform different robot shapes for locomotion [7, 8, 12, 31, 33, 48, 51, 52, 56, 57, 75, 76].

2.5.2 Strut Actuation Method

Strut actuation methods can be achieved by adjusting the length of strut elements to produce different cable tensions at the strut ends to which cables are attached. In general, elastic cables are used to connect between strut ends to allow the strut length adjustable, resulting in structural configurations. The example of a class 2 tensegrity robot, in the X-Y plane, moved by the strut actuation method is shown in Figure 2.47. The robot consists of three strut elements that serve as linear actuators (LAs) and two spring cables. Two LAs are fixed along the X-axis, and another is placed between two LA to rotate on the left and right sides. The spring cables are used to connect between strut ends to hold the middle LA positions.

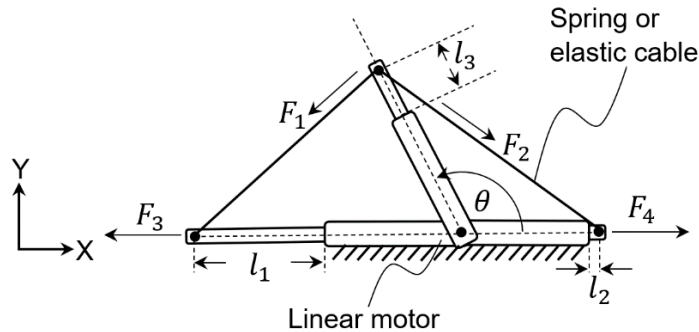


Figure 2.47 Class 2 tensegrity robot driven by the strut actuation method.

To deform the robot shape, the left LA and right LA are used to exert forces F_1 and F_2 , respectively by adjusting slider length l_1 and l_2 to rotate the tip of the middle LAs. Similar to the cable actuation method, if the F_1 is higher than the F_2 , the middle LA angle (θ) will be rotated on the left. The spring constant and cable lengths also relate to F_1 and F_2 . Therefore, the middle LA angle (θ) can be controlled using inverse and forward kinematic equations [74] to calculate the target length of the LA-slider l_1 , l_2 and l_3 . However, this concept only describes how the strut moves using the strut actuation method to change cable tensions that attach to each strut ends, resulting in structural deformation.

In research into tensegrity robots driven by the strut actuation methods, LAs have been employed as a strut element of the robots. Each strut element end is attached to elastic cables to form the robot shape. To deform the robot structures, the strut element exerts pushing and pulling force by adjusting the length of the strut elements to produce different cable tensions, resulting in the movements of the strut elements to change the robot's COM for locomotion [72]. Although the cable and strut actuation methods provide advantageous functions for tensegrity robot locomotion, there are still some disadvantageous functions that need to be addressed, which are summarised in Table 2.2

Table 2.2 Summary of the advantages and disadvantages of the existing structural configuration methods.

Actuation methods	Structural configuration concepts	Advantages	Disadvantages
Cable actuation	The use of active actuators to spool and unspool cables connected between strut ends to move strut positions inside robot structure to make the robot rolling	- High cable-pulling forces - Rolling and crawling locomotion with a rolling motion	- Low speed for robot configurations - Vertical motion restriction due to the lack of a wall-pressing mechanism - High energy usage because actuators require constant power for configuration
Strut actuation	The use of active LAs being strut elements to exert forces, generating different cable tensions to move the strut for locomotion	- High pushing and pulling forces that are used to produce traction force between robot legs and environmental surfaces.	- Low speed for robot configurations and locomotion - Vertical motion restriction due to a lack of inelastic cable to pull and push parts - High energy usage because actuators require constant power for configurations
Cable and strut actuation	The use of rotary actuator to actuate cables actively to move strut elements and also adjust strut-slider length to exert pressing forces to hold the structure vertically	- High cable-pulling forces and pressing forces - Horizontal and vertical locomotion abilities	- Low speed for robot configurations and locomotion - High energy usage because actuators require constant power for configurations

The disadvantages of the existing actuation methods of the tensegrity robots are low speed for robot configurations, which relate to the mechanism design of compressive and tensile elements, and high energy used for the structural configuration process because actuation methods require constant power.

Therefore, to enhance the existing actuation method, a new design of structural configuration concepts that relate to the individual element design for the compressive and tensile element of tensegrity robots should be researched. Thus, the research questions of this project are as follows:

- 1) How can a new actuation method be designed to swap a robot structure between soft and hard, increase the speed of robot configurations, and generate different cable tensions and high pressing forces in order to move vertically?
- 2) How can a tensile element be designed to provide useful functions, including a high speed for rolling a cable, less power usage, and cable length control?
- 3) How can a simple control rule be designed that is useful for tensegrity robots performing different tasks using the new actuation method?

In order to study the existing mechanical design of tensile and compressive elements of the existing tensegrity robots, a number of effective actuation mechanisms are reviewed in the following to gain knowledge that may be used to design a new actuation method related to the individual element design, including tensile and compressive elements, to answer the research questions.

2.6 Individual Element Designs for Tensegrity Robot

To achieve tensegrity robot deformation, the individual elements for actuating cables and struts and the structural deformation method are important. There are many different designs of individual elements for tensegrity robots. A DC-geared motor is a major component used to actuate both cable lengths and strut lengths due to the high-rotational torque, lightweight mechanism, and low costs. Existing actuated cable modules are designed using active actuators able to generate high-rotational force to roll actuated cables durably and adequately, and the extension spring tends to be used to connect actuated cables and strut ends to prevent cable damage when there is excessive tension.

Figure 2.48 presents an example of the individual element designs for tensegrity robots. The cable actuation was designed using a miniature DC-geared motor spooling an inelastic cable, which is attached to the extension spring before connecting to other struts, as presented in Figure 2.48 (a). Tension sensors were used to measure cable tension, sending values to the control system and identify the robot motions. The tension sensors mounted at the end caps of ReCTeR compliant tensegrity robot is shown in Figure 2.48 (b). The idea to place the motors and controller module in the middle of the strut is presented in Figure 2.48

(c). The actuated cables are passed through an aluminium rod and connected to an extension spring before hooking with other end caps.

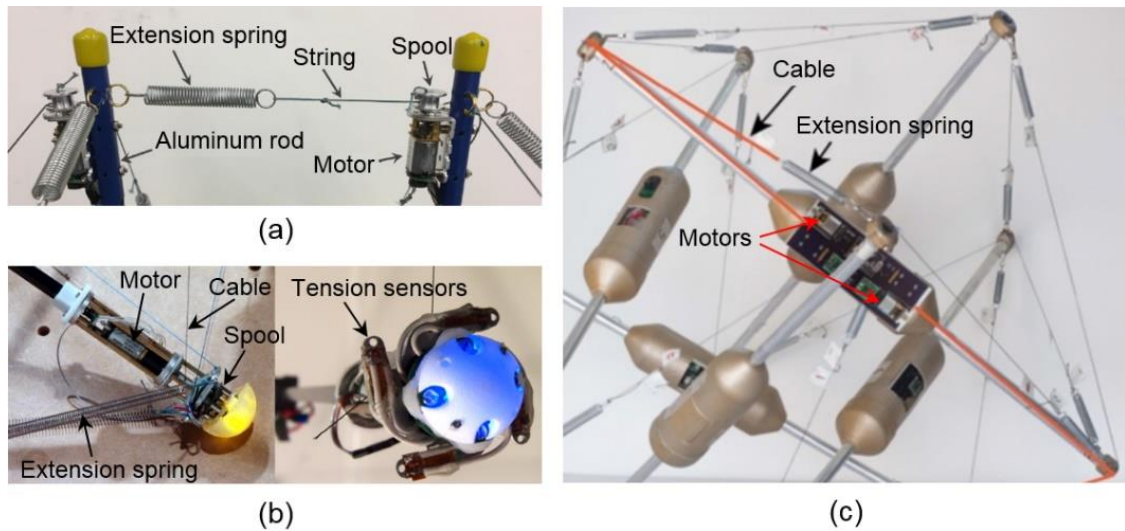


Figure 2.48 Examples of the individual element designs for spooling actuated cables to deform robot structures by using DC-g geared motors, extension springs, and inelastic cable: (a) the actuated cable system of T12-R [57], (b) strut module of ReCTeR compliant tensegrity robot [31], and (c) rod-centred actuation module of the soft spherical tensegrity robot [8].

Another concept involves using the elastic lattice platform [77] to connect strut ends and provide significant control over system tensions. To deform the robot structure, DC-g geared motors are used to spool cables, which are inserted into the aluminium rod. The cable tip is passed through the rod and spooled by the motor, as presented in Figure 2.49 (a).

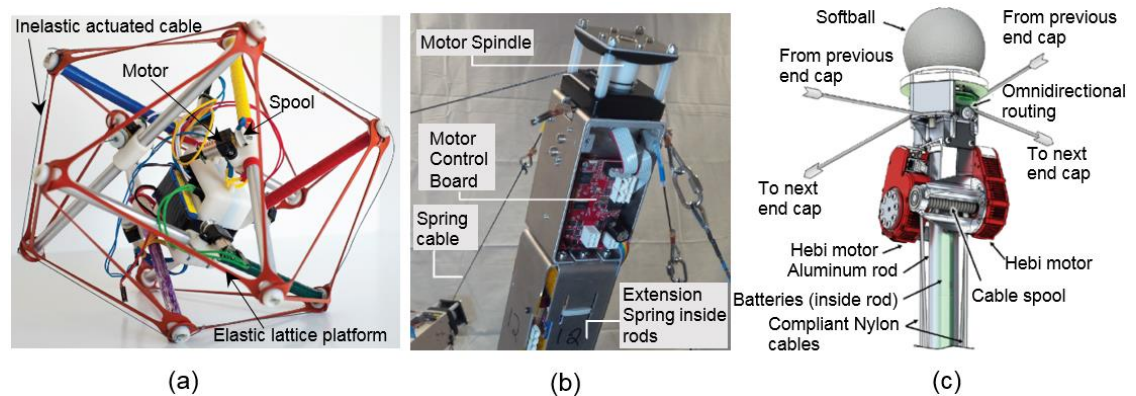


Figure 2.49 Example of the individual element designs for adjusting elastic cable length to deform the robot structure: (a) The use of elastic lattice platform to construct the TT-4_{mini} prototype [77], (b) the strut module of SUPERball [51], and (c) the end cap design of the SUPERball v2 [56].

Figure 2.49 (b) presented the development of the individual elements for a six-rod tensegrity robot named SUPERball [51]. A DC-g geared motor was used to spool spring cables named Vactran to deform the robot structure. The Vactran

cable was attached to the extension spring inserted inside the rod. A force sensor attached to the strain gauge was placed between the extension spring and endcap to measure impact forces and cable tensions. Furthermore, each controller module was equipped with a nine-axis inertial measurement unit (IMU) to provide the position and rotation data of the rod.

Figure 2.49 (c) shows the individual element design of SUPERball v2 [56] to control the robot's cable lengths to change its shape for rolling locomotion. Two Hebi motors were attached to each end cap of the rod, which were used to roll a military spec 750 nylon cable that links to other end caps.

LAs are effective actuators that construct a tensegrity robot with the strut actuation method; it is a compressive element able to exert two directional forces by extending and retracting slider lengths to deform the robot structure. However, to allow the robot to change its shape, elastic elements and extension springs should be a tensile element used to connect each strut end, as presented in Figure 2.50 (a). Moreover, the linear motor can be a tensile element that can be placed in the middle between each rod connecting to the elastic rope on both ends of the LAs before mounting on the top of each rod, as illustrated in Figure 2.50 (b). Additionally, the LAs can be used to design a climbing robot moving in a vertical direction; they cooperate with cable spooling mechanisms, which consist of DC-g geared motors, compression springs, and elastic cables. These components are used for lifting and rotating the robot structure moving in both vertical and horizontal directions, as presented in Figure 2.50 (c).

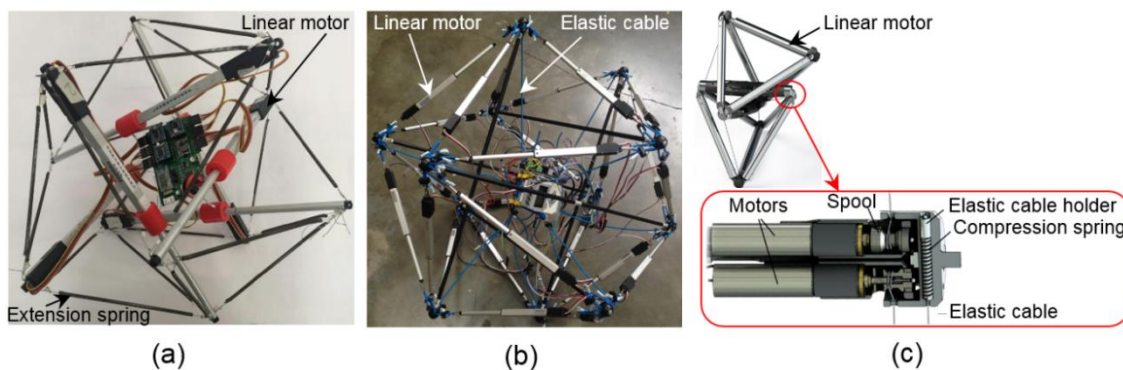


Figure 2.50 Example of the individual element designs for adjusting strut length to deform robot structure by using an LA, extension spring, and inelastic cable: (a) six-bar tensegrity robot [9], (b) six-strut tensegrity robot [78] and (c) the cooperation of an LA and cable adjustment method to deform the DuCTTv2 structure [14].

However, the existing individual element mechanisms still have a number of limitations. Firstly, although LAs and DC-g geared motors provide high torques to exert pushing, pulling, and spooling forces for robot configurations, they have low speed, resulting in their long-term use in structural configurations, specifically

swapping between soft and hard structures due to the mechanical limitations. Secondly, the individual elements for robot configurations must be powered continuously, resulting in a short-term operation if powered by batteries. Thirdly, due to the high-torque actuator, the overall weight of the tensegrity robots is still heavy. If high-torque and high-speed elements are used for the individual elements to increase configuration speed, the weight of the robot will increase. To overcome these limitations, a new actuation method and individual element design for tensegrity robot configurations are researched in this project.

2.7 Tensegrity Robot Constraints

Although tensegrity robots provide advantageous properties that modular robots do not, such as force distribution, lightweight design capability, and compliant structure to swap between soft and hard bodies, they may not be appropriate for some applications, which require a small number of actuators, fast movement in a vertical direction and high-precision motions, as explained as follows:

- 1) Tensegrity robots require a large number of actuators for locomotion; for example, the three-strut tensegrity robot requires at least three actuators for crawling locomotion in a straight path, whereas a normal wheel robot needs at least one actuator;
- 2) Although a tensegrity robot is able to move vertically, it can only be used the inchworm motion behaviour using LAs to exert pressing force between robot legs, environmental surfaces, and rotary actuators to spool cables to push and pull robot modules for turning and moving upwards and downwards. Therefore, the locomotion speeds of the robot rely on actuator speeds, which normally have low speed due to the high torque requirement; and
- 3) Tensegrity robots may be inapplicable for high-precision movements because the robot structure generates vibrations caused by the tensile elements that connect each strut ends without rigid joints. Therefore, tensegrity robots naturally produce vibration itself during locomotion and interactions with the environment.

2.8 Literature Summary

This chapter introduced and reviewed tensegrity robots that have unique properties beneficial in the field of exploration and inspection robotics. The mechanical design of the compressive and tensile elements of tensegrity robots and their configurations and control strategies were reviewed in this chapter to

understand how robots move and to understand the current limitations and issues that need to be addressed.

The unique properties of tensegrity robots were demonstrated and evaluated to ensure that the tensegrity structures potentially provide advantageous features in terms of inspection and exploration robotics. The fault tolerance and force distribution properties have been tested to demonstrate that tensegrity structures provide effective features that robots need for exploration and inspection tasks, such as landing and moving operations. A four-strut tensegrity robot was developed and demonstrated regarding fault tolerance. The robot was tested with one and two actuators damaged. The results suggest that the robot can move to reach a target point. Although the robot moves at a slower speed, it can demonstrate a certain degree of fault tolerance concerning actuator damage [33]. In addition, six-strut tensegrity robot drop tests were performed at the heights of 3.4m with 8m/s falling speed [56] and 10m with 11m/s falling speed [6]. After landing, the robot mechanisms and electronics control modules still performed other experiments because the impact forces were distributed to the robot's network of tensile elements and strut elements of the robot.

The mechanical designs, control strategies, locomotion types and speeds, and research aims of the reviewed tensegrity robots are summarised and compared in Table 2.3. The existing tensegrity robots reviewed could perform four locomotion types (rolling, crawling, climbing, and jumping) depending on structure geometries. For example, a three-strut tensegrity robot is able to move using the crawling locomotion, using strut elements to produce friction between the ground and the strut element tips. On the other hand, rolling locomotion is suitable for a six-strut tensegrity structure with an icosahedron geometry due to the highest speed for locomotion.

Although tensegrity robots have advantageous functions that traditional robots do not have, such as force distribution and fault tolerance ability, existing actuation methods for structural configurations of tensegrity robots still have a number of limitations. For the cable actuation method, a DC-gear motor used for spooling a cable has a small size and high torque; however, this motor has low speeds when rotating its shaft because the geared box reduces the speed of the motor shaft. Even if a high-speed and -torque motor can be used to increase the speed, the motor weight also increases following the larger mechanism to achieve higher performance, and the motor requires greater power for operations, which is disadvantageous when powered by batteries. For the strut actuation method, strut elements are used to exert pushing and pulling forces by adjusting the strut-slider lengths, while elastic tensile elements, such as rubber, spring, and nylon wires, are used to connect the struts and allow strut length extensions. From this

configuration, the robot structure cannot be deformed to have a rigid body due to the flexibility of the cable. Moreover, vibrations may occur during locomotion due to the spring value of the elastic cable. Therefore, existing strut actuation methods are not suitable for designing a reconfigurable tensegrity robot able to swap its structure between soft and hard structures for a specific task. Moreover, both cable and strut actuation methods require high power for robot configurations because DC-geared motors and LAs need constant power to adjust strut lengths and spooling cables.

Therefore, this project focuses on the design of a new actuation method, consisting of compressive and tensile elements that would provide rapid speed configurations, swapping between soft and hard structures, lightweight elements and less-power usage to fill the research gaps in the field of tensegrity robotics.

Table 2.3 Comparison of the reviewed tensegrity robots

Robot / class	Research aims		Strut length / number	Type of locomotion / speed	Reference, year
Controller type	Demonstration	Control loop	Actuators / actuation method	Sensors	Environmental test
Jumping Tensegrity Robot / class 1	Improved SMA spring design for medical tools, multi-environment robots and robots collaborating with humans		12.5cm / six bars	Rolling and jumping / 2.88 cm/s	[16], 2019
Trial-and-error method	Simulation and Implementation	open	TPSMA spring / cable actuation	-	Rough terrain in a laboratory
SUPERball v2 / class 1	Testing of a novel-robust mechanism to withstand high-impact landing (8m/s before touching the ground) and packing /unpacking method		2 m / six bars	Rolling / --	[56], 2018
Steerable controller for locomotion [79] and equilibrium manifold controller for pack/unpack process.	Simulation and implementation	Closed	24 DC-Geared motors / cable actuation	Rotary encoder for position, velocity and torque control	3.4m drop test
TT-4mini / class 1	Testing of a novel multi-cable actuation scheme to achieve reliable locomotion on inclined surfaces of up to 24°		25 cm/ six bars	Rolling / 6.7 cm/s	[76], 2017
One-cable and two-cable actuation policies.	Simulation and implementation	Open	Six DC-geared motors / cable actuation	--	24° incline-flat surface in a laboratory
T12-R / class 1	Proposed straight rolling locomotion and simulated control strategy		45cm / 12 bars	Rolling / --	[57], 2017

Robot / class	Research aims		Strut length / number	Type of locomotion / speed	Reference, year
Controller type	Demonstration	Control loop	Actuators / actuation method	Sensors	Environmental test
Dynamic relaxation and multi-generation Monte Carlo	Simulation	Open	24 DC-geared motors / cable actuation	--	--
DucTT and DucTTv2 / class 3	Testing of a simulation software performance and control strategies for duct inspection tasks		35 – 45 cm / two-tetrahedron modules	Crawling and climbing / 1.4cm/s	[14, 15], 2014/2016
Force density method for inverse kinematic control policy and cable length control	Simulation and implementation	Closed	Two LAs and eight (12-watt Maxon BLDC) DC-geared motors / cable and strut actuation	Hall sensors and position sensors	Straight pipe in a laboratory
Spherical Mobile Robot / class 1	Testing and evaluation of a new concept for rolling locomotion of the mobile robot		0.7 m diameters/ two-curved modules	Rolling/-----	[10], 2016
Movement of internal masses	Simulation and implementation	Closed	Two stepper motors with gearbox / payload actuation	Position (rotary encoder), velocity (accelerometer)	Flat ground in a laboratory
Six-Bar Tensegrity Robot/ class1	Deriving of a robot model and testing of a software simulation of the six-bar tensegrity robot		200mm / six telescopic bars	Rolling / -----	[9], 2016
Movement locus of the centre of gravity	Simulation	Open	Six LAs/ strut actuation	None	----
TT-3, a six-bar spherical tensegrity robot with/without payload / class 1	Test and analysis a new Rod-centred strut and endcap design		No mention in the paper (around 1m) / six struts	Rolling (implementation) / --- --hopping (simulation)	[8], 2016 / [48], 2016
Evolutionary algorithm [80] and the greedy search algorithm with a heuristic function	Simulation and implementation	open	24 brushed DC-geared motors/ cable actuation	None	Flat-outdoor terrain
Parallel kinematic mechanisms for distributed actuation	Test and analysis hardware		0.29 mm	-----	[71], 2016
Bang-Bang controller	Simulation and implementation	Closed	4 (PAMs) / cable actuation	Displacement sensors, force sensors.	Flat ground in a laboratory
SUPERBall 2014 and SUPERBall 2015 / class 1	Untethered, underactuated control and validation		1.5 m and 1.7 m / six struts	Rolling / 0.2 m/s and 0.5 m/s	[51], 2015 and [31], 2016

Robot / class	Research aims		Strut length / number	Type of locomotion / speed	Reference, year
Controller type	Demonstration	Control loop	Actuators / actuation method	Sensors	Environmental test
Linear-Quadratic-Gaussian (LQG) / Coevolutionary algorithms	Simulation and implementation	Closed	12 DC-gearred motors / cable actuation	Tension (force sensor), length (encoder), torque sensor, motion sensor	Flat and slope outdoor terrain
ReCTeR / class 1	Untethered, underactuated control and simulator validation		1 m / six struts	Rolling/ speed 0.6 m/s	[31], 2014
Motion capture experiments	Implementation / simulation	Open	6 DC-gearred motors / cable actuation	Motion capture	Flat ground in a laboratory
Icosahedron with and without payload / class 1	Robust feedback controller with minimal assumptions		1 m / six struts	Steerable rolling over unknown terrain/ actuator speed 0.6 m/s	[81], 2014
Reactive controller with coevolution	Simulation	Closed	24 actuation variables / cable actuation	Force sensors (ground impact)	-----
Icosahedron tensegrity robot / class 1	Low-cost, modular and rapidly tensegrity robot, design actuated policies for locomotion		0.69 m / six struts	Rolling/ actuator speed 5 mm/s	[7], 2014
A greedy search algorithm uses a heuristic function for adjusting a robot body	Simulation and implementation	Open	24 LAs / strut actuation	Vicon motion tracking	Flat ground in a laboratory
Icosahedron with/without payload / class 1	Hardware constraint and power consumption information		----- / six struts	Forward rolling on flat terrain/ 0.2 m/s	[55], 2014
Stepwise functions with coevolution	Simulation	Open	24 variables / cable actuation	None	-----
ReCTeR / class 1	Robust controller with uncalibrated sensors, link with CPGs		1 m / six struts	Crawling (implementation)/ actuator speed 0.6 m/s, various (simulation)	[75], 2013
Physical reservoir computing	Simulation and implementation	Closed	6 DC-gearred motors / cable actuation	Tension sensors	Flat ground in a laboratory
Icosahedron with and without payload / class 1	Simple, distributed implementation		----- / six struts	Forward rolling on flat terrain/-----	[82], 2013
Sine waves with coevolution	Simulation	Open	24 and 36 variables / cable actuation	None	-----

Robot / class	Research aims		Strut length / number	Type of locomotion / speed	Reference, year
Controller type	Demonstration	Control loop	Actuators / actuation method	Sensors	Environmental test
Vibration-Driven mobile robot based tensegrity structure / class 1	Low-cost hardware uses body dynamics for locomotion		0.115 m / six struts	Various/ 10.98 mm/s	[83], 2013
Vibration driven	Simulation and implementation	Open	two electromagnets / vibrating actuation	None	Flat table in a laboratory
Three cells, class 2 tensegrity beam/tensegrity swimmer	Test of hardware with CPG control		----- / multiple struts	Fin movement/----	[42, 43]
CPG resonance entrainment	Simulation and implementation	Both	Two LAs / cable actuation	Tension and position	Flow tank in a laboratory
Three-DoF actuated robot / class 1	Test on HW platforms and well-studied		0.55-0.95 m / three struts	Fixed base/----	[84], 2011
Kinematic controllers	Simulation and implementation	Both	Three prismatic actuators/ strut actuation	Force sensors	Platform in a laboratory
15-50 bars tensegrity tower / class 1	Communication through body		----- / 15 – 50 bars	Crawling-like tension/----	[17, 38, 39], 2008
Morphological communication	Simulation	Closed	15 – 50 actuator variables / cable actuation	Sensors	-----
Any tensegrity/ class 1	Control theory approach			Position/trajectory control/----	[5], 2009
Feedback nonlinear control	Simulation	Closed	Variables / cable actuation	Full state	-----
Icosahedron with pneumatic actuator / class 1	Insightful control, original hardware implementation		0.6 m / six struts	Rolling/ -----	[50], 2009 and [52], 2012
Pneumatic actuators	Implementation	Open	24 pneumatic actuators / cable actuation	-----	Flat ground in a laboratory
TR-3 and TR-4 tensegrity prisms / class 1	First dynamic locomotion		1 m / three and four struts	Crawling/60 cm/min ²	[33], 2006
Genetic algorithms	Simulation for three and four bars and implementation for three bars	Open	Three DC-g geared motors / cable actuation	None	Flat ground in a laboratory

Chapter 3 New Structural Deformation Concept

This chapter introduces a new concept of structural configuration using the cooperation between retractable-passive joint with a cable locking mechanism (PRM) and adjustable-length strut element (SE). The proposed concept may be used to address existing issues, particularly slow speeds for robot configurations and high-power usage, which were discussed in the previous chapter (see Table 2.1). Differences between the existing and proposed structural configuration concepts are described. The concept of the proposed method to design different classes of tensegrity robots, including 1, 2 and 3, are then introduced to demonstrate how different classes of tensegrity robots can be designed for locomotion using PRM and SE elements. The basic structural deformation concept, including two PRMs and one SE called 3-DOF structure is then presented in order to describe the fundamental movements of the end-effector positions, including straight and rotational motions. Finally, the end-effector movement concept of a 5-DOF structure is proposed and analysed. The forward kinematic equations of the end-effector position of each structure are solved to identify their position for use in closed-loop control systems.

3.1 Differences between Existing and New Structural Deformation Concepts

The differences between existing and proposed structural deformation concepts are presented in this section. A cross-shape tensegrity structure is employed to describe to understand each deformation concept clearly. The structural deformation concept of existing tensegrity robots is divided into two methods. The first method involves using active rotary actuators to adjust cable lengths to roll and unroll cables attached to each strut end. The different cable lengths produce cable tensions to move strut elements to deform robot shapes, as shown in Figure 3.1.

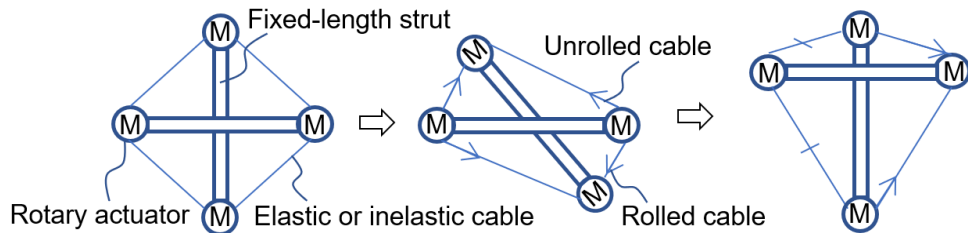


Figure 3.1 Structural configuration concept using rotary actuators to roll and unroll cables that connect between strut ends

A linear actuator (LA) may be used for the cable actuation method to connect each strut end instead of cables, as shown in Figure 3.2. The robot can deform its structures by changing the lengths of each LA.

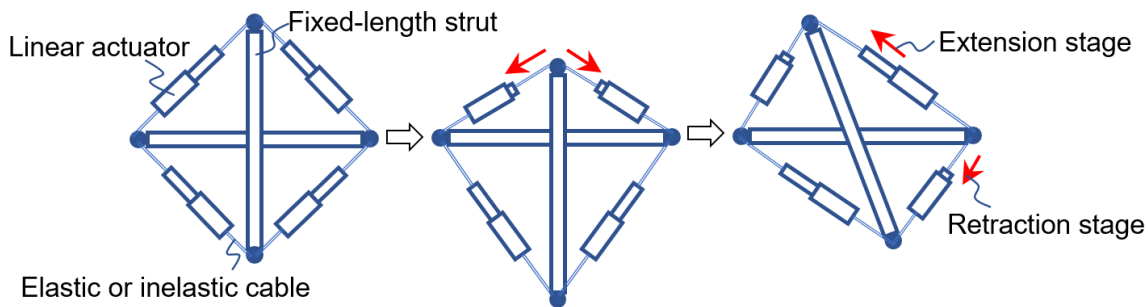


Figure 3.2 Structural configuration concept using LAs to adjust cable lengths by placing between strut ends.

The second method involves adjusting strut lengths to produce different tensions of elastic cables, which attach to each strut end. The changes in each strut length produce different cable tensions to move strut elements to deform robot shapes, as shown in Figure 3.3.

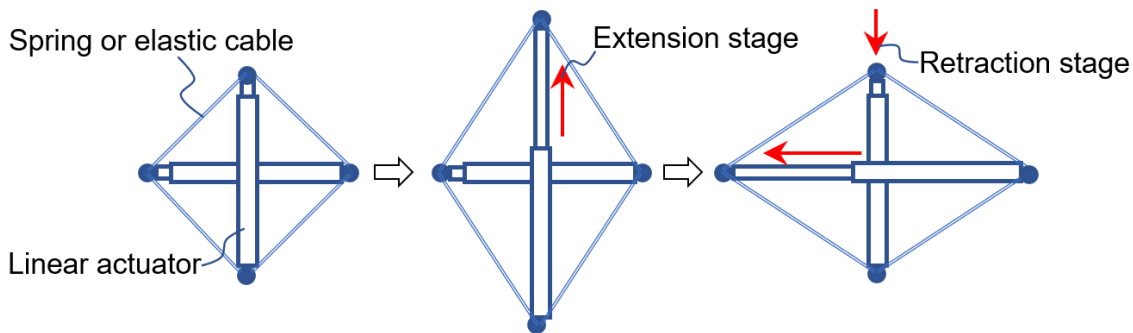


Figure 3.3 Structural configuration concept by using strut actuation method.

The combination of rotary and LAs can be used to deform the configurations of tensegrity robots, as shown in Figure 3.4.

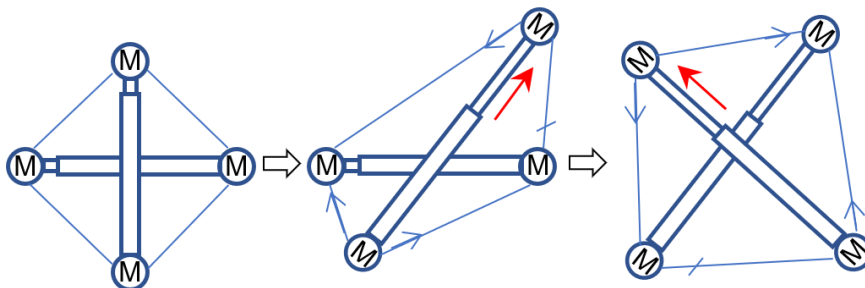


Figure 3.4 Structural configuration concept using rotary actuators and LAs to change different cable tensions

For the proposed concept, instead of using active actuators, including linear and rotary actuators, to spool cables or adjust strut lengths, the cooperation between

an active actuator and passive-retractable joint to deform robot structures is introduced in this paper. The active actuator is an adjustable-length strut element (SE), and a passive-retractable joint that restricts and releases cable lengths is a passive-retractable joint with a cable locking mechanism (PRM). To deform the robot shape, the PRM is used to restrict and release cables while extending or retracting the SE length to generate varied cable tensions to move SE positions, resulting in a change in robot configurations, as shown in Figure 3.5. The summary of differences between existing and proposed structural deformation concepts are shown in Table 3.1.

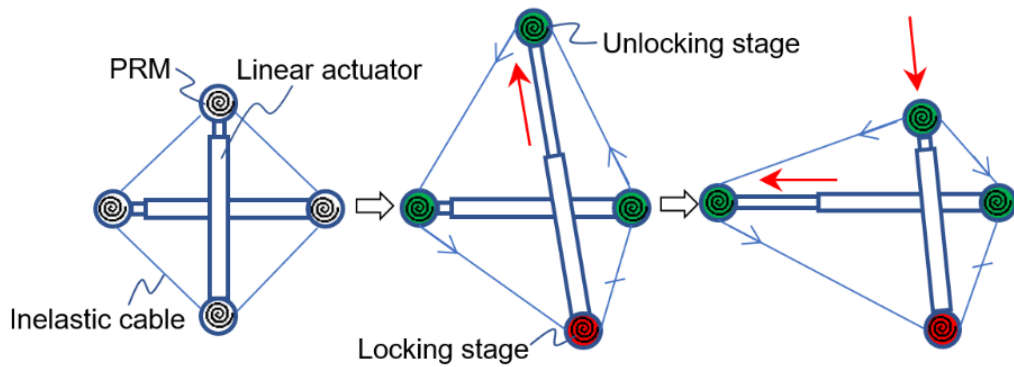


Figure 3.5 Proposed structural configuration concept using cooperation between PRMs and SEs to change different cable lengths and tensions

The expectation for the proposed structural deformation concept is to potentially address existing tensegrity robot limitations (see Table 2.1) by increasing configuration speeds, low energy use, and moving vertically with a compliant structure.

Table 3.1 Differences between effective existing and proposed structural configuration concepts for tensegrity robots; cross-shape tensegrity structures are used to explain how to change robot configurations using different actuation methods.

Actuation concept	Tensile element	Compressive element	Structural configuration concept
Cable actuation [7, 8, 12, 13, 48, 51, 56, 57, 77, 85]	Elastic and inelastic cables are actuated actively by using rotary actuators attached to the ends of each compressive element. The cables can also be actuated by LAs by placing them between strut end.	Fixed-length strut or bar	Adjust cable lengths to move strut elements to produces different cable tensions to deform robot shapes, as shown in Figure 3.2 (a). Adjust cable lengths by placing LAs between strut ends to deform robot shapes, as shown in Figure 3.2 (b).

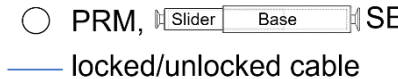
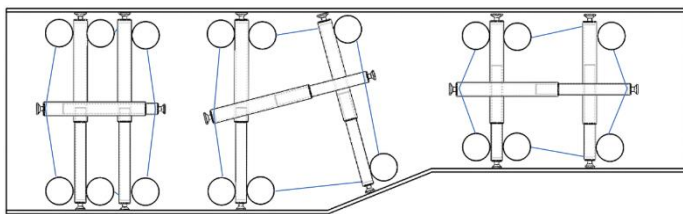
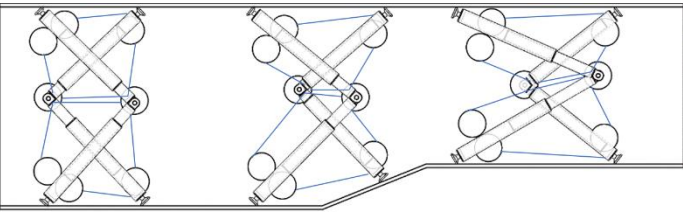
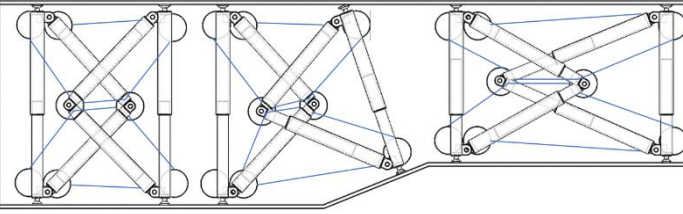
Actuation concept	Tensile element	Compressive element	Structural configuration concept
Strut actuation [46, 72]	Fixed-length elastic cables or springs	The length of strut elements is changed actively using LAs to exert force to change different cable tensions.	Adjust strut lengths to produce different tensions between elastic cables attaching to each strut ends to deform robot configurations, as shown in Figure 3.3
Cable and strut actuation [14, 73]	Inelastic cables are actuated actively by using rotary actuators attached to each end of strut elements.	The length of the strut element is changed actively using LAs to exert forces to change different cable tensions.	Adjust strut and cable lengths to create different cable tensions and move the strut elements to make the robot deform its shapes, as shown in Figure 3.4
Proposed actuation [1]	Inelastic cables pull passively using passive retractable joints. The cables can also be restricted and released using a locking mechanism. This element is called a PRM. The PRM is mounted on both end sides of the SE.	The SE length can be adjusted actively by using LAs to exert forces to push and pull cables of the PRMs connected to each SE.	Restrict and release cables using PRMs to lock and unlock cable lengths while changing strut lengths to produce different cable tensions to deform robot structures, as presented in Figure 3.5.

3.2 Different Classes of Tensegrity Structures Using a Proposed Actuation Concept

The proposed actuation concept can be applied to design different classes of tensegrity robots. Examples of tensegrity robot class 1, 2 and 3 can be designed, using cooperation between PRM and SE elements. In this research, crawling locomotion based on a wall-pressing motion is selected to design different classes of tensegrity robots because it is appropriate for crawling and climbing motions that allow a robot to move in both vertical and horizontal directions.

Table 3.2 presents an example of class 1, 2 and 3 tensegrity robots designed using the proposed actuation method to deform the robot structures in different configurations for crawling locomotion.

Table 3.2 Examples of class 1, 2 and 3 tensegrity robots using PRM and SE elements for the robot configurations.

Class	Number of SE	Number of PRM	Robot structure in the X-Y plane	
1	3	6	 One strut element connected to others without rigid joint	
2	4	8	 Two strut elements connected by one rigid (revolute) joint	
3	6	8	 Three SEs connected by three rigid (revolute) joints	

For a class 1 tensegrity robot, no rigid joint is used to connect SEs. PRMs containing cable rolling and braking parts are tensile elements used to connect SEs, whereas SEs are compressive elements used to exert push and pull forces. Robot configurations can be achieved by adjusting the SE-slider length to exert different cable tensions forces when restricting or releasing cables controlled by PRM locking procedures. Without a rigid joint, the connecting point where the cable connects to the SE provides six degrees of freedom surrounding the point to allow the robot structure to be flexible and adaptable, following different environmental sizes. The minimum number of SEs and PRMs to make the robot crawl in straight and curved lines is three SEs and six PRMs, as shown in

Table 3.2 (class 1).

The class 2 tensegrity robot can be constructed using the proposed actuation method. Two SEs are connected by one rigid (revolute) joint, and SE tips connect to other SEs through PRM cables. The robot configurations can be achieved similar to the class 1 tensegrity robot. However, the number of SE and PRM is increased, resulting in an overall weight increase.

To increase structural strength, a class 3 tensegrity structure is employed using three rigid joints connecting three SEs that exert force, and PRMs are used to restrict and release cables spooled by the SEs to deform robot shapes for locomotion, as shown in Table 3.2 (class 3).

However, both class 2 and class 3 tensegrity structures limit structural deformation ability due to restrictive motions of the rigid joint, and the weight of the robot increases following the number of SEs. The heavyweight structure can reduce the speed of the robot configuration process. Therefore, this project will focus on only the class1 tensegrity structure that provides the best flexible ability and lightweight structure.

3.3 New Concept of the Passive-Retractable Joint with a Cable Locking Mechanism (PRM)

This section introduces a new concept of the passive-retractable joint with a cable locking mechanism (PRM) used for the fast speed and limited energy use for robot configurations. The basic concepts of the new PRM are to roll and release a cable without an active actuator unlike a tensile element of conventional tensegrity robots. The new PRM will also restrict cables that are spooled by other elements for structural configurations. Therefore, the fundamental motions of the new PRM can be divided into two stages.

The first stage is called an unlocking stage, which allows cable length adjustable, as shown in Figure 3.6. Cable directions depend on the values of cable-pulling force (F_R) and pulling force (F_{Pull}). If the cable-pulling force is higher than the pulling force, the cable length is decreased retracted towards the left (see green-dash arrow) and if the pulling force is higher than the cable-pulling force, the cable length is increased and extended to the right (see red-dash arrow). From these motion behaviours, the cable remains in tension at all lengths due to the cable-pulling force.

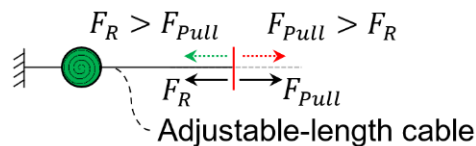


Figure 3.6 The locking stage of the new PRM.

In this stage, the cable-pulling force can be calculated with the following formula:

$$F_R = \tau_R / r, \quad (3.1)$$

where τ_R is the torque of the PRM, and r is the radius of cable storage. The torque can be determined by application requirements detailed in Chapter 4.

The second stage of the PRM is called a locking stage, which can limit the length of the cable. Ideally, in this stage, the cable-pulling force becomes zero, and other elements cannot increase the cable length, as presented in Figure 3.7 (a). The cable can be tight if other elements pull the cable and slack if other elements push the cable, as shown in Figure 3.7 (b).

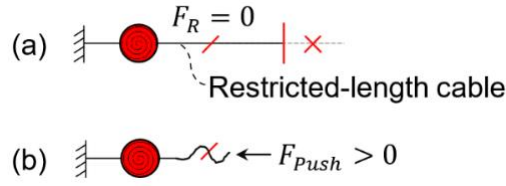


Figure 3.7 The unlocking stage of the PRM: (a) locking stage (red circle) and (b) locking stage during applying a pushing force.

The locking and unlocking stages of the PRM can restrict and release cable lengths to produce different cable lengths and tensions, whereas other elements push or pull the PRM cable, resulting in the possibility of creating structural configurations for locomotion tasks. To understand further the fundamental motions of class 1 tensegrity robots, the basic structure, one SE and two PRM are used to describe how to change SE positions by defining locking and unlocking stages for the PRMs during adjusting the SE-slider lengths, as detailed in the following sections.

3.3.1 Single SE and Two PRMs for 3-DOF Structure

The fundamental straight movement of the end-effector using the proposed structural deformation method is introduced through a single SE and two-PRM structure, as presented in Figure 3.8. This system consists of one SE placed between two PRMs. The PRM-B cable tip is attached to the strut base tip, and the PRM-A cable tip is attached to the strut-slider tip. The other side of both PRM-A and PRM-B is fixed on the ground. Therefore, the SE can move along the X-axis between the PRM-A and PRM-B.

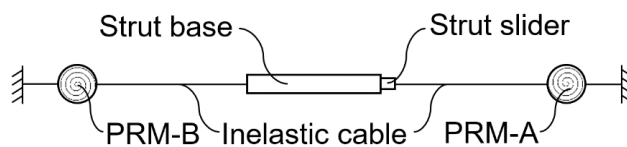


Figure 3.8 The single SE and two PRMs structure (top view).

The minimum number of the PRM and SE that can control a strut base moving in a straight path is investigated. Figure 3.9 (a) presents the initial position of the SE (ST_{ini}), which lies in the middle of the structure. In this analysis, the black dot is the centre of the strut base and represents the end-effector of the structure. For the end-effector direction, moving to the left is the negative direction, whereas moving to the right is the positive direction. In this stage, both PRM-A and PRM-B generate cable-pulling forces (F_{RA} and F_{RB}) against one another to maintain the SE in the middle position.

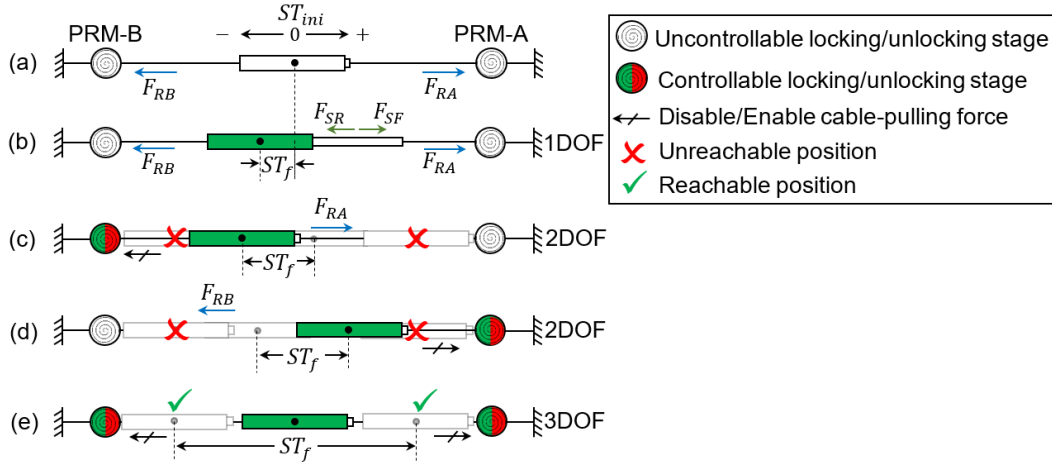


Figure 3.9 The end-effector movement capability of 1-DOF, 2-DOF and 3-DOF system: (a) initial stage, (b) 1-DOF system, (c) 2-DOF system with PRM-B controllable, (d) 2-DOF system with PRM-A controllable and 3-DOF system.

For the 1-DOF structure (see Figure 3.9 (b)), if the SE exerts forward force (F_{SF}) and reverse force (F_{SR}) in the structure, the PRM-A and PRM-B are set as the unlocking stage by default. This configuration cannot control the end-effector position (ST_f) because the cable-pulling forces of both PRM-A and PRM-B pull the SE against one another, even when SE length is extended or retracted.

For the 2-DOF structure (see Figure 3.9 (c)), the position control of the end-effector has a number of limitations. Although the PRM-B is set to lock and unlock cable length to move the end-effector in both positive and negative directions, the end-effector cannot be moved to the minimum and maximum positions (see the red cross-shaped signs). This inability is because the cable-pulling force of the PRM-A is constantly pulling the strut slider while changing the strut-slider length. Similarly, if the PRM-A is set as controllable and PRM-B is set as not controllable, the end-effector can be moved with a displacement limitation.

For the 3-DOF structure present in Figure 3.9 (e), the end-effector can be moved between the maximum and minimum position between the PRM-A and PRM-B because the cable-pulling force and locking force of the PRM-A and PRM-B can

be enabled and disabled while changing SE lengths to push and drag the end-effector positions to the left and right.

Fundamentally, the end-effector position can be moved to the left and right by applying two stages per one movement cycle, namely the extension and retraction stages. The left- and right-motion patterns are described in Algorithm 1 and Algorithm 2, respectively.

Algorithm 1: LEFT-MOTION PATTERN

Input: Motion step and End-effector position

Output: PRM-A, PRM-B, Output motion step and SE-slider target length

```

1  Position error  $\leftarrow$  Calculate the position error of the end-effector.
2  if Position error  $\neq 0$ 
3      if Motion step = 0 then // Initial stage
4          PRM-A, PRM-B  $\leftarrow$  Apply unlocking stage.
5          SE-slider target length = 0  $\leftarrow$  Apply initial length for the SE-slider.
6      else if Motion step = 1 then // Extension stage
7          PRM-A  $\leftarrow$  Apply locking stage to restrict PRM-A cable length.
8          PRM-B  $\leftarrow$  Apply unlocking stage to allow PRM-B cable adjustable.
9          SE-slider target length =  $S_{TF}$   $\leftarrow$  Apply calculated target length to the SE-
              slider to produce forward force(  $F_{SF}$ ) and then move the
              end-effector to the left side ( $S_{TF}$ ), see Figure 3.10 (step 1).
10     else if Motion step = 2 then //Retraction stage
11         PRM-A  $\leftarrow$  Apply unlocking stage to allow PRM-A cable adjustable.
12         PRM-B  $\leftarrow$  Apply locking stage to restrict PRM-B cable length.
13         SE-slider target length = 0  $\leftarrow$  Apply 0mm target length for the SE-slider
              to spool the PRM-A cable with the reverse force ( $F_{SR}$ )
              that is higher than the cable-pulling force of the
              PRM-A ( $F_{RA}$ ), see Figure 3.10 (step 2). This step
              for next movement cycles.
14     end if
15     Motion step++ // Increase motion step after finishing the extension or retraction
              stages.
16     if Motion step > 2 then // If the current stage is the retraction stage, then
17         Motion step = 1 // Set the next step as extension stage.
18     end if
19 end if

```

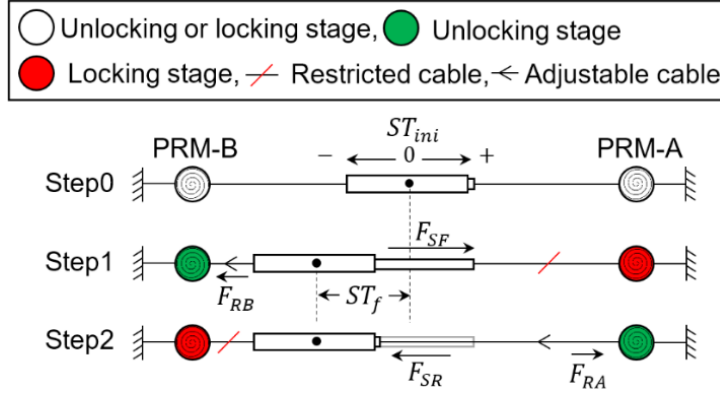


Figure 3.10 The left-motion behaviour per movement cycle.

Algorithm 2: RIGHT-MOTION PATTERN

Input: Motion step and End-effector position

Output: PRM-A, PRM-B, Output motion step and SE-slider target length

```

1  Position error ← Calculate the position error of the end-effector.
2  if Position error != 0
3      if Motion step = 0 then // Initial stage
4          PRM-A, PRM-B ← Apply unlocking stage.
5          SE-slider target length = 0 ← Apply initial length for the SE-slider.
6      else if Motion step = 1 then // Extension stage
7          PRM-A ← Apply unlocking stage to allow PRM-A cable adjustable.
8          PRM-B ← Apply locking stage to strict PRM-B cable length.
9          SE-slider target length =  $F_{SF}$  ← Apply calculated target length to the SE-slider
              to produce forward force(  $F_{SF}$ ), see Figure 3.11 (step 1) and then
              provide free lengths for dragging the end-effector in the
              next step. The end-effector is still in the same position.
10     else if Motion step = 2 then //Retraction stage
11         PRM-A ← Apply locking stage to restrict PRM-A cable length.
12         PRM-B ← Apply unlocking stage to allow PRM-B cable adjustable.
13         SE-slider target length = 0 ← Apply 0mm target length for the SE-slider
              to drag the end-effector to the right side(  $ST_F$  ). In this step, force
              the reverse force(  $F_{SR}$ ) is higher than the cable-pulling force
              of the PRM-B(  $F_{RB}$ ), see Figure 3.11 (step 2).
14     end if
15     Motion step++ // Increase motion step
16     if Motion step > 2 then // If the current stage is the retraction stage, then
17         Motion step = 1 // Set the next step as the extension stage.

```

18 | **end if**
 19 **end if**

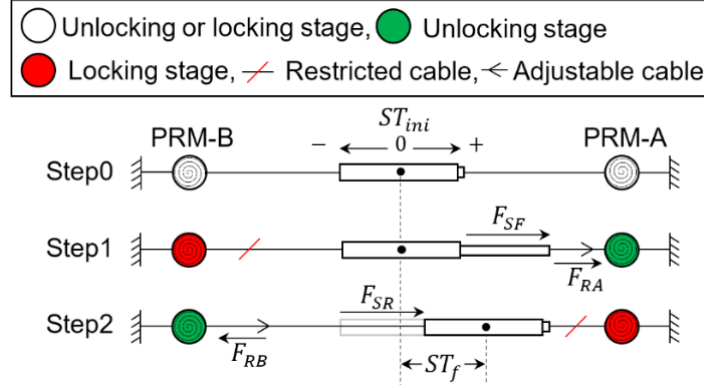


Figure 3.11 The right-motion behaviour per cycle.

Based on the structure motion analysis, the position control of the end-effector is unique because it cannot be moved by adjusting two cables directly in the same way as a cable-direct-driven structure. In contrast, the proposed structure has only one active actuator to exert two directional forces by extending and retracting the strut-slider length to generate a push force (F_{SF}) and pull force (F_{SR}). These forces control the end-effector positions travelling to the left and right-hand sides by cooperating with cable-pulling forces and locking forces of the PRM-A and PRM-B. Therefore, the locking and unlocking procedures of the PRM-A and PRM-B and the extending/retracting of the strut-slider length must be designed to move the end-effector to desired positions. This strut-slider length in each movement cycle relates to the travelling time from a starting point to the target point. The longer strut-slider length is applied, the less travelling time is achieved.

In order to control the end-effector position, the forward kinematic equations of the end-effector need to be determined. Figure 3.12 presents the kinematic diagram of the 3-DOF structure. Due to the PRM-B cable attaching directly to the end-effector, the end-effector position can be calculated by the change in PRM-B cable length (ΔL_B) and the end-effector initial position (ST_{ini}), as computed in the following equations:

$$ST_f = ST_{ini} + \Delta L_B \quad (3.2)$$

and

$$ST_f = ST_{ini} + (L_{B_{ini}} - L_{B_f}), \quad (3.3)$$

where ST_f is the end-effector position, $L_{B_{ini}}$ is the initial length of the PRM-B cable and L_{B_f} is the current length of the PRM-B cable.

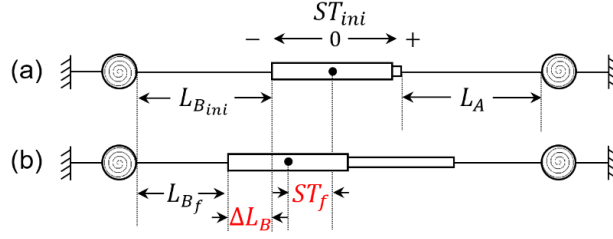


Figure 3.12 Kinematic diagram of the 3-DOF structure: (a) the initial position of the end-effector and (b) the end-effector movement.

The kinematic equations of the end-effector position are used to calculate the current position of the end-effector for closed-loop control, which will be demonstrated and evaluated both kinematic equations and control performance in Chapter 6.

For the fundamental movement of the end-effector travelling on the straight line through the proposed 3-DOF structure, the minimum number of the SE and PRM, which are able to control the end-effector position moving to the left and right, is one SE and two PRMs. Furthermore, the cable length of all PRM and strut-slider lengths should be measured physically by sensors in order calculate the end-effector position via kinematic equations.

Aside from the straight motion of the end-effector, an angular motion is required for general robot ability to achieve locomotion tasks. Therefore, another structural configuration analysis describes how the proposed structural deformation method may be used to control the end-effector angle in the 3-DOF structure.

The triangular shape of the 3-DOF structure is adopted to analyse the rotational motion of the SE when applying the locking and unlocking stage of the PRM cables while adjusting SE-slider length. The triangular structure is illustrated in Figure 3.13; it consists of one SE able to exert force in two directions (F_{P1} and F_{P2}) and two PRMs able to exert cable-pulling forces (F_{CP}) passively in one direction and restrictive force by locking a cable with a braking mechanism. These components are connected with inelastic cables to form the tensegrity structure.

For this investigation, one end side of the SEs and PRMs is placed on fixed points in the X and Y plane, and the SE can be extended to the left and right, depending on cable tensions generated in the locking and unlocking stages of the PRMs when changing SE length.

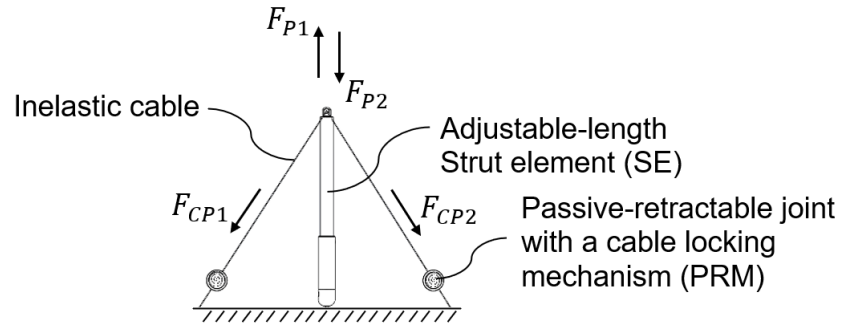


Figure 3.13 Basic concept of the proposed tensegrity structure.

In order to change the SE angle, the SE length and the cable-locking stage of the PRMs are controlled simultaneously. For example, to make the SE tend to the left (see Figure 3.14), the left PRM is locked to restrict cable length and disable the F_{CP1} , and the right PRM is unlocked to adjust cable length and enable the F_{CP2} . During the SE extending stage, the SE can produce F_{P1} to pull cables from the PRMs, and it tends to the left due to the high-tension cable caused by the locking stage. The SE can tend until the cable length on the right-hand side is locked, or the SE reaches maximum length. To return to the initial position, the SE length is retracted to the minimum length. The right cable is then reeled inside the PRM with the cable-pulling force (F_{CP2}).

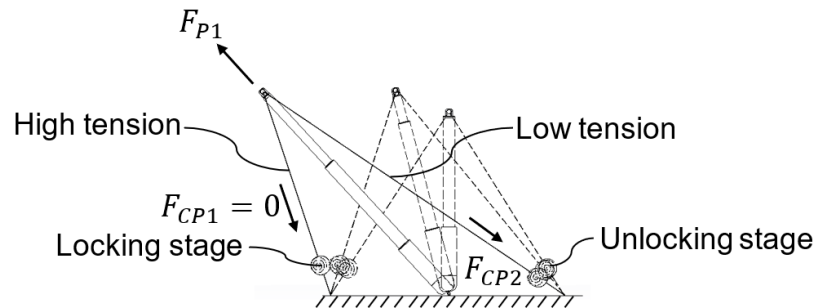


Figure 3.14 The structural configuration of the triangular structure.

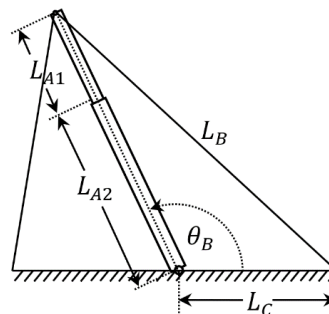


Figure 3.15 Kinematic diagram of the triangular structure.

Figure 3.15 presents the kinematic diagram of the SE angle. The kinematic equation of the SE angle (θ_B) can be derived simply using the Cosine rule, as shown in the following formula:

$$\theta_B = \cos^{-1} \left(\frac{(L_{A1} + L_{A2})^2 + L_C^2 - L_B^2}{2(L_{A1} + L_{A2})L_C} \right) \quad (3.4)$$

This equation can be used to calculate SE angle after substituting the cable length (L_B), the displacement between SE rotating joint and fixed point of the cable (L_C), and SE length ($L_{A1} + L_{A2}$) into the equation. However, this equation is accurate if the cable remains in tension and can be used to design a control rule for locking and unlocking the PRM cables, as demonstrated in Chapter 6.

Based on the structural configuration analysis of 3-DOF structures, the proposed structural deformation concept may be potentially used to generate straight and rotating motions of an end-effector beneficial for locomotion tasks. In addition, the locking and unlocking stage of the PRMs when changing the SE lengths can make the structure soft or hard by creating different cable tensions. For the rigid structure, the cable locking stage is applied to the left and right PRM while extending the SE lengths. The more that the SE length increases, the more cable tension increases, resulting in the structure becoming rigid. This rigid structure can be changed to the soft structure suddenly by applying the unlocking stage to either one side or both sides to reduce cable tensions. These soft and rigid structures provide compliant properties that enhance the capability of the robot to move in both structured and unstructured environments.

3.3.2 Single SE and Four PRMs for 5-DOF System

In order to investigate the ability to simultaneously control the positions and angles of the end-effector in the X and Y planar, a 5-DOF structure is presented and analysed. The 5-DOF structure consists of four PRMs (PRM-A, PRM-B, PRM-C, and PRM-D) and an adjustable-length SE. The SE is placed in the middle of the structure. The PRM-A and PRM-C are placed on the top-left and top-right sides of the LA. Table tips are connected at the top of the strut slider represented as P_2 position. Inelastic cables are used to connect two PRMs and the ground. On the bottom of the structure, PRM-B and PRM-D are placed on the bottom-left and bottom-right sides of the SE, and their cable tips are connected at the middle bottom of the strut base, represented as P_1 . The end-effector position of the structure is the middle point of the SE base, represented as P_3 (see red dot in Figure 3.16).

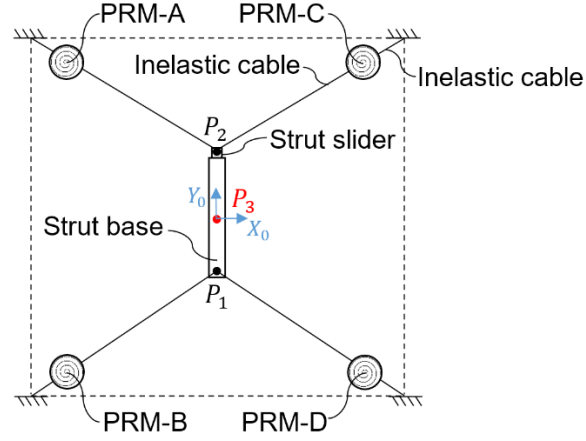


Figure 3.16 The 5-DOF structure planar.

The control of the end-effector positions is challenging because it cannot be achieved by directly actuating each cable length via inverse kinematic equations in the same way as the 4-cable cable-direct-driven robot (CDDR) [86]. In contrast, the 5-DOF structure has only one SE, namely an active-LA that generates dynamic force to manoeuvre the end-effector positions. The SE cooperates with four PRMs able to spool the cable passively via rotational mechanisms. These PRMs can also restrict cable length by locking rotational mechanisms. Therefore, before extending and retracting the SE-slider length, PRMs are first set as the locking or unlocking stage to restrict and release cable lengths to produce different cable tensions, resulting in the movements of the end-effector travelling to desired positions.

A. Workspace Analysis

The workspace of the end-effector depends on a number of parameters. Firstly, the cable-pulling forces of the PRMs define the workspace boundary of the end-effector. For example, for the top areas, if the end-effector target position is set above point P_0 and four PRM stages are set, based on Figure 3.17 (a), the end-effector position is moved downwards to point P_1 while extending the strut-slider length rather than moving upward. This dynamic exists because both cable-pulling forces (F_{RA} and F_{RC}) produce a pressing force (F_p) to press the strut-slider tip while extending the strut-slider length, resulting in the strut-base or the end-effector moving downwards. Similarly, at the bottom, if the end-effector target position is set as P_2 , four PRM locking and unlocking stages can be defined based on Figure 3.17 (b). Then, the strut slider is extended to move the end-effector to the target point. However, the end-effector cannot be moved to the target point due to the pressing force (F_p) generated by cable-pulling forces (F_{RB} and F_{RD}).

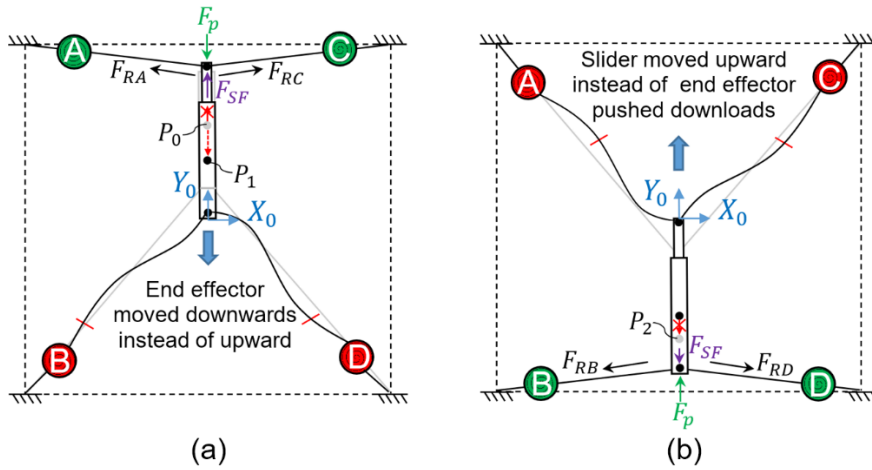


Figure 3.17 The end-effector movement limitations: (a) moving restriction upward and (b) moving restriction downwards.

Secondly, the PRM cable lengths affect the end-effector position and SE angle adjustment. For example, if the end-effector is moved close to the edge of the structure at the point P_1 (see in Figure 3.18) and the PRM-B cable length already reaches the maximum length (L_{Bmax}), the end-effector cannot be moved to the point P_2 . It is because the PRM-B cable restricts the strut-base-tip motion along the circular path of the locked cable of the PRM-D. In contrast, if the end-effector target is defined at the point P_3 , the end-effector can be moved from the point P_1 to the target point by applying the locking and unlocking stages of all PRMs and then retracting the strut-slider length. It is because the SE angle can be changed suitably and possibly.

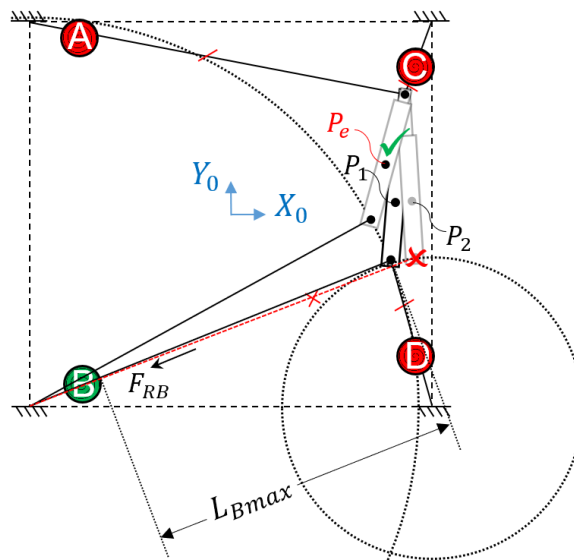


Figure 3.18 The strut-element angle adjustment restriction due to the PRM cable limitation.

From the example of the end-effector movement and the SE angle adjustment restriction, the workspace of the end-effector for the 5-DOF can be analysed, as illustrated in Figure 3.19 (blue area).

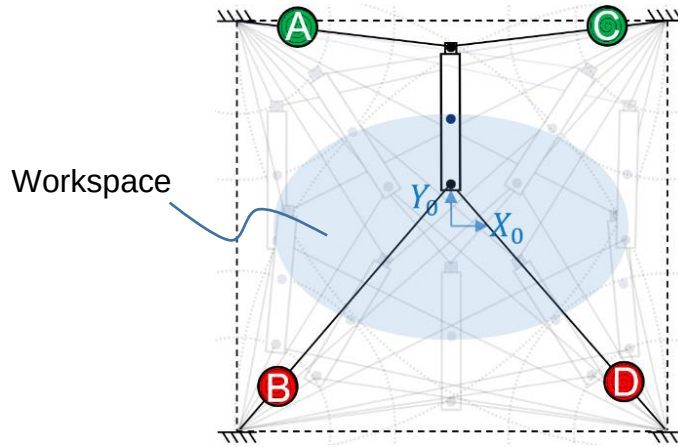


Figure 3.19 Workspace analysis of the end-effector positions. The end-effector (middle black dot of the SE base) could be moved in the light blue area.

B. End-Effector Motion Analysis

The movement of the end-effector to achieve target positions is unique. In the 5DOF structure, the concept of the end-effector motion is divided into two phases. The first phase involves finding the locking and unlocking stages of four PRMs by considering the cable-pulling forces generated by each PRM, interacting with two tips of the SE. These cable-pulling forces may be enabled and disabled by applying the unlocking and locking stages of the PRM, respectively. The unlocking and locking stages are defined, depending on the two tips of the SE directions able to move the end-effector close to a target point. After observing the cable-pulling forces of the 3-DOF structure, these forces will be enabled when the SE tip is moved to the desired directions. However, PRM alone will not be able to control the end-effector position. The push and pull forces of the SE must be applied to all PRMs by extending and retracting SE lengths, which is the second phase.

The second phase involves determining to what extent SE-slider length should be extended. This phase can be achieved using the different displacement between a target point and a current point of a displacement error. The first and second phases will be used to design control rules to enable and disable the cable-pulling force of the PRMs and calculate SE-slider length to control the end-effector positions, as detailed in Chapter 6.

However, to understand how the proposed actuation method may be used to control the end-effector position of the 5DOF structure, this sub-section describes

the movements of the end-effector caused by applying the locking and unlocking stage of four PRMs before changing SE-slider lengths. In this structure, the end-effector can be moved in straight and zigzag paths, depending on target points (d_{ref}). The straight path is used if the end-effector can move to the target point in one motion cycle, including extension and retraction stages of the SE-slider length, such as if the end-effector target point (d_{ref}) is defined at the red dot, as indicated in Figure 3.20.

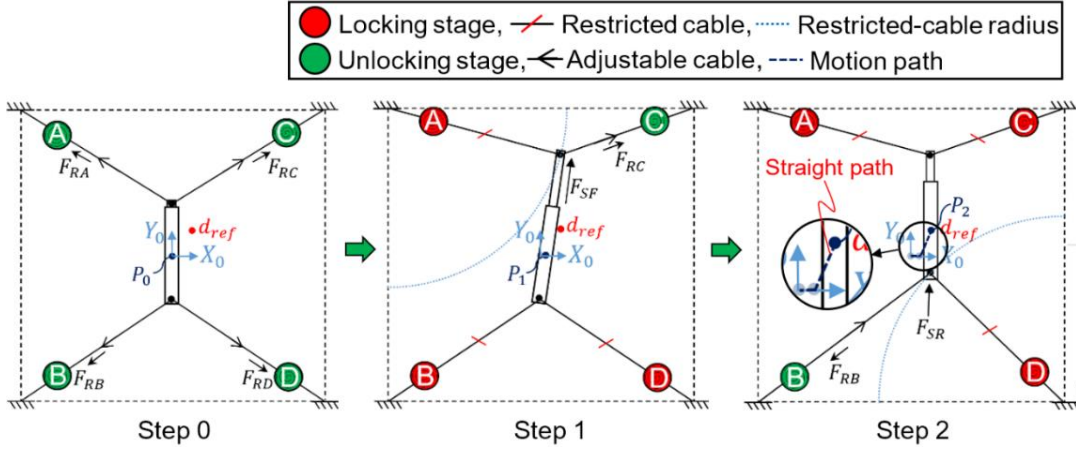


Figure 3.20 The end-effector straight path motion: the blue-curve line is the motion path of the PRM cable that is restricted by the locking stage. The four corners of the structure are defined as the centre of each curve path.

In **step0**, the end-effector is placed in the middle of the structure, which is the initial stage in which PRMs are defined as the unlocking stage to enable four cable-pulling forces (F_{RA} , F_{RB} , F_{RC} and F_{RD}) to maintain the end-effector position. The target point (d_{ref}), indicated by the red dot, is on the upper-right side of the initial position (P_0).

Step1 is the extension stage of the first motion cycle and begins with the first phase, in which the cable-pulling force (F_{RC}) of the PRM-C is only enabled to pull the SE-slider tip because it is an appropriate method to move the end-effector close to the target point. However, the end-effector does not move. Therefore, the second phase must be completed by fully extending the SE-slider length to exert forward force (F_{SF}), resulting in the movement of the SE-slider tip along PRM-A restricted-cable radius, which is pulled by the cable-pulling force (F_{RC}), as shown in Figure 3.20 (step1). In this step, the end-effector can move slightly following the SE-slider tip.

Step2 is the retraction stage of the first motion cycle. The first phase involves enabling only cable-pulling force of the PRM-B (F_{RB}) to allow the cable to adjust. The second phase involves retracting the SE-slider length to produce the reverse force (F_{SR}) to drag the SE-base tip to move up to the right along the restricted-

cable radius of the PRM-D until the end-effector reaches the target point, as shown in Figure 3.20 (step2).

For the zigzag motion path, if the end-effector does not reach the target point within one motion cycle, other motion cycles must be performed to move the end-effector to a target point. This zigzag motion behaviour mostly occurs in the proposed 5-DOF structure. For example, if the target point (d_{ref}) is defined as the red dot, as shown in Figure 3.21 (Step 0), the end-effector can be moved to the target position within five-step motions.

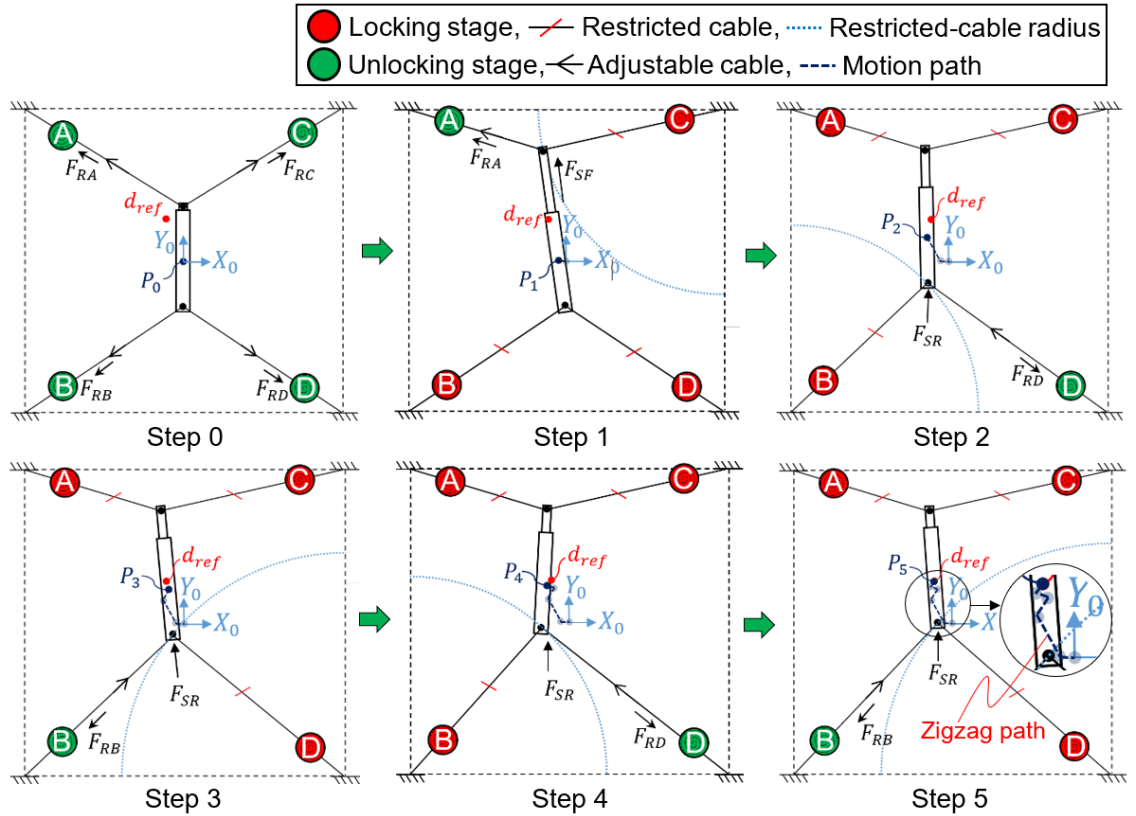


Figure 3.21 Movement analysis example for the zigzag motion behaviour to control the end-effector position; (Step 0) initial position, (Step 1-2) first movement cycle, (Step 3-4) second movement cycle and (Step 5) a half of third movement cycle.

Step0 is the initial step in which all PRMs are defined as being in the unlocking stage to enable all cable-pulling forces to maintain the end-effector, standing in the middle of the structure.

In **step1**, due to the target point being above the initial position, the first phase of the first motion cycle involves enabling the cable-pulling force of the PRM-A (F_{RA}) to pull the slider tip upward. The second phase then involves extending the SE-slider length to exert forward force (F_{SF}). Thus, the slider tip is dragged to the left along the restricted-cable radius of the PRM-C, following the cable-pulling force (F_{RA}), and the end-effector is moved to P_1 due to the change in strut-base angle.

In **step 2**, the first phase involves enabling PRM-D by applying the unlocking stage to allow the PRM-D cable to adjust. The second phase then involves retracting the SE-slider length to produce a reverse force (F_{SR}) to drag the SE-base upward along the restricted-cable radius of the PRM-B, resulting in the end-effector moving upward to the point P2, as shown in Figure 3.21 (step2). In this step, the end-effector cannot move to the target point due to the PRM-B cable length restriction.

Therefore, in **step3**, the first phase involves enabling the cable-pulling force of the PRM-B (F_{RB}) by applying the unlocking stage to allow the end-effector to move up and get closer to the target point. For the second phase, it may be observed that the strut-slider still has an available stroke length. Therefore, the strut slider continues to pull back its length to drag the SE-base tip along the restricted-cable radius of the PRM-D to move the end-effector close to point P_3 , as shown in Figure 3.21 (step3). However, the current end-effector position is on the right and still below the target position.

Step4 involves moving the end-effector up to the left direction. Thus, the first phase is enabling the cable-pulling force of the PRM-D (F_{RD}) by applying the unlocking stage and locking the rest PRM cables. The second phase is retracting the strut-slider length to drag the SE-base tip along the restricted-cable radius of the PRM-B to move the end-effector position to the point P_4 , as shown in Figure 3.21 (step4).

In **step5**, the end-effector is moved to the target position, which can be achieved by applying the unlocking stage for the PRM-B in the first phase. The second phase is then retracting the SE-slider continuously to drag the SE-base tip along the PRM-D cable radius. Eventually, the end-effector is moved to P_5 with the zigzag path, as shown in Figure 3.21 (step5).

From the above end-effector motion analysis, the end-effector position is only considered, meaning that the SE angle is neglected. Therefore, to analyse further end-effector motion, the rotational motions of the end-effector are investigated in terms of how they are beneficial in controlling the strut angle in a robot structure in order to twist or turn the structure, moving in different directions.

The SE angle (θ_l) is considered for the design of the first and second phases. The locking and unlocking stages of all PRMs directly relate to the SE angle of the same value as the end-effector angle, which can rotate clockwise (CW) and counter clockwise (CCW). The motion analysis of the end-effector moving to the target point and target angle (θ_{ln}), n is the number of target angles.

Figure 3.22 presents the motion analysis of the SE rotation in the CW direction. Two target angles (θ_{l1} and θ_{l2}) are defined for this analysis.

Step0 is the initial position of the SE angle and end-effector position. The reference point to measure the SE angle is at the strut-base tip, where the PRM-B and PRM-D cable are connected. The CW rotation is assigned a positive value, whereas the CCW rotation is assigned a negative value.

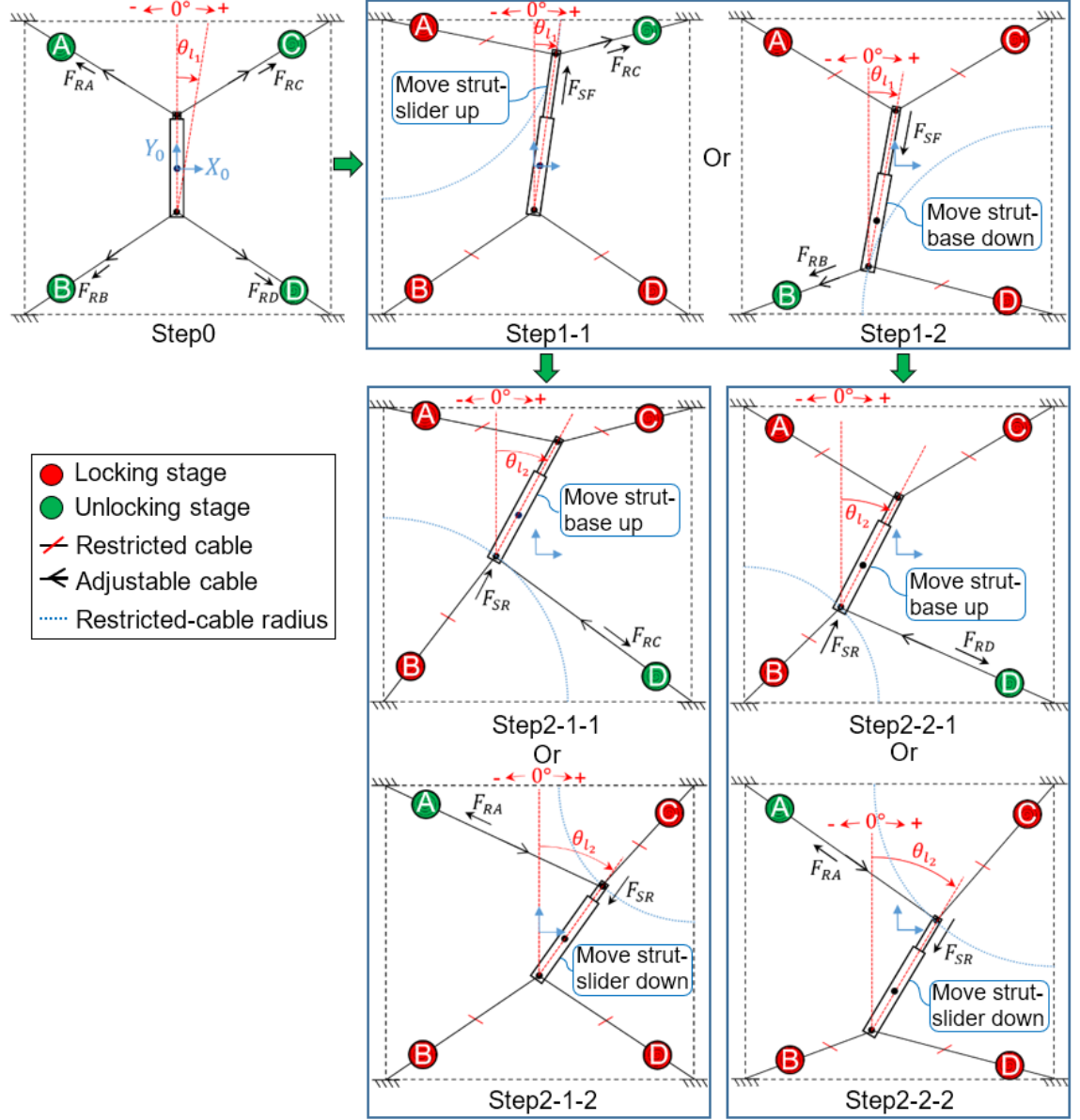


Figure 3.22 Strut element angle adjustments for CW rotation.

In order to rotate the SE clockwise to the target angle (θ_{l1}), the movement behaviours of the SE can be divided into two conditions depending on target positions. In the first condition (**step1-1**), if the end-effector target position is defined on the right of the current position, the first phase involves applying the locking and unlocking stages for the PRMs, following step1-1, where the second phase is applied by fully extending the SE-slider length. Following this phase, the SE-slider tip is pulled by the PRM-C cable-pulling force (F_{RC}), resulting in the SE angle rotating to the target angle (θ_{l1}). For the second condition (**step1-2**), if the

end-effector target position is defined below the current position, the first phase involves applying the locking and unlocking stages of the PRMs following step1-2, where the strut-base is moved downward along the restricted-cable radius of the PRM-D, whereas the second phase is to extend the SE-slider lengths. Finally, the SE can be rotated in the CW direction to reach the target angle (θ_{l1}).

If the target angle changes to θ_{l2} , the SE angle can be rotated by two movement conditions. The first condition (**step2-1-1**) occurs when the end-effector target position is above the current position. The first phase is applying the locking and unlocking stages of the PRMs following step2-1-1, and the second phase is retracting the SE-slider length to move the end-effector upward. The SE angle can then be rotated to the target angle (θ_{l2}). The second condition (**step2-1-2**) occurs when the end-effector target point is below the current position. The first phase is applying the locking and unlocking stages of the PRMs following the step2-1-2 while applying the retraction stage of the SE-slider in the second phase to pull the SE-slider tip to tend the end-effector to the target angle (θ_{l2}). These angular adjustment processes can be employed in step2-2-1 and 2-2-2 in order to change the SE angle and the end-effector position to the target point, simultaneously.

Figure 3.23 presents the motion analysis of the SE rotation in the CCW direction. The movement behaviours to change the SE angle consist of two conditions depend on the current and target position of the end-effector in the same way as the CW rotational motions.

For the first condition (**step1-1**), if the target angle is defined as θ_{l3} and the target position is above the current position, the first phase is applying the locking and unlocking stages of four PRMs following step1-1; extending the SE-slider tip is the second phase. In this step, the end-effector is rotated CCW to reach the target angle (θ_{l3}).

For the second condition (**step1-2**), if the end-effector target position is below the current position, the SE-base should be moved downward by applying locking and unlocking stages for the PRMs, following step 1-2 in the first phase and then extending the SE-slider length to push the SE-base downwards and tend CCW, reaching the target angle, as presented in Figure 3.23(step1-2).

The CCW angle can be increased up to the maximum angle (θ_{l4}), and there are two conditions for step1-1 and 1-2 to increase the SE angle reaching a maximum angle.

The first condition (**step2-1-1**) occurs when the end-effector target position is above the current position. In this step, the first phase is applying the locking and

unlocking stages for all PRMs following step2-1-1 while retracting the SE-slider length, resulting in the SE-base tip moving upwards to tend the SE angle to θ_{l_4} .

For the second condition (**step2-1-2**), if the end-effector target position is below the current position, the first phase is applying the locking and unlocking stages for all PRMs following step2-1-2 before retracting the SE-slider length in the second phase in order to tend the SE-angle to θ_{l_4} . These angular motion conditions can be used for step2-2-1 and step2-2-2 to adjust the SE angle to desired degrees and move the end-effector to target positions.

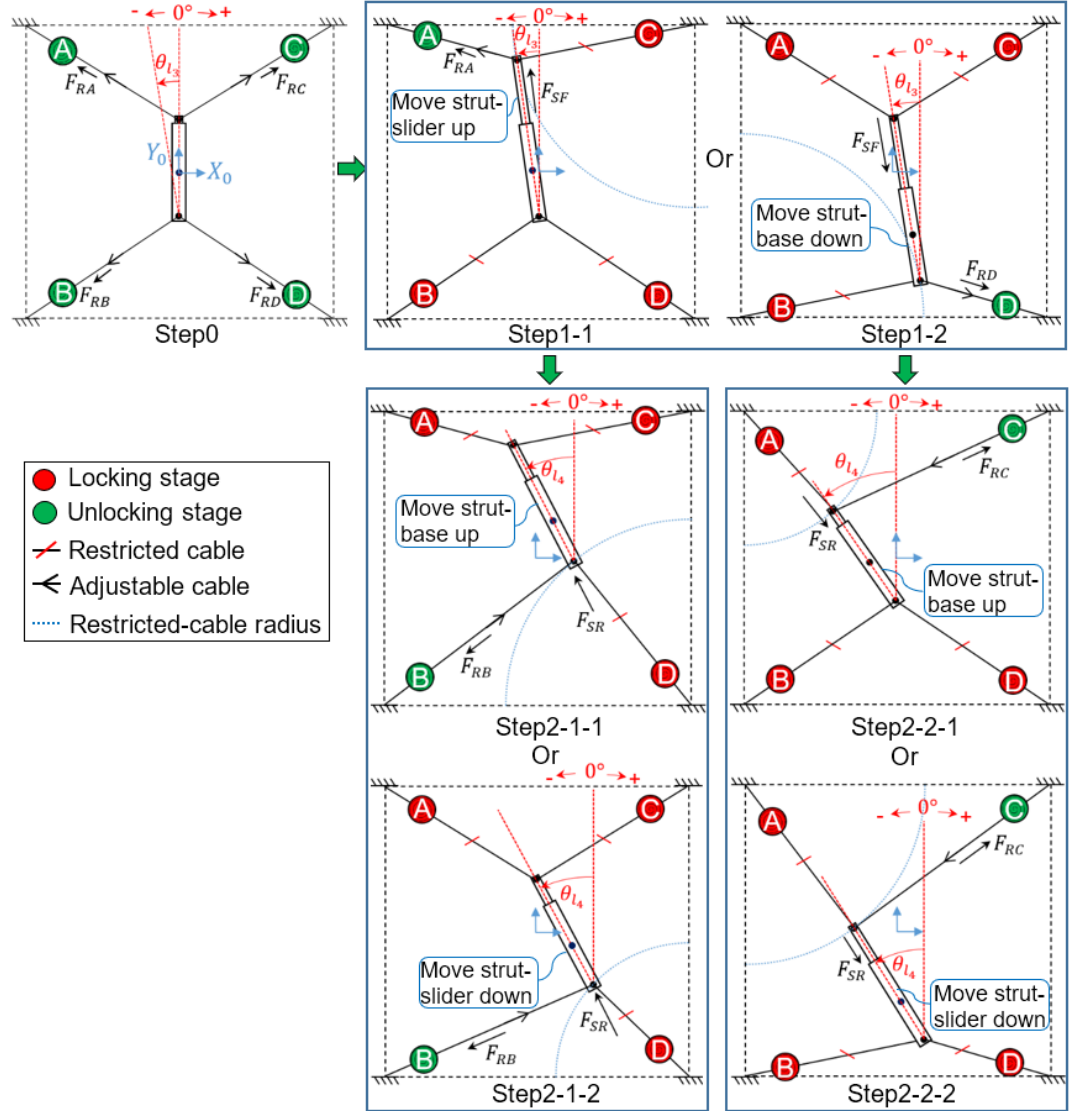


Figure 3.23 The SE angle adjustments for CCW rotation.

These structural analyses reveal the basic motion concept of the SE and end-effector position and angle by applying the locking and unlocking stages for the PRM-A, PRM-B, PRM-C, and PRM-D in the first phase and changing the SE-slider length in the second phase. The target and current positions of the end-effector are important; they are used to design the control rules for the locking and unlocking stages for PRMs before changing strut-slider length. The change

in length of the strut slider is the key factor of the movement characteristics of the end-effector. If the change in length is short, the end-effector can be moved smoothly; however, the moving time will be longer. If the change in length of the SE-slider is long, the end-effector motion will be unsmooth, causing zigzag motion; however, the end-effector can be moved faster to reach a target point.

C. Kinematic Analysis of 5-DOF Structure

To identify the end-effector position, the forward kinematic of the end-effector position is derived. To simplify the cable length definition of the structure, the PRM body and cables are assumed to be a straight line and always remain in tension. The reference frame (X_0, Y_0) is shifted to the bottom-left point of the frame. The length of each cable is denoted as L_i and the cable angle is θ_i ($i = A, B, C$ and D). The kinematics diagram of the 5-DOF structure is illustrated in Figure 3.24.

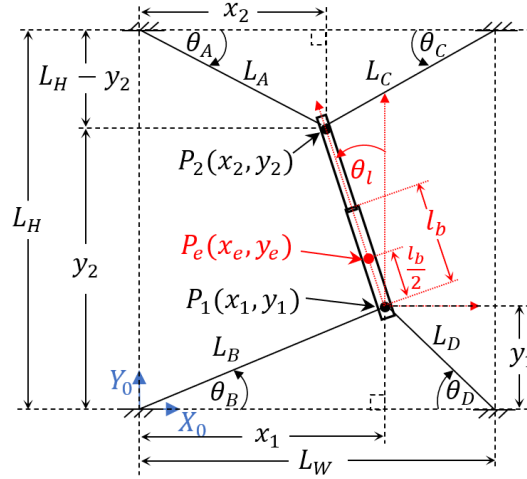


Figure 3.24 The 5DOF kinematics diagram.

In order to calculate P_e from cable length L_A, L_B, L_C , and L_D , the strut-base-bottom position (P_1) can be calculated using the cosine rule of the trigonometry function. Thus, to calculate the P_1 , the angle θ_B is as follows:

$$\theta_B = \cos^{-1} \frac{L_W^2 + L_B^2 - L_D^2}{2L_W L_B}. \quad (3.5)$$

Then, using the right-angle rule, the $P_1(x_1, y_1)$ can be given as follows:

$$x_1 = L_B \cos \theta_B \quad (3.6)$$

and

$$y_1 = L_B \sin \theta_B. \quad (3.7)$$

To calculate the P_2 , the θ_A is as follows:

$$\theta_A = \cos^{-1} \frac{L_A^2 + L_W^2 - L_C^2}{2L_A L_W}. \quad (3.8)$$

Thus, the $P_2(x_2, y_2)$ can be given as follows:

$$x_2 = L_A \cos \theta_A \quad (3.9)$$

and

$$y_2 = L_H - (L_A \sin \theta_A). \quad (3.10)$$

However, the end-effector point $P_e(x_e, y_e)$ does not connect to the P_1 and the strut-slider tip (P_2) directly; it is at the middle length of the strut-base length (l_b) and relates to the strut-base angle (θ_l) which subjects to the Y-axis, as presented in Figure 3.25.

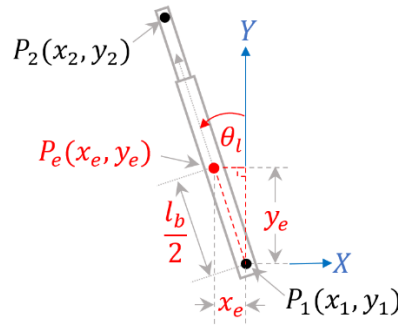


Figure 3.25 Kinematic diagram of the strut-base.

Therefore, the strut-base angle can be computed by using the right-angle rule between P_2 and P_1 .

$$\theta_l = \tan^{-1} \left(\frac{x_2 - x_1}{y_2 - y_1} \right) \quad (3.11)$$

The $P_e(x_e, y_e)$ also relates to the P_1 ; therefore, the x_e and y_e can be given as follows:

$$x_e = \frac{l_b}{2} \sin \theta_l + x_1 \quad (3.12)$$

and

$$y_e = \frac{l_b}{2} \cos \theta_l + y_1. \quad (3.13)$$

both x_e and y_e can be used to identify end-effector positions sending to a control module for a closed-loop control system in the 5-DOF structure. However, due to the origin (zero position) of the structure is in the middle, X and Y positions can be negative (-) and positive (+) values which may cause a computation error. To avoid this issue, angle and distance parameters are used instead because it has only position value to define target positions such as (45°, 40mm) or (225°, 60mm). For this reason, both x_e and y_e are converted to the end-effector angle (θ_f) and end-effector distance (d_f) measured between origin and target points.

To achieve the coordinate transformation, the right-angle rule of the trigonometry function is used to convert x_e and y_e to θ_f and d_f . In this case, the reference frame is returned to the centre of the structure, where θ_f and d_f are identical to zero, as presented in Figure 3.26.

In this new frame, the positions of the end-effector can be divided into four sectors: (x_{e1}, y_{e1}) ; $(-x_{e2}, y_{e2})$; $(-x_{e3}, -y_{e3})$; and $(x_{e4}, -y_{e4})$. These sectors are employed to identify the signs of the X and Y position to calculate the end-effector angle (θ_f) and the end-effector distance (d_f), as described in Equations (3.14) and (3.15), respectively.

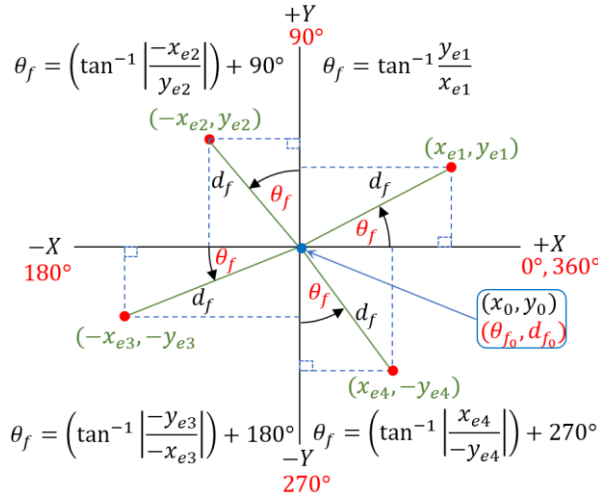


Figure 3.26 New reference frame of the structure, including end-effector angle (θ_f) and distance (d_f).

$$f(\theta_f) = \begin{cases} \tan^{-1} \frac{y_{e1}}{x_{e1}}, & \text{if } x_{e1} \geq 0 \text{ and } y_{e1} \geq 0 \\ \left(\tan^{-1} \left| \frac{-x_{e2}}{y_{e2}} \right| \right) + 90^\circ, & \text{if } x_{e2} < 0 \text{ and } y_{e2} > 0 \\ \left(\tan^{-1} \left| \frac{-y_{e3}}{-x_{e3}} \right| \right) + 180^\circ, & \text{if } x_{e3} < 0 \text{ and } y_{e3} < 0 \\ \left(\tan^{-1} \left| \frac{x_{e4}}{-y_{e4}} \right| \right) + 270^\circ, & \text{if } x_{e4} > 0 \text{ and } y_{e4} < 0 \end{cases} \quad (3.14)$$

$$f(d_f) = \begin{cases} \sqrt{x_{e1}^2 + y_{e1}^2}, & \text{if } x_{e1} \geq 0 \text{ and } y_{e1} \geq 0 \\ \sqrt{x_{e2}^2 + y_{e2}^2}, & \text{if } x_{e2} < 0 \text{ and } y_{e2} > 0 \\ \sqrt{x_{e3}^2 + y_{e3}^2}, & \text{if } x_{e3} < 0 \text{ and } y_{e3} < 0 \\ \sqrt{x_{e4}^2 + y_{e4}^2}, & \text{if } x_{e4} > 0 \text{ and } y_{e4} < 0 \end{cases} \quad (3.15)$$

The end-effector angle and distance kinematic equations are utilised to compute the end-effector position using PRM cable lengths (L_A, L_B, L_C, L_D), strut-slider-base length (l_b), and structure dimensions (L_H and L_W). This current position data is sent to a closed-loop position control system to control the end-effector position and angle.

The inverse kinematic problem in this structure may not be appropriate for controlling the end-effector position and angle because that the cable length control of the proposed structure has a unique character due to the PRM properties, in which the cable length of each PRM directly relies on the cable locking and unlocking stages during adjusting the strut-slider length. This system is not driven directly using an active rotary actuator in the same way as a cable-direct-driven robot (CDDR) structure. Therefore, in this project, the forward kinematic equation is only used to design control rules for the PRM locking/unlocking stage procedure while adjusting the strut-slider length to identify the end-effector positions sending to control rules to produce PRM locking and unlocking stage procedures that are described in Chapter 6.

3.4 Summary

This chapter presented the capabilities of the new structural deformation concept, which control the strut-element positions by restricting and releasing the cable length of PRMs to generate different cable tensions while changing strut-slider lengths. 3-DOF and 5-DOF structures were studied to demonstrate the fundamental movements of the end-effectors, including straight and zigzag motion behaviours. The unlocking and locking procedures of the PRMs during changing strut-slider lengths defined the movement characteristics of the end-effector. The change in strut-slider length per movement cycle also relates to the smoothness of the motion path. The shorter the change in strut-slider length is shorter, the greater the smoothness of the motion path that can be achieved.

Although the end-effector movement of the proposed 5-DOF structure may not be smooth in the same way as the 4-cable CDDR driven by four active actuators, the proposed actuation method may be that it requires less power usage for structural configurations to move end-effector positions. It is because that the proposed actuation method requires constantly power for only one active actuator to exert force and may require short-term power for four PRMs to restrict and release cable lengths for structural configurations and move end-effector positions, as demonstrated and evaluated in Chapter 6.

The analysis of the structural configurations suggest that the end-effector could move to target points by applying the locking and unlocking stages of the PRMs before changing SE-slider length. However, instead of using software simulation to simulate end-effector dynamic motions, the physical hardware of the SE and PRM are tested and evaluated, as described in a power spring design and selection section in Chapter 4. Chapter 4 also details the development and implementation of SE and PRM based on the structural deformation concept.

Chapter 4 Individual Element Design and Implementations

This chapter details the mechatronic designs of individual elements employed in constructing a reconfigurable tensegrity robot using the proposed structural deformation method. The individual elements consist of strut elements (SEs) able to change their length and tensile elements that are passive-retractable joint with a cable locking mechanism (PRM). The property requirements for the SE and PRM regarding required forces are also analysed in this chapter. Following this analysis, the physical prototypes of the SE and PRM are designed, manufactured, and assembled. Finally, the design and development of electronic control boards for the individual elements and other interface boards are described.

4.1 Individual Element Requirements

To achieve the proposed structural deformation method for locomotion tasks, the SE and PRM should be designed appropriately, considering individual element requirements analysed in the following sub-sections.

4.1.1 Strut Element

In the case of the crawling and climbing locomotion based on the wall-pressing method focused on in this project, SE length must be changeable and exert sufficient force against a wall or environmental surfaces to maintain its position. Furthermore, the pull force of the SE should be enough to drag and push other modules forward, upward, and turning to produce inch-worm motion behaviour.

To meet these requirements, the SE should change its length by extending and retracting the SE slider to exert force in one degree of freedom to generate push and pull forces to deform the structure for locomotion. In order to achieve these required properties, a lightweight prismatic actuator or linear actuator (LA) offering high-thrust forces is required.

The force generated by the LA should be high enough to ensure that the robot can drive itself through an environment, maintaining its position and overcoming external forces exerted on it, such as fluid flow and airflow.

The highest force would be a holding stage, where the SE feet, or end caps, press on a wall to maintain their position. In this stage, it is anticipated that the maximum force occurs when the robot maintains its position along the vertical direction against gravity. The total force is distributed equally amongst two contact points,

which are the minimum contact points at which the robot can hold its body in a vertical direction where the SE is perpendicular to the walls. A diagram of the forces acting on one of the two contact points is presented in Figure 4.1.

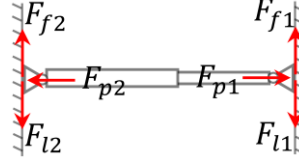


Figure 4.1 Diagram of the forces acting at contact points when the SE is perpendicular to the walls.

In the holding stage, the friction force (F_{fn}) of both end caps should be higher than the loading force (F_{ln}) for $n = 1$ and 2. Otherwise, the end caps would slip and fall off. To overcome this problem, two constraints are imposed by the following conditions:

$$F_{f1} \geq F_{l1} \quad (4.1)$$

and

$$F_{f2} \geq F_{l2}. \quad (4.2)$$

Friction forces (F_{fn}) can be calculated by the SE pushing force (F_{pn}) multiplied by the coefficient of friction (COF) (μ_n) at the contact point between the end cap and the wall. On the other hand, loading force (f_{ln}) can be calculated by using the SE weight (m) multiplied by the gravity (g) and divided by the number of contact points ($C_n = 2$) as follows:

$$F_{p1}\mu_1 \geq \frac{mg}{C_n} \quad (4.3)$$

and

$$F_{p2}\mu_2 \geq \frac{mg}{C_n}. \quad (4.4)$$

However, if the SE is not perpendicular to the walls with any angle (θ) (see Figure 4.2), the friction forces (F_{fn}) can be calculated as follows:

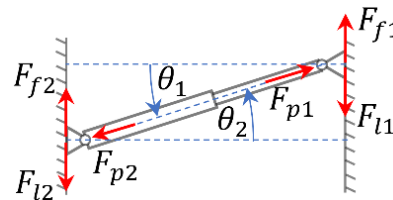


Figure 4.2 The diagram of the forces acting at contact points when the SE is not perpendicular to the walls with any angle (θ_n).

$$F_{p1} \sin \theta \mu_1 \geq \frac{mg}{C_n} \quad (4.5)$$

and

$$F_{p2} \sin \theta \mu_2 \geq \frac{mg}{C_n} \quad (4.6)$$

To calculate the required pushing force of the SE, the robot weight (m) and the COF of the end cap surfaces (μ_n) need to be estimated because the robot has not been physically implemented. The robot weight (m) may be approximately 3kg, include six strut modules (200g x 6=1200g), and 12 PRM (150g x 12=1800) modules. Both strut and PRM weights are defined based on the general miniature LA weight and other standard components displayed on a datasheet. For the COF, a rubber sheet is glued on the end cap feet, and the clear acrylic is used for the wall; therefore, the static COF between dry rubber and acrylic is 0.8 [87]. In this project, the pushing forces of the SE perpendicular to the walls are considered due to the identical pushing forces between the two end caps. Therefore, to substitute all parameters into Equation (4.3) or (4.4), the required pushing forces that are used to select a LA can be calculated using the following equation:

$$F_{pn} \geq \frac{3kg * 9.81}{2 * 0.8} = 18.4N \quad (4.7)$$

In this project, the expected robot should move inside a pipe between 250mm to 300mm, which is the range of pipe diameters used in the water industry. Therefore, the initial length of the SE should be shorter than 250mm, and the maximum length of the SE should be longer than 300mm. Both required actuator force and length will be used to select the LA for the SE. The end caps of the SE should have force sensors to detect and measure pressing forces interacting with the end caps. The sensor is used to find the minimal pressing force that can hold the SE vertically. A summary of the SE requirements is presented in Table 4.1.

Table 4.1 Summary of the SE requirements.

Specification requirements	Value	Unit
Initial strut length	<250	mm
Maximum strut length	350	mm
Pushing force range	>18.4	N
Pressing force detection range	0.2 - 30	N

4.1.2 Tensile Element

To achieve the proposed structural deformation concept, the requirements of a tensile element or PRM including a retractable-cable element and cable locking element are designed and analysed considering the cable-pulling forces, braking resistance for designing a braking mechanism, encoder resolution for measuring cable lengths and the maximum cable length.

A. Retractable-Cable Element

The requirement of the retractable-cable element involves reeling a cable keeping inside cable storage by using a small cable-pulling force without any actuator. To meet the requirements, a spiral power spring is adopted because it can exert passive-recoil forces and provide rotational motion mechanically. The power spring, which is also known as motor springs or clock springs, is a thin strip of the rectangular cross-section manufactured in the spiral shape, as presented in Figure 4.3(a). For the power spring configuration, the spring is confined in a circular case, in which the outer end tip of the spring held in the case is a rotational component. The centre tip is hooked with an arbour, which is a fixed component. On the other hand, the case and the arbour are completely separated, allowing the rotational part to spin around the fixed component. An example of the power spring configuration is presented in Figure 4.3(b).

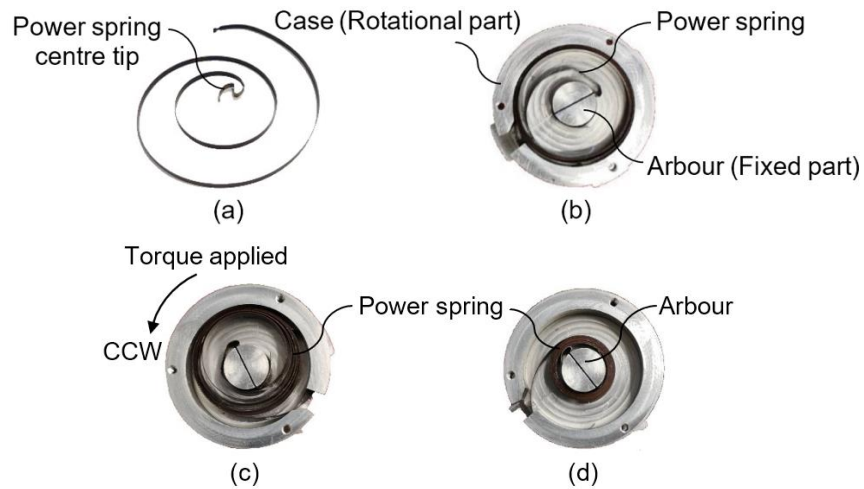


Figure 4.3 Power spring configurations: (a) power spring (uncase), (b) power spring (in case), (c) rotated one revolution, and (d) completely wound down on an arbour (six revolutions).

The cable-pulling force produced by the power spring may be generated by applying torque to the rotational component in the counter clockwise (CCW) direction (see Figure 4.3 (c)). This power spring can be wound up on the arbour until completely wound down on the arbour, as illustrated in Figure 4.3 (d).

Theoretically, the torque of the power spring depends on the number of turns of the power spring related to the basic geometrical parameters of the power spring, which are described following the spiral power springs theory and design in [88, 89]. The schematics of the power spring in uncaged condition were confined in the cage without applying force and completely wound down on the arbour, as shown in Figure 4.4 (a), (b), and (c), respectively.

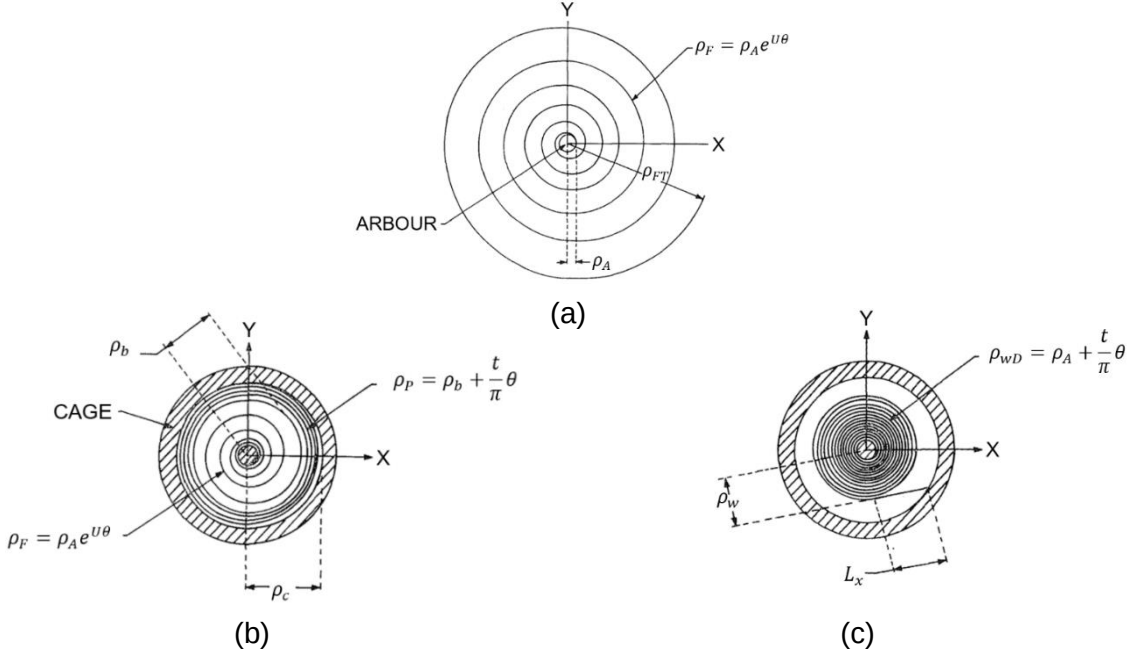


Figure 4.4 The schematics of a power spring [88]: (a) uncaged condition, (b) confined in the cage with no torque and (c) completely wound down on the arbour.

In order to derive power spring equations, three configurations of the power spring are assumed based on the spring's mathematical shape. Firstly, the uncaged stage (Figure 4.4 (a)) of the spring may be identified as a logarithmic spiral. Therefore, the radial distance from the origin to the centre line of the spring (ρ_F) may be computed as the following formula:

$$\rho_F = \rho_A e^{U\theta}, \quad (4.8)$$

where ρ_A is the radius of arbour plus half of the spring thickness, U is the shape factor constant of logarithmic spiral, and θ is the angular coordinate of the polar coordinate system. Secondly, when the spring is put in a cage without torque (Figure 4.4 (b)), some portions of the spring are unpacked as the logarithmic spiral and some portions are packed as an Archimedean spiral shape described in the following formula:

$$\rho_P = \rho_b + \frac{t}{\pi} \theta, \quad (4.9)$$

where ρ_P is the radial distance from the origin to the centre line of the spring in the outer packed zone, ρ_b is the radial distance from the origin to the centre line of the spring between unpacked and packed zones, t is the thickness of the

spring, and θ is the spring angle of the polar coordinate system. Thirdly, when the spring is completely wound down on the arbour (Figure 4.4 (c)), the entire spring shape is an Archimedean spiral as same as the spring shape in the packed zone. Therefore, the radial coordinate of the spring wound-down configuration (ρ_{wD}) can be derived as the following formula:

$$\rho_{wD} = \rho_A + \frac{t}{\pi} \theta, \quad (4.10)$$

where ρ_A is the radius of the arbour plus half of the spring thickness.

To consider the torque-turn in the packed and unpacked zone, Figure 4.5 presents the relationship between torque and the number of turns of the power spring compared between theoretical torque and hypothetical experiment. The theoretical torque-turn curve is divided into two stages. The first stage is the number of turns at which the material in spring is not completely active (downward curve), resulting in the inconstant increasing of the torque. The second stage is the number of turns at which all material in the spring is active, resulting in a constant increase of the torque (straight line).

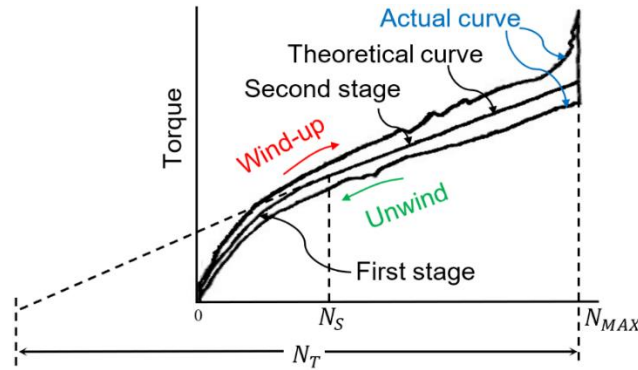


Figure 4.5. The torque-turn curve of the power spring [88], N_S is the number of turns that spring is not all active, N_T is a maximum number of turns available that the spring is not confined in the cage, and N_{MAX} is the maximum number of turns available from the power spring in the cage.

To consider the spring configuration in Figure 4.4 (b), before a torque is applied, the spring initially consists of two zones, namely packed and unpacked. As torque is applied, the spring will peel away from the packed zone and become an unpacked zone, where the spring coils do not touch one another. As this unpeeling process continues, the applied torque required to peel away spring from the inside of the packed zone may be computed from the curvature differences derived from the logarithmic and Archimedean spiral geometries.

In the first stage of the torque-turn curve, the bending at any point is constant and equal to the applied torque if the spring has a narrow width, constant length, and fixed outer end. There, the spring torque can be given with the following equation:

$$T = \frac{2\pi EIN}{L_0}, \quad (4.11)$$

where T is the spring torque, E is the elasticity modulus of the spring material, I is the moment of inertia, N is the number of turns, and L_0 is the active length of spring while applying torque (unpacked zone). For more normal cases, a wide spring is more appropriate than a narrow spring. Therefore, the spring torque may be computed with the following formula:

$$T = \frac{2\pi EIN}{(1 - \nu^2)L_0}, \quad (4.12)$$

where ν is Poisson's ratio. For the second stage of the torque-turn (straight line), the spring torque can be calculated with the following formula:

$$T = \frac{2\pi EIN}{(1 - \nu^2)L_0} (N_T - N_{max} + N) \quad (4.13)$$

From the spiral power spring characteristic curves, the second stage is carried out to define the initial cable-pulling force of the PRM in order to reel the cable without a dead zone, where the power spring torque is not enough to reel the cable keeping inside a cable storage component.

Therefore, a minimum requirement of the rotational torque (τ_R) able to rotate the rotational component should be analysed. It is assumed that the minimum requirement of the rotational torque for the power spring relates to the minimum cable-pulling force (F_{Rmin}) needed to sufficiently pull the SE when one side of the SE is not fixed by other components, as shown in Figure 4.6 (b).

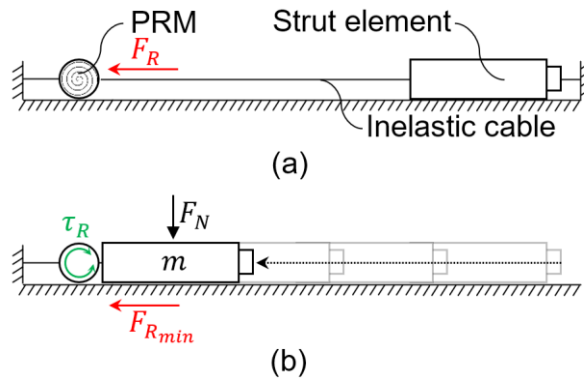


Figure 4.6 The minimum requirement of the cable-pulling force for the power spring design and selection: (a) fixed cable stage and (b) retractable cable stage.

Therefore, the minimum cable-pulling force (F_{Rmin}) that the power spring needs to produce should be higher than the friction force of the SE, as calculated with the following formula:

$$F_{R_{min}} > \mu F_N, \quad (4.14)$$

and

$$F_N = mg, \quad (4.15)$$

where $F_{R_{min}}$ is the minimum cable-pulling force requirement (N) of the power spring, μ is the coefficient of friction (COF) of the contact point between the SE surface and ground surface, F_N is the normal force (N), m is the SE weight (kg), and g is gravity ($\frac{m}{s^2}$). The minimum-required torque (τ_R) of the rotational component generated by the power spring can be computed with the following equation:

$$\tau_R(N) = F_{R_{min}} r, \quad (4.16)$$

where r is the radius of the cable storage driven by the power spring. These retractable cable concepts and required rotational torque equations can be used to design and select rotational parts, which are attached to the power spring case to roll and release the cable.

Based on this design, the COF is assumed as 1, and the overall weight of the SE integrated two end caps may be estimated as 120g. Therefore, by substituting these parameters into Equation (4.14), the minimum cable-pulling force ($F_{R_{min}}$) can be calculated as 1.2N or 120 g, which is the minimum requirement of the power spring for the passive-retractable cable element.

For structural configurations, the PRM should provide sufficient cable length. The cable length must be more than the maximum length of the SE. Furthermore, the PRM should have a cable length measurement sent to a control module for a closed-loop control system. The resolution of the measurement must be more than 1 unit per millimetre to minimise positioning error in a closed-loop control system.

B. Braking Element

The braking element needs to be able to produce braking force against the retractable-cable element to restrict the cable. Therefore, the braking element should produce sufficient friction to halt the rotational elements generated by a power spring.

To design a braking element properly, locking devices in robotics are studied and selected. The locking devices in the fields of robotics may be categorised into three groups [90]. The first group includes locking devices based on mechanical locking that use types of obstruction of a part by another part, as shown in Figure 4.7: (a) a latch with one locking position; (b) a latch with multiple locking positions; (c) a ratchet; and (d) a cam-based locking device (Geneva mechanism).

These mechanical locking devices generally have low energy consumption for the locking stage. Moreover, these devices are of a low weight, a small component, low price, and their locking torque is only limited by the strength of the components. However, these devices also have disadvantages. Firstly, they cannot be locked at all positions. Secondly, they are hard to unlock while working under load due to the friction between the two interfering components. Finally, the system will be shocked when applying force against the locking stage.

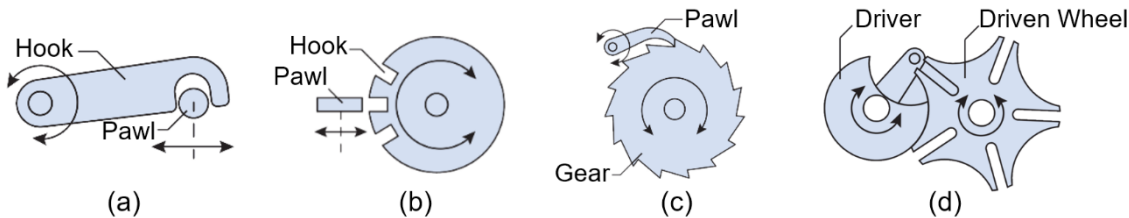


Figure 4.7 Example types of mechanical locking devices [90]: (a) a latch with one locking position, (b) a latch with multiple locking positions, (c) a ratchet and (d) a cam-based locking device.

The second group is comprised of friction-based locking devices that produce friction to restrict motion components. Friction can be generated by pushing a fixed part attached to a movable component. Therefore, friction-based locking devices can lock in all positions and be performed as a controllable brake. Figure 4.8 presents example mechanisms of friction-based locking devices: (a) a bistable mechanism; (b) a self-amplifying brake; (c) a capstan; and (d) a thermic lock

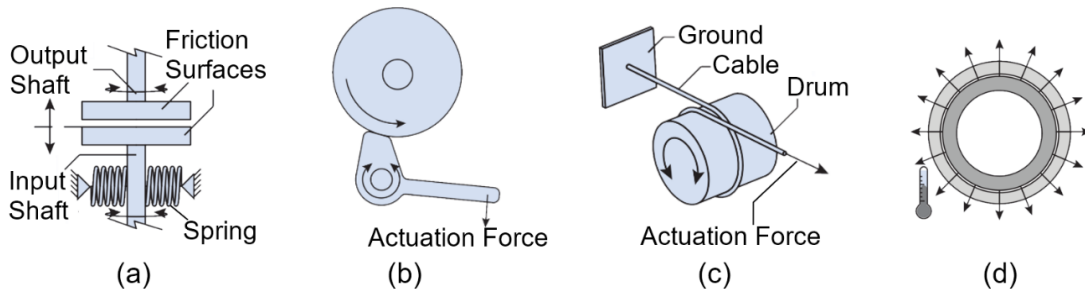


Figure 4.8 Examples of friction-based locking devices [90]: (a) a bistable brake, (b) a self-engaging brake, (c) a capstan and (d) a thermic lock.

The third group is comprised of singularity locking devices characterised by a position-dependent transfer ratio in the same way as vacuum box mechanisms. For example, the locking devices have a specific active component linking to another passive component. The braking stage can be achieved by moving the active component to the desired position to drive and lock the passive component, as presented in Figure 4.9.

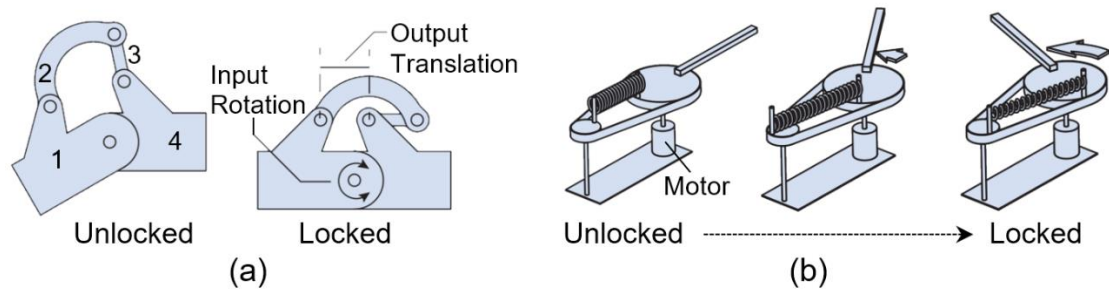


Figure 4.9 The example types of singularity locking devices [90]: (a) the two different four-bar mechanisms and (b) a nonlinear spring mechanism.

After analysing the advantages and disadvantages, friction-based locking devices provide a controllable-positioning brake by driving a locking part attached to another component at every position. Moreover, this device completely decouples between the frictional and movable components in the unlocking stage, resulting in zero friction between the braking component's surface and the moveable component [90]. For this reason, the friction-based locking device method has been adopted to design a locking part for restricting the rotational component of the passive-retractable joint with a locking mechanism (PRM).

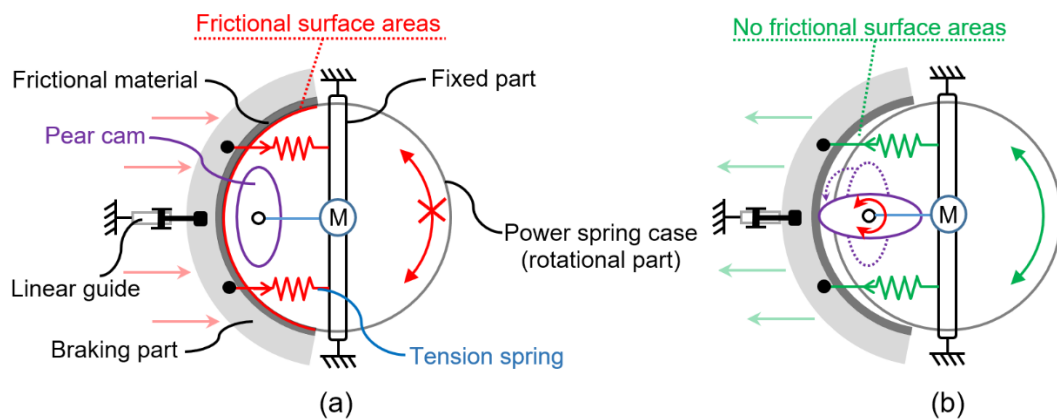


Figure 4.10 Locking component conceptual design: (a) locking stage and (b) unlocking stage.

The conceptual design of the locking component is illustrated in Figure 4.10; it consists of a braking component, which is designed to be curved to increase the friction on the frictional surface areas (see red curve in Figure 4.10 (a)), where the friction material is attached to the rotational component. Two tension springs are hooked between two points of the braking and fixed components in order to create tension. In the middle of the fixed component, a high-torque actuator (M) is mounted to drive a pear cam pushing the braking component out from the power spring case along with the linear guide, which is used to linearly guide the motion of the braking part. Figure 4.10 (b) illustrates the unlocking stage of the locking component. The actuator (M) produces torque to rotate the pear cam

pushing the frictional material out from the rotational part separately. As a result, the rotational component attached to the cable storage can rotate freely.

For the force analysis of the locking stage, two tension springs produce tension to press the frictional material attaching to the frictional surface areas, causing a frictional force acting at the contact surface (F_{RN}). This force restricts the power spring case, which is the rotational component the PRM in Figure 4.11 (a).

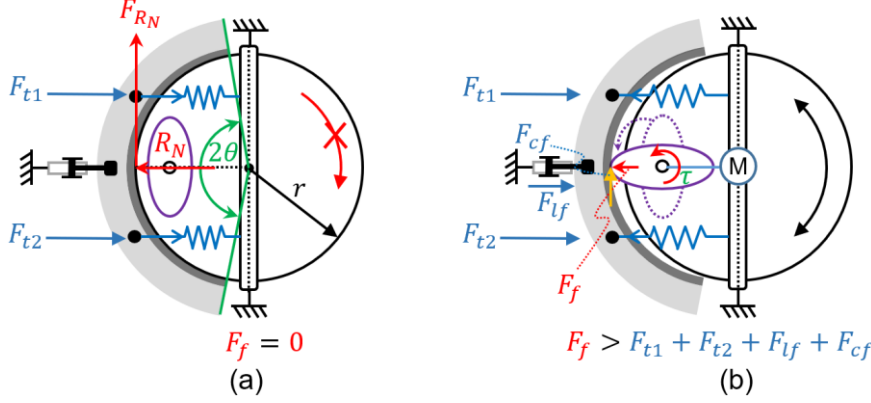


Figure 4.11 Force analysis of the locking component: (a) locking stage and (b) unlocking stage.

Thus, the braking torque (T_B) can be computed with the following equation [91]:

$$T_B = F_{RN}r = \mu' R_N r, \quad (4.17)$$

where R_N is the force pressing the braking material on the rotational component, r is the radius of the rotational component, and μ' is the equivalent coefficient of friction, which is calculated with the following equations:

$$\mu' = \frac{4\mu \sin \theta_F}{2\theta_F + \sin 2\theta_F}, \quad (4.18)$$

where θ_F is the angle of the contact area, and μ is the actual coefficient of friction between two friction materials. To substitute (4.18) in (4.17), the braking torque can be then calculated as follows:

$$T_B = \left(\frac{4\mu \sin \theta_F}{2\theta_F + \sin 2\theta_F} \right) R_N r. \quad (4.19)$$

This braking torque is used to define the total tension force; it is assumed that two tension springs would produce equal tension force. For the unlocking stage, the required torques that the actuator needs to produce the forward force (F_f) must overcome the summation of spring tension forces (F_{t1} and F_{t2}), linear guide friction (F_{fl}), and the friction between pear cam and brake shoe (F_{cf}). Under this

condition, the pear cam can push the braking component out from the rotational part separately, resulting in no frictional surface areas, as shown in Figure 4.11 (b).

Based on the required force analysis of both retractable cable and braking elements, the requirements of the PRM able to perform structural configurations can be summarised in Table 4.2.

Table 4.2 Property requirements of the PRM.

Specifications	Value	Unit
Encoder resolution	>1	Pulse per millimetre
Maximum cable length	> maximum length of the SE	mm
Cable-pulling force (F_R) range	>1.2	N
Braking resistance	>1.5 $\times F_R$	N
Cable length control	Lock/unlock	stage

4.2 Individual Element Implementation

This section describes the mechanical design and implementation of the adjustable-length SE and PRM. The electrical control boards of each element are then designed and developed, including a high-level control board, low-slave control boards, and other interface boards that control all SEs and PRMs.

4.2.1 Mechanical Design

The mechanical design consists of two modules, namely the SE module and the PRM module. Each module includes hardware selections, including actuators, structural components, and sensors.

A. Strut module

The purpose of the SE is to generate sufficient pressing force between robot legs called end caps and environmental surfaces for locomotion. The device is also used to apply both push force and pull forces for tensile elements to produce different cable tensions and deform robot structure configurations. To fulfil these properties, the required force between end caps and environmental surfaces should be analysed for the actuator selection process. Moreover, feedback sensors such as displacement and force sensors are studied and chosen based on the pressing force requirements to maintain the robot's positions.

A.1 Actuator Selection

Based on the criteria of actuator size and required force, a search is undertaken to find suitable actuators for the prototype. The search considers primarily the micro-LA from Actuonix motion devices. After searching through Actuonix products, the micro-LA model L12-100-100-12-P (see Figure 4.12) was selected because it provides a 100mm slider stroke, a length of 170-270mm, weight of 40g, and maximum force of 42N. This working length provides a free length of 80mm to design the two end caps of the SE module.



Figure 4.12 Image of the micro-LA from Actuonix motion devices Inc. model L12-100-100-12P.

A.2 Sensor Selection

Sensors are necessary to achieve closed-loop control and monitor the operating stage of a robotic system. A thin film potentiometer is adopted to send feedback voltage to a control module and is integrated mechanically inside the selected LA, as presented in Figure 4.13. The resistance values of the potentiometer are varied linearly following the wiper sliding along the resistive film. This wiper causes the short circuit of a certain portion of the resistance. Therefore, if a power supply applies for the potentiometer, the varied resistance causes the output voltage adjustments to send the voltage to an electronics control board converting to digital data to compute LA-slider displacements.

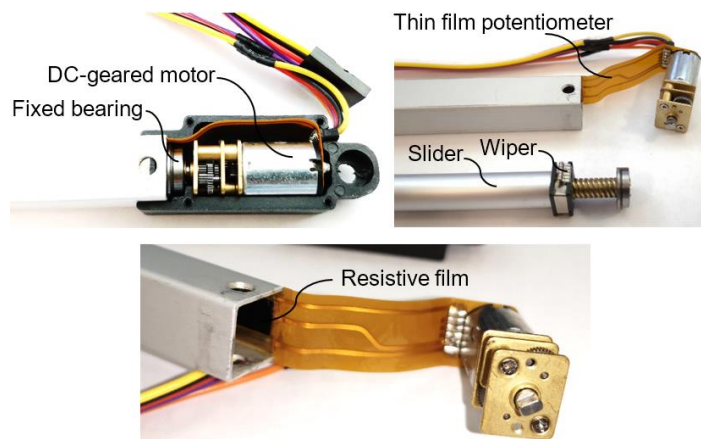


Figure 4.13 Images of the thin film potentiometer installation.

To sense the pressing force between robot feet and the environment, force sensors are indispensable to be integrated into an SE module. A force-sensing resistor (FSR) is considered for use in this application. The FSR is a passive component that exhibits a decrease in resistance when there is an increase in the force applied to the active area. This resistance is used to create a sensor able to detect force or pressure [92]. In this project, the FSR with 15.25 mm diameter, 1 mm thick (see Figure 4.14) is selected due to the low cost, sizeable pressing area, easy installation, and off-the-shelf products. However, other FSR types or brands can also be used if they provide similar characteristics. The force-sensitive range of the selected FSR is between 0.2N to 20N or approximately 20g to 2kg. Although FSR is not suitable for precision measurements, its force sensitivity is optimised for utilising in human touch control of electronic devices [93], which is potentially used in robotic applications. However, to ensure that the selected FSR works properly in this application, preliminary tests and evaluations are presented in Appendix C.5.

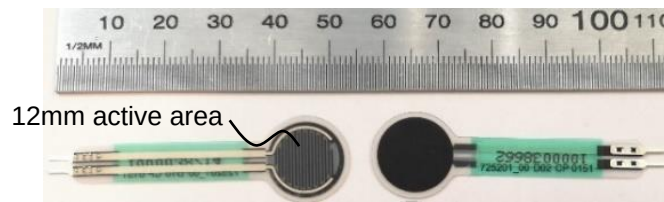


Figure 4.14 Image of the selected FSR.

Another essential sensor is the inertial measurement unit (IMU), which is used to measure the strut motions sending to the master control board to determine the current angle of the robot structure and control the robot turning in different desired directions. The IMU is an electronic device that measures a body's specific force, angular rate, and orientation using a combination of accelerometers, gyroscopes, and magnetometers. A miniature IMU board model MPU6050, triple-axis gyroscope, and accelerometer [94] are used to measure the strut angle rotating along the X (roll), Y (pitch), and Z (yaw) axis, as presented in Figure 4.15.

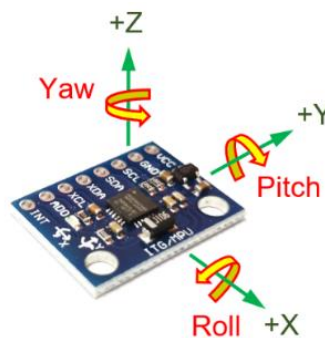


Figure 4.15 Image of MPU6050, an IMU sensor for LA angular measurement.

The MPU6050 is selected because it is an off-the-shelf item, small-sized, low cost, and already demonstrated and evaluated in robotics work [95]. However, other IMU boards that provide similar features may also be used.

A.3 End Cap Design

The end caps are designed to push environmental surfaces to hold a robot in the desired position. These end caps are mounted on the LA-slider tip and the LA-base tip, as shown in Figure 4.16 and Figure 4.17, respectively. Each end cap consists of two main components, namely a fixed and movable component. The fixed component is mounted on the LA tip and is used to connect cables via plastic ball nuts installed on the left and right sides of the connecting base. A force-sensitive resistor (FSR) is used to detect the pressing force between the end cap and environmental surfaces. The output signal of the FSR is sent to the controller module to receive the current stage of the end caps. The FSR is attached to the top surface of the connecting base.

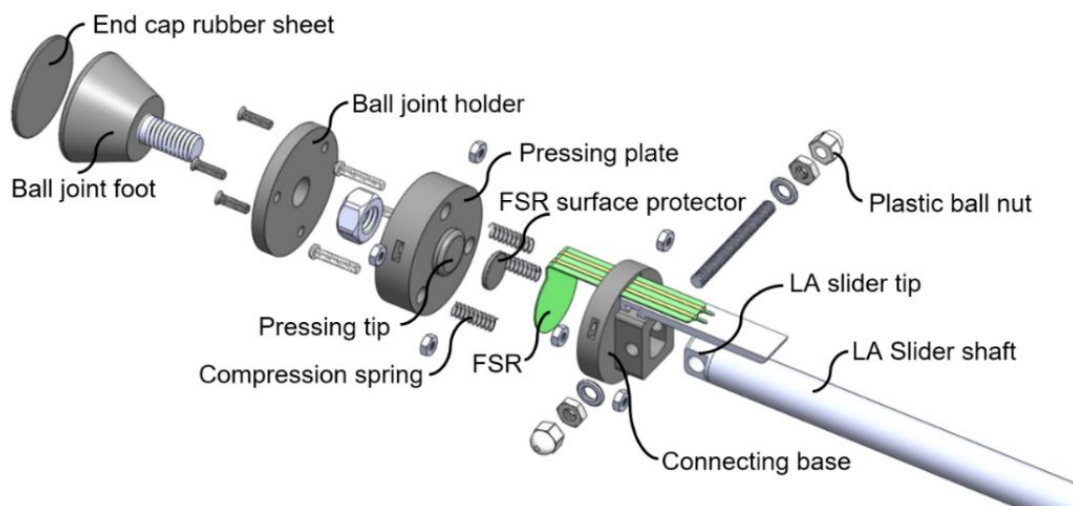


Figure 4.16 3D model of the end cap attached to the LA-slider tip.

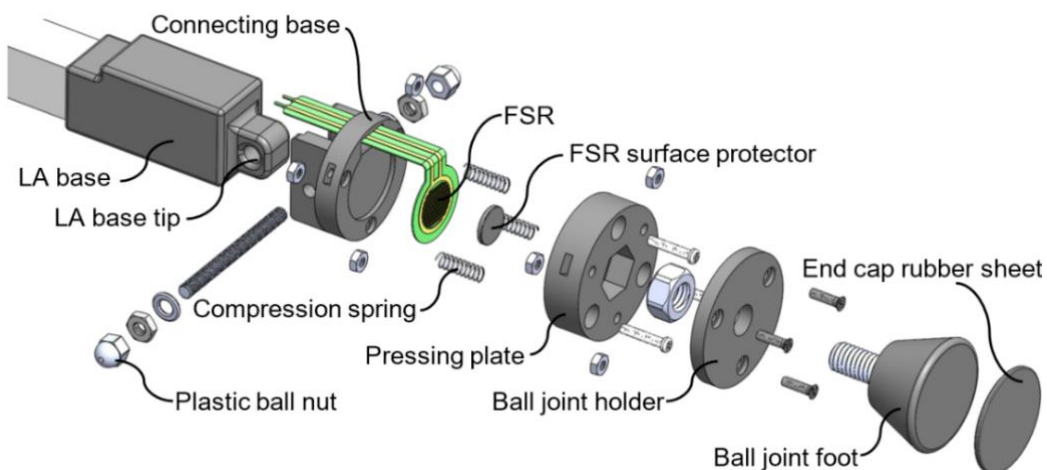


Figure 4.17 3D model of the end cap attached to the LA-base tip.

For the movable components, an 8-mm pressing tip that protrudes from the pressing plate is designed to press the FSR surface area. This pressing tip size is determined based on trial and error experimentally, as detailed in Appendix C.5. If nothing is pressing on the end caps, the pressing tip can be passively pushed from the FSR surface area independently via three compression springs (3 mm diameter and 10 mm length). These springs produce a tiny pushing force, which assumes that it does not affect the FSR sensor performance. A ball joint foot is used to be able to adjust the angle of the end cap passively to allow the end cap to attach to the environmental surface with different angles. This joint is mounted on a ball joint holder via a 6 mm nut. Finally, to increase the adhesion efficiency between the ball joint foot surface and the environmental surface, a Nitrile rubber sheet of 1 mm thickness is glued on the ball joint foot surface. The integrated three-dimensional (3D) model of the end caps and IMU board installed on the LA is presented in Figure 4.18.

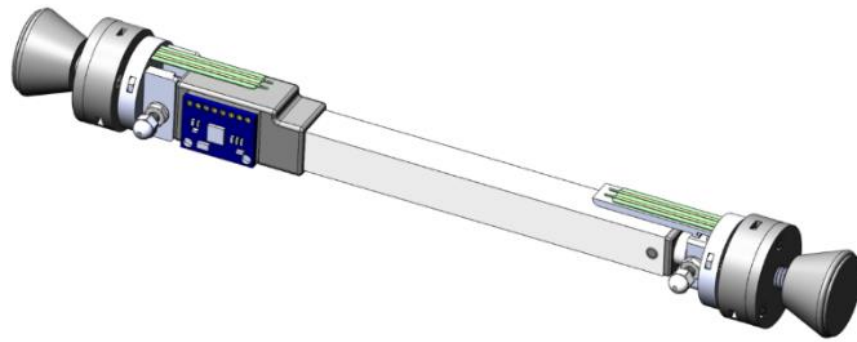


Figure 4.18 3D model of the strut module integrated with end caps and IMU board.

B. Passive-Retractable Joint with Cable Locking Mechanism (PRM)

There are two purposes for designing and developing the PRM. Firstly, the PRM is designed to roll a cable keeping inside cable storage, which is driven by a spiral power spring that passively exerts a cable-pulling force. Furthermore, the cable can be released from the cable storage with a strut module that deforms robot configurations, and the maximum cable length is limited by the number of the power spring turns. Secondly, the PRM is designed to lock and unlock the rotational component to restrict and release cables spooled by a strut module to change the robot shapes for locomotion. Therefore, to properly develop the PRM, the design and selection of the power spring, locking components, and unlocking items should be performed to meet the required braking force requirement as detailed in the following subsections.

B.1 Power spring design and selection

Power springs are a crucial component of the PRM and produce a force to spool a cable passively during the unlocking stage. Furthermore, the cable-pulling force

also affects the braking component. For example, if the spring constant is high, powerful-braking components are needed to overcome the high force generated by the power spring. To build the powerful-braking parts, large mechanisms and a high-power actuator are needed, causing an increase in PRM size and weight. Therefore, the selection of the power spring should be suitable for the selected LA due to PRM weight optimisation.

In terms of the minimum cable-pulling force described in section A, the minimum requirement of the cable-pulling force of 1.2 N or 120 g is used to design a power spring. However, portable, lightweight commercial items that contain a power spring inside are sought out rather than a custom power spring being designed due to fast development, low cost, and reliability. The retractable key chain (RC) integrates a power spring inside to produce cable-pulling forces between 1.25 N and 3.5 N and provides a cable length of 60 cm that meets power spring and cable length requirements. Images of the retractable key chain are presented in Figure 4.19.



Figure 4.19 Images of the retractable key chain (RC): (a) assembled case (original item) and (b) disassembled case.

To ensure that the selected RC is able to produce the cable-pulling force properly, the force of the power spring is physically and repeatably measured using a spring balance. The RC case is fixed on a bench. The spring balance clasper then hooks with a keyring holder and pulls the cable from the RC case. The cable-pulling force is displayed on a spring balance scale, as presented in Figure 4.20, and the relationship between the cable-pulling force and cable length is plotted in Figure 4.21.

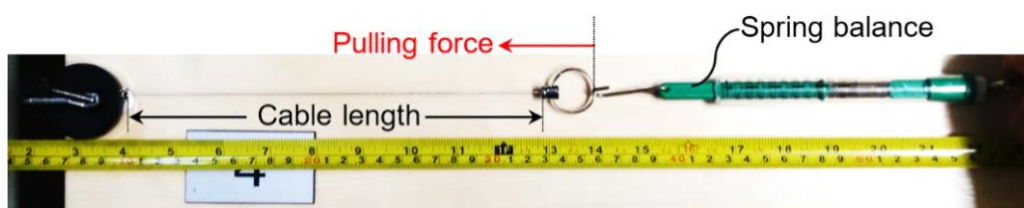


Figure 4.20 The cable-pulling force demonstration.

This result suggests that the more that the cable is drawn out, the more cable-pulling force is produced against the spring balance. The cable-pulling forces of the power spring are measured by spooling cable lengths between 0 and 60 cm, producing the cable-pulling forces between 1.25 N and 3.8 N.

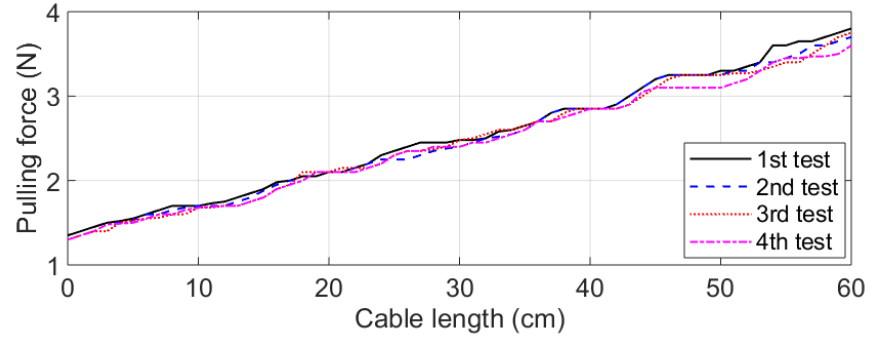


Figure 4.21 Relationship between the pulling force and the cable length.

In order to ensure that the power spring inside the RC is potentially used for the proposed actuation method, it is used to construct a cross-shape tensegrity structure to demonstrate RC performance experimentally rather than performing software simulation due to the lack of precise hardware parameters. The RC case is modified by adding a nut and screw on the top of the case to lock and unlock a rotational component of cable storage. A simple cross-shape tensegrity structure and its configuration test are shown in Figure 4.22 (end-left picture).



L - locking stage, **UL - unlocking stage**

Figure 4.22 Captured video of the pulling forces demonstrations of the power spring inside the retractable key chains.

The results suggest that the RC could produce the cable-pulling force necessary to spool each cable sufficiently while extending and retracting two miniature linear motors. The RC could also exert cable-pulling forces to move the linear motors to the initial stage. Therefore, it is anticipated that the selected power spring inside the RC is suitable for developing the passive-retractable joint with a cable locking mechanism (PRM). The captured video of the structural configurations, using the proposed actuation method is presented in Figure 4.22. This cross-shape tensegrity structure is also shown in [1] to perform structural configurations by using the proposed actuation method.

B.2 Actuator Selection

Once the power spring has been chosen to produce the cable-pulling force, the next step is to choose an appropriate DC-g geared motor to drive braking parts to lock the rotational components of the PRM.

The cable-pulling force of the selected power spring can generate the cable-pulling force up to 4N at a cable length of 55 cm. Therefore, the braking parts would be designed to produce the braking force, which should be more than one time of the cable-pulling force due to safety in the mechanical engineering design [96, 97]. Therefore, the safety factor of 2 is selected for the braking force requirement of 8N.

Based on the conceptual design of the braking component, a rubber sheet is selected to produce the frictional force attaching to the rotational component made from aluminium. Therefore, the static coefficient of friction (μ) at the contact point is approximately 0.8 (dry rubber and dry aluminium) [87]. The contact area angle (θ_F) is designed as 80° . The required force of 8 N is defined as the force pressing at the contact area (R_N), and the radius of the rotational parts is determined by the radius of the wheel of the selected retractable key chain of 12.5 mm. To substitute all parameters in Equation (4.9), the braking torque of the rotational part can be calculated as 1.9558 N. This braking torque is adopted to define the total tension force. It is assumed that two tension springs would produce tension force equally. Therefore, each tension spring should have an initial spring value of 0.98 N, (1.96 / 2), which is used to search for an appropriate tension spring for the cable restrictor mechanism.

The tension spring search considers primarily miniature tension springs from Misumi Ltd. After searching for different tension spring types, tension spring model UFSP4-0.5-10 is selected. This model has an initial tension of 0.92 N, spring constant of 0.13 N/mm, Outer diameter of 4 mm, wire diameter of 0.5 mm, and length of 10mm. However, the spring needs to be cut to 3mm in length for installation. The spring constant is then increased approximately three to 0.39 N/mm. By connecting two parallel springs, the total spring constant (k_T) becomes 0.78 N/mm. Similarly, the total initial tension (T_{IT}) becomes 1.84 N. It is assumed that, to unlock the rotational component, the tension spring elongation (S_{Travel}) would be 7 mm. Therefore, the total tension force that the motor should drive the pear cam may be solved by the following formula [98]:

$$T_{IT} = L_d - k_T S_{Travel}, \quad (4.20)$$

$$L_d = T_{IT} + k_T S_{Travel}, \quad (4.21)$$

where L_d is the weight (Kg) or applying force (N) that elongates the spring coil. To substitute spring parameters into Equation (4.21), the pressing force that the motor needs to produce torque transmitting to the pear cam is 7.26 N.

However, it is assumed that the linear guide friction (F_{fl}) and the brake shoe friction (F_{cf}) are small due to the use of lubricants for frictional components. Therefore, the pressing force is only used to calculate the required torque of a motor to drive the pear cam with a radius of 2.7mm. By using a basic torque formula, the required torque of the motor can be then calculated as 0.02 N.m. and the pressing force multiplied by the radius of the pear cam.

After searching for the miniature DC-gear motor, a DC-gear motor, providing a speed of 31.4 rounds per minute (RPM) and a torque of 2.3kg. cm or 0.23 N.m is chosen because the motor torque is higher than the minimum motor torque requirement of approximately 10 times; the image of the motor is presented in Figure 4.23.

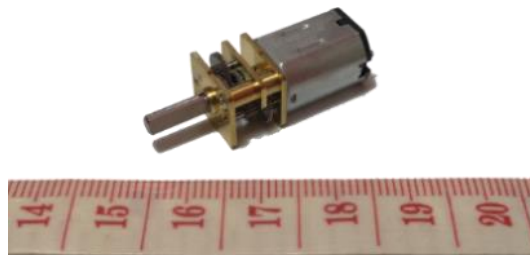


Figure 4.23 Image of the selected miniature DC-gear motor.

B.3 PRM Mechanical Design

This section describes the mechanical design of the passive-retractable joint with a cable locking mechanisms (PRM) module. This joint comprises two main components: rotational and braking or locking components, as shown in Figure 4.24.

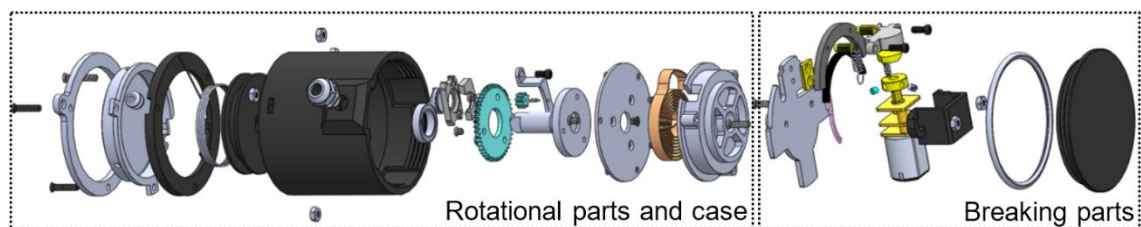


Figure 4.24 Further details of the PRM mechanisms.

B.3.1 Rotational Part Design

A 3D model design of the rotational component is shown in Figure 4.25. A spiral power spring is placed inside the power spring case, and the middle-end of the power spring is hooked with a fixed anchor that is part of a motor mounting plate,

as present in Figure 4.25 (b). The other end side of the power spring is hooked with a power spring case, which is the base of the rotational components. To prevent the power spring ejecting from its case, a covering plate is placed on the top connected to the 6.35 mm diameter shaft. A ball bearing is used to reduce friction between the shaft and the PRM case provided with a smooth rotation. The vertex of the shaft is attached to cable storage for rolling the 0.45 mm stainless steel wire rope. From this design, the cable storage is rotated following the rotational directions clockwise (CW) and counter clockwise (CCW) of the power spring case.

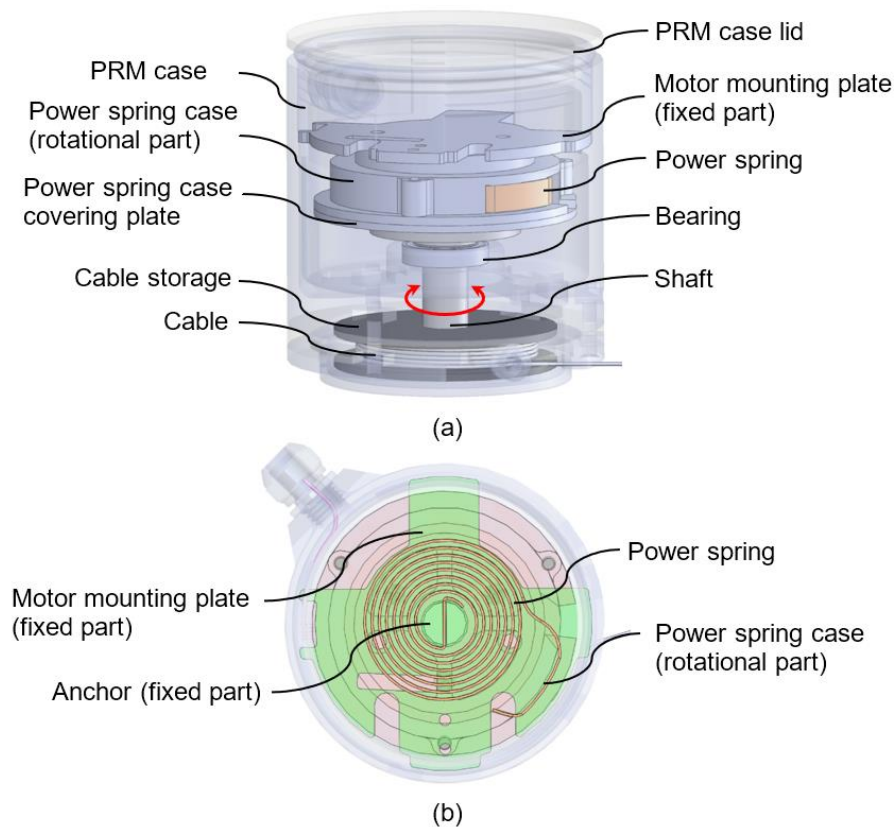


Figure 4.25 Mechanical design of the rotational components of the PRM: (a) the design of fixed and rotational elements and (b) the power spring installation design.

Figure 4.26 illustrates how to install a spiral power spring inside the case, a process that consists of three stages. Firstly, the power spring case is put on the motor mounting plate. Secondly, the power spring is placed in the case by inserting the middle of the power spring into the anchor of the motor mounting plate. Finally, the power spring case covering plate and the rotational shaft are placed on the top of the power spring case.

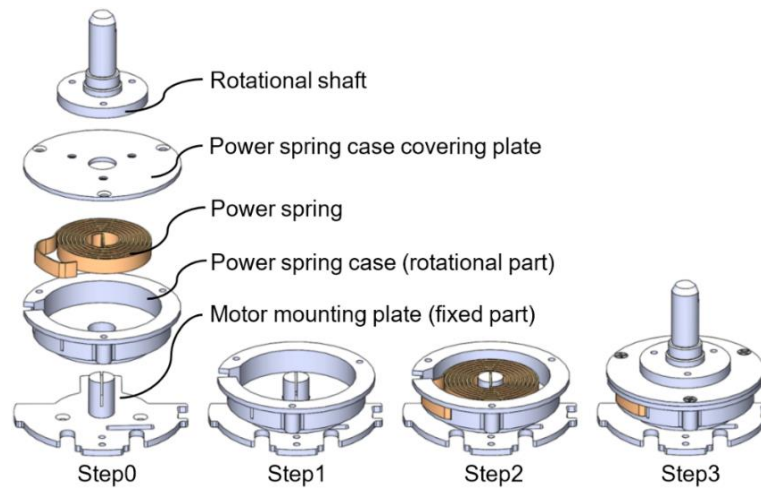


Figure 4.26 Design of the rotational part assembly procedure.

To measure the cable length of the PRM, which is used to calculate the kinematic characteristics of a robot, a miniature encoder is used to generate a signal sent to the controller module. Due to the space limitations inside the PRM case, the encoder size needs to be appropriately selected. In this design, a miniature magnetic rotary encoder (model: RM08ID0009B02L2G00, 512 counts per revolution (CPR)) is used due to the tiny parts and IP68 standardised testing [99]. The picture of the magnetic encoder is presented in Figure 4.27.

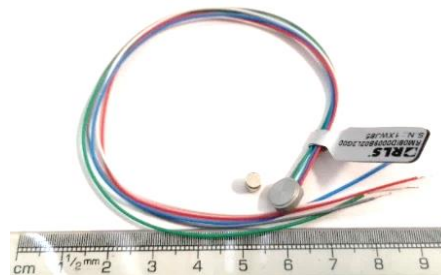


Figure 4.27 Miniature magnetic rotary encoder with 512 CPR.

To generate encoder signals, a magnet should be rotated and centrally located above the encoder surface to create magnetic fields. Therefore, in order to rotate the permanent magnet, a 46-teeth driving gear is designed; it attaches to the shaft, which drives an 8-teeth driven gear, as presented in Figure 4.28. A gear shaft is inserted through the driven gear to hold the driven gear holder. A 4 mm magnet is glued on the bottom side of the driven gear. To support the magnet rotation, a miniature bearing is used to wear on the magnet; it is placed above the encoder with a gap of 0.2-0.5 mm and is supported by a bearing holder. From this design, when the driving gear is rotating, the driven gear is also rotating, leading to turning the magnet to emit different magnetic fields to the encoder. Eventually, encoder signals A and B are generated and sent to an electronics control board to calculate cable length.

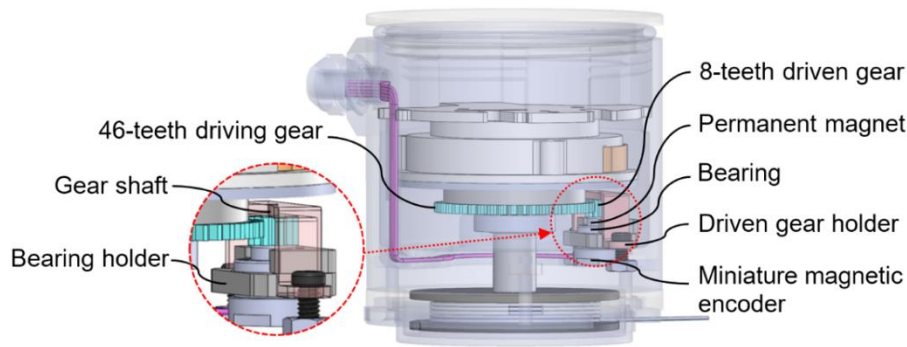


Figure 4.28 Cable length measurement mechanism design

B.3.2 Braking Part Design

The mechanical design and principle of the locking and unlocking stage of the PRM are described in this section. According to the conceptual design of the breaking parts, the friction-based method is adopted to design the braking mechanism, as illustrated in Figure 4.29.

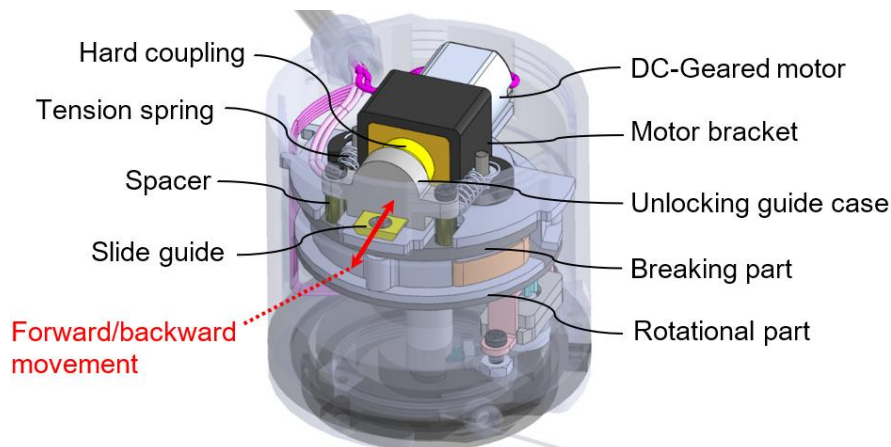


Figure 4.29 3D model of the braking mechanism.

To produce frictional force between the rotational and breaking components, a set of braking mechanisms is designed. The braking component is designed in a curved shape to provide braking areas that can attach to the braking surface area firmly, as shown in Figure 4.30. This braking component is connected to an unlocking guide case via two spacers. The unlocking guide can be sliced forward and backwards depending on tension forces generated by two tension springs and the push force produced by a ball plunger screwed in a hard coupling. This coupling is connected to a DC-geared motor and integrated by a 2 mm permanent magnet for a reed switch used for checking home and locking stages.

In order to understand the mechanical motions, the movement behaviours of the braking parts are explained thoroughly. In the locking stage, the DC-geared motor shaft rotates CW. Simultaneously, the ball plunger tip circularly slopes down

following the unlocking guide surface until the reed switch detects the magnetic fields created by the 2 mm magnet. In this magnet position, the reed switch senses the magnetic field and sends a signal to the control board. The control board then sends a command to stop the motor rotation. In this stage, the ball plunger movement is stopped at the lowest level of the unlocking guide surface, where no pushing force is applied to counteract the tension force produced by two tension springs. Therefore, the tension forces of two tension springs drag the braking component backwards, causing the braking material (rubber) attached to the braking surface area (aluminium). In this contact area, a high-frictional force occurs to brake or lock the power spring case rotation, meaning that the spin of the cable storage is restricted in this stage.

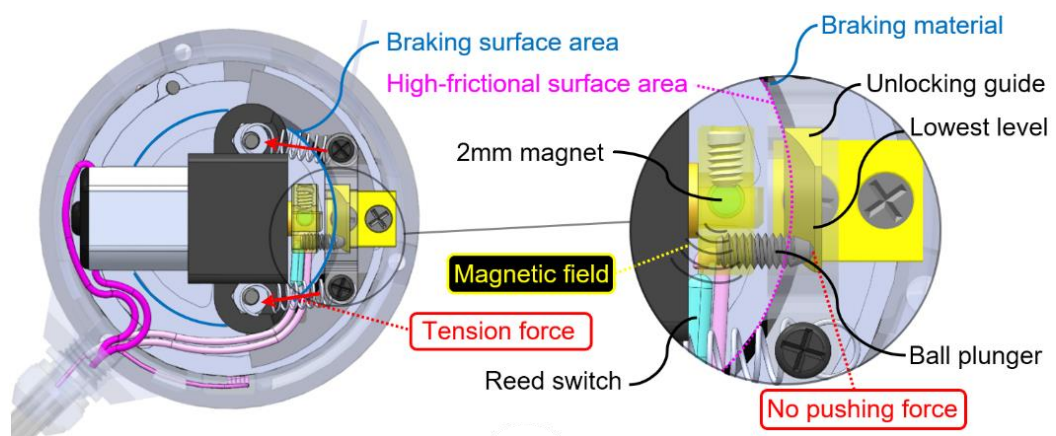


Figure 4.30 Braking component motions in the locking stage.

In the unlocking stage, the motor shaft rotates CCW over period that can move the ball plunger tip to slop up to the highest level of the unlocking guide surface. In this position, the ball plunger tip produces a high-pushing force, which is higher than the pulling force. The unlocking guide case is then moved forward, resulting in a separation between the braking material and the braking surface area, as shown in Figure 4.31.

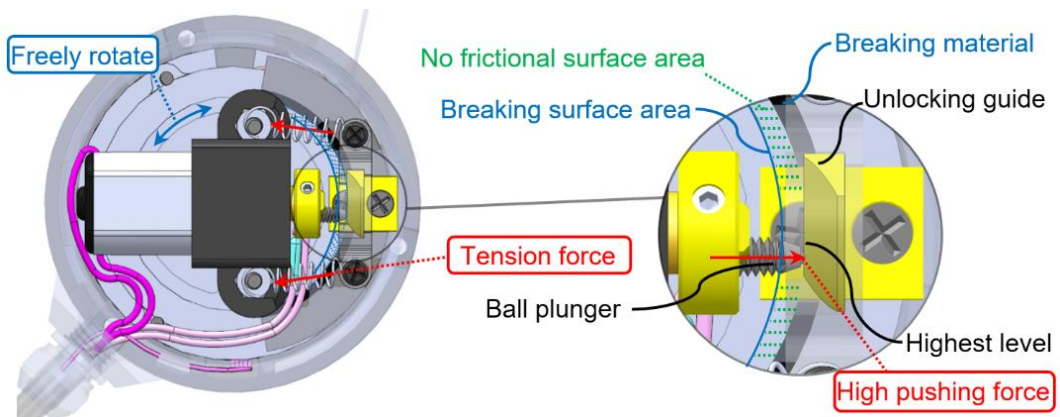


Figure 4.31 Braking component motions in the unlocking stage.

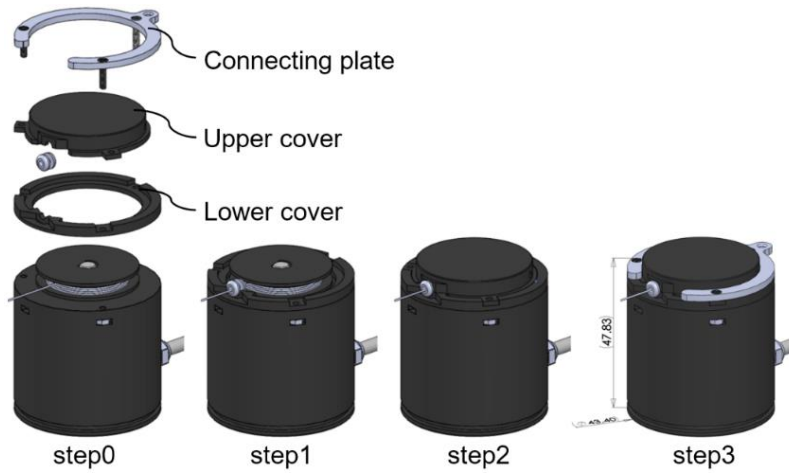


Figure 4.32 Design of the cable-storage cover.

The lower and upper covers are designed to envelop the cable storage to protect the cable storage rotation. A connecting plate is designed to connect the PRM with other mechanisms. The assembly procedure of the upper cover, lower cover, connecting plate, and overall dimension of the PRM (47.83mm height and 43.4mm diameter) is presented in Figure 4.32.

4.2.2 Individual Module Manufacture and Assembly

The manufacturing of the strut module and cable restrictor module prototypes are developed with consideration of their weight, cost, and durability. Non-frictional components are mostly created by three-dimension (3D) printing technology with lightweight material. On the other hand, the frictional or torsional components are made of brass, aluminium, and stainless steel, depending on functionality and machining possibility in each element using Computer Numerical Control (CNC) technology. The details of the manufacturing and assembling procedures of the SE and PRM are described in the following section.

A. Strut Element Module

The manufacturing of each part of the strut module is constructed from the 3D printing machine with the filament of Polycarbonate Acrylonitrile Butadiene Styrene (PC-ABS). This filament is used because it can reach a high temperature (98°C) resistance, durability, and lowest cost, compared to other materials, as summarised in [100]. After manufacturing and assembling 3D printed parts with LAs detailed in Appendix A.1, physical SEs are presented in Figure 4.33.

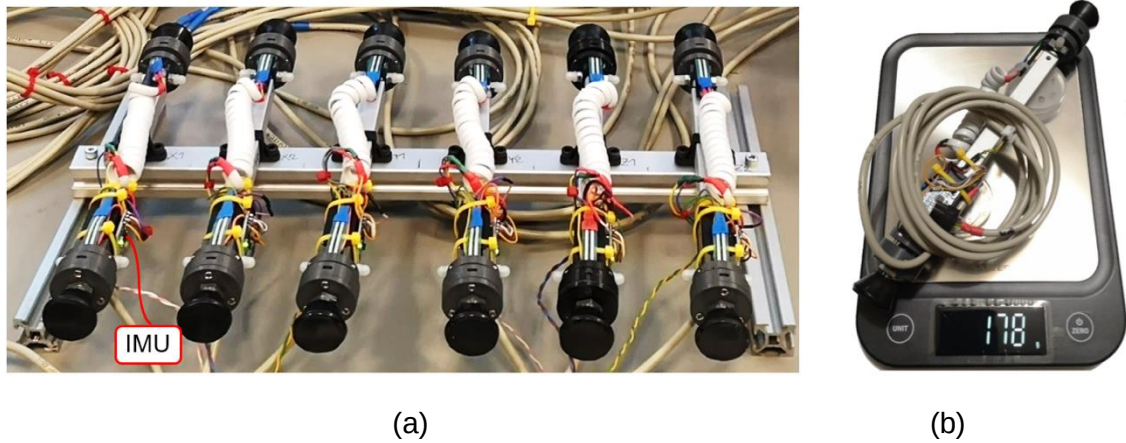


Figure 4.33 Image of strut module prototype: (a) the FSR wiring of six-strut element and IMU installation and (b) the overall weight (178g) of the strut module, including cable and connector.

B. Passive-Retractable Joint with a Cable Locking Mechanism

The mechanical components of the passive-retractable joint with a cable locking mechanism (PRM) are manufactured using both 3D printing and CNC Technologies. The 3D printing machine is used to create non-frictional components to minimise the weight of the PRM module. Different material types of filaments are used due to an appropriate material being available in the manufacturing service at the time. The first set of the PRM prototype for PRM-A to PRM-F are printed from PC-ABS, while the second set for PRM-G to PRM-L is printed from ABS-M30 [101]. After manufacturing and assembling PRM detailed in Appendix A.2, the first and second version of PRM prototypes are present in Figure 4.34 and Figure 4.35, respectively.

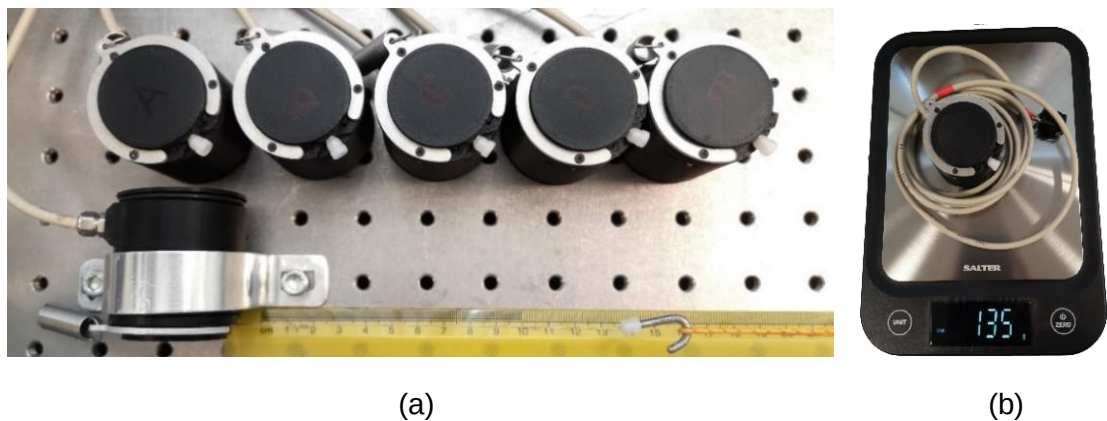


Figure 4.34 The physical PRM prototype version 1: (a) PRM-A to PRM-F and (b) the first version PRM prototype weight of 135 g.

The weight of the PRM prototype first version and second version is slightly different because some part sizes in the second version are reduced. Firstly, the

anchor diameter of the motor mounting plate is reduced from 7 mm to 6 mm to alleviate the weight and increase the maximum turn of the power spring.

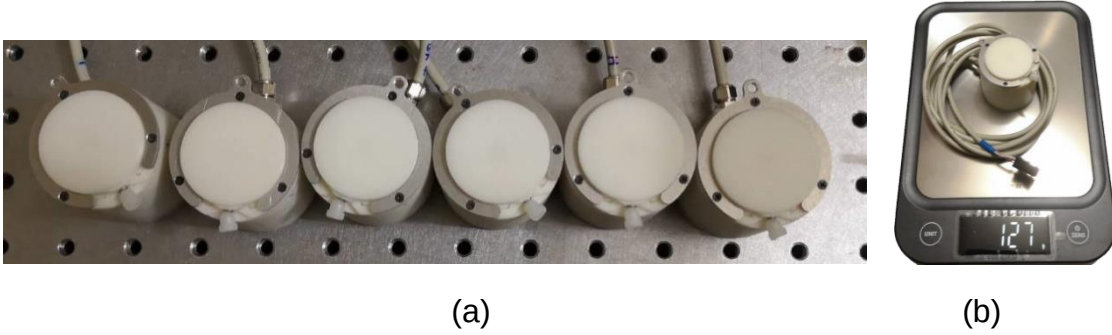


Figure 4.35 Physical restrictor mechanism (PRM) version 2: (a) PRM-G to PRM-L and (b) the second version PRM prototype weight of 127 g.

4.3 Electronic Design and Implementations

This sub-section describes the design of electronic control boards for each element and interface boards. The control module of this project consists of a high-level control (HLC) or master module and 18-low-level control (LLC) modules. The HLC is the master control module that generates control signals for the locking and unlocking stages of all PRMs and the extending and retracting stages of all SEs for the robot configurations. Each LLC communicates with the HLC via I²C protocol to perform a closed-loop control. A simple wiring diagram of the electronic control system is presented in Figure 4.36.

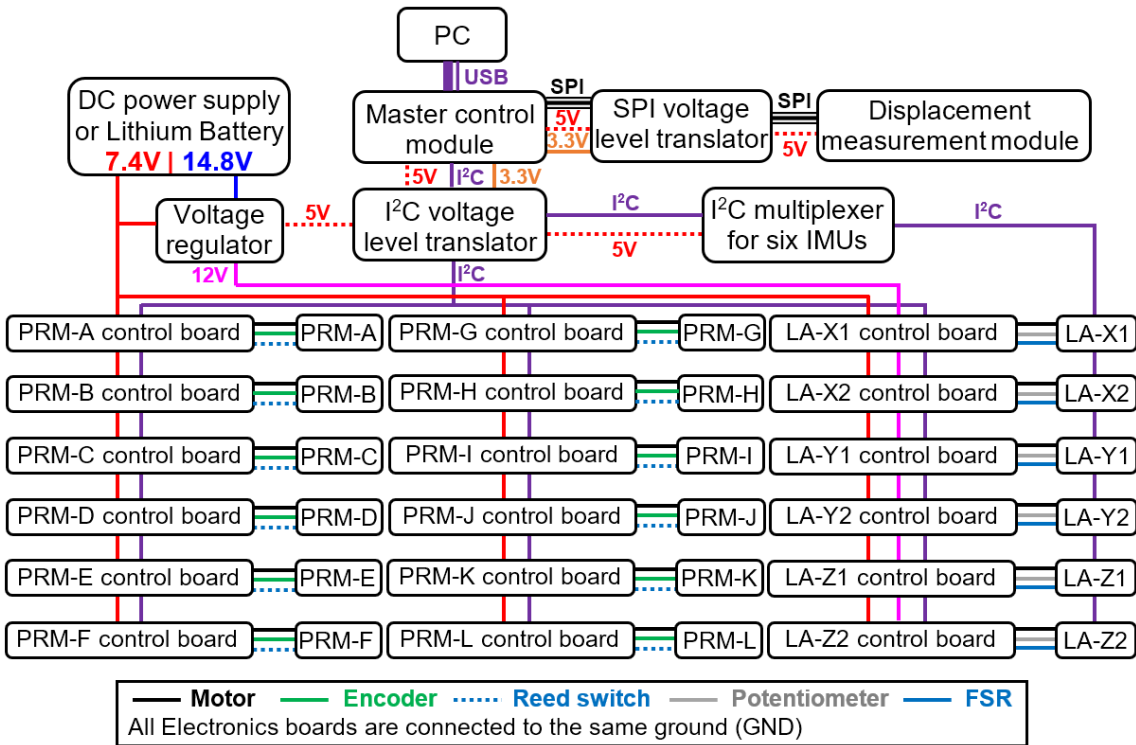


Figure 4.36 The simple wiring diagram of the electronic control system

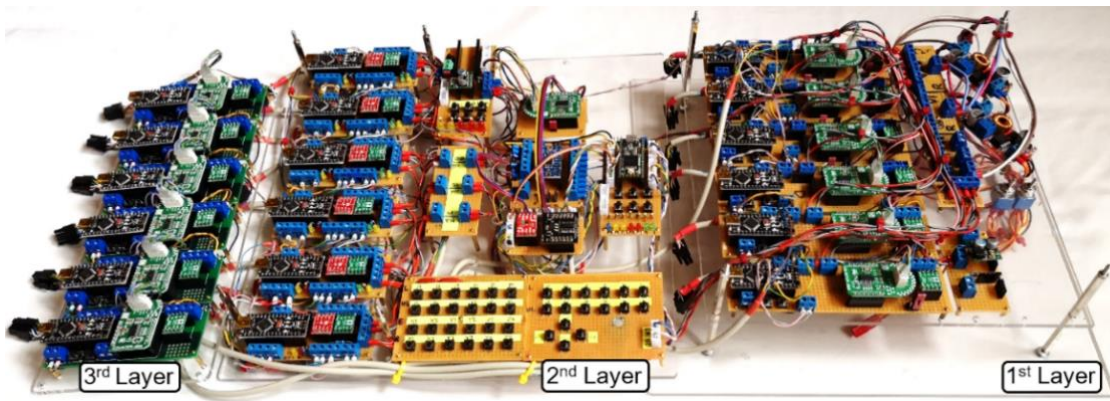
The wiring diagram begins with a PC used for writing code and programming into each microcontroller in control boards using open-source Arduino Software (IDE), which communicates with the master control module via a USB cable. Furthermore, a serial motor of the software is used to display and gather feedback data from the master control module, which transmits and receives data from slave control modules via I²C communication.

Due to the different operating voltages between the master module (3.3 V running for Teensy 3.23) and slave module (5V running for Arduino Nano), voltage level translator boards PCA9306 and TXS0104, are adopted for both I²C and serial peripheral interface (SPI) communications. These voltage translator boards also prepared to connect to other sensor or interface boards, which is generally compatible with 5V. However, there is an issue with the I²C bus used for assigning the IMU board address. The IMU board can only be assigned 0x68 and 0x69, which is not enough for six-LA modules. There, I²C multiplexer board TCA9548A is used to solve the problem.

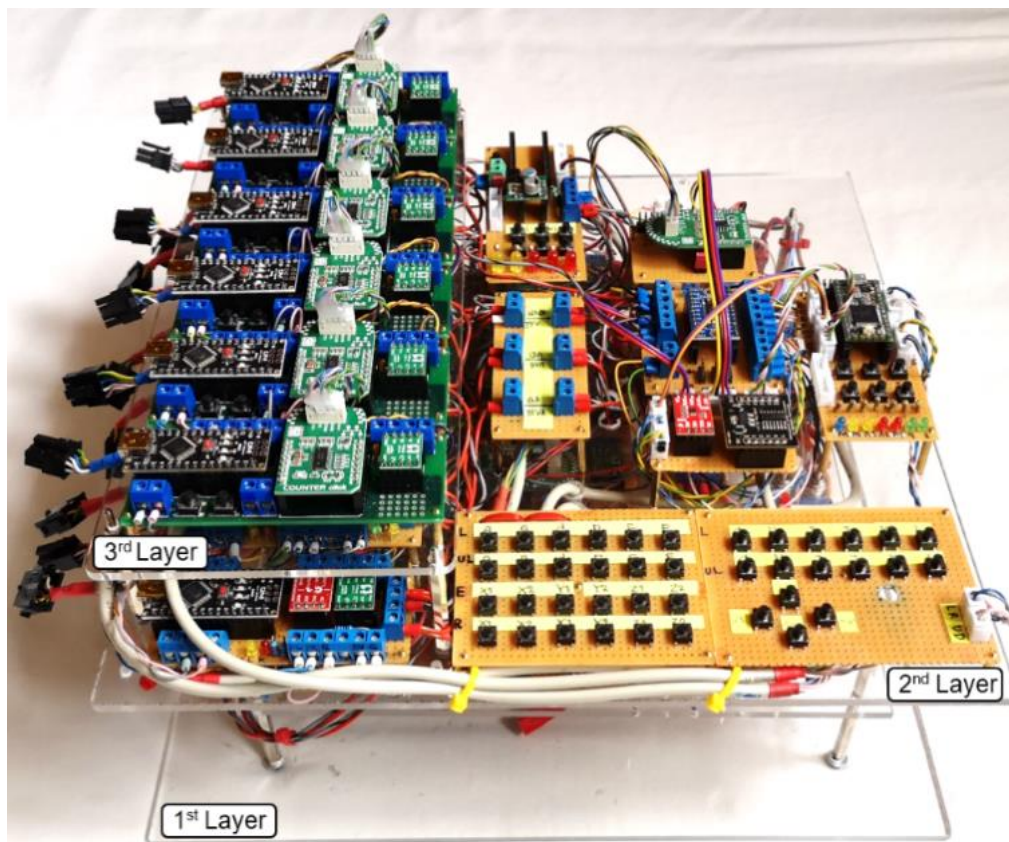
For the displacement measurement module, the encoder buffer COUNTER click board is used to gather the encoder signal generated by a miniature magnetic encoder to measure robot displacement. The encoder buffer board is used to read the encoder signal via SPI protocols rather than reading from the encoder directly using the interrupt function. Therefore, the encoder data can be stored, and the controller module can receive data anytime. Because the operating voltage between master and slave controller boards is different, the voltage level translator module is used to switch between 3.3 and 5 V.

To provide the main power supply to all electronics boards, two channels of the adjustable DC power supply are used. The first channel is adjusted as 7.4 V, 4 A to provide for three routes across the system. The first route is applied to all slave control boards. Another route is applied for all DC-gear motor drives integrated inside each slave PRM control board individually. The final route connects the voltage regulator board to step down the voltage becoming as 5 V, 2.5 A (D24V22F5, Pololu) and supplies the master control board. For the second channel, this route is adjusted as 14.8 V, 4 A sent to the voltage regulator module, providing 12 V output to apply for the LA motor drive module inside each LA control module. The output voltage of 7.4 V and 14.8 V are used instead of 5V and 12 V due to the same voltage and current values available for a lithium battery to supply all electronic control boards. Other details of this section, including microcontroller module selection, motor drive module selections, communication method, schematic diagrams of the electronic control boards, and implementations are detailed in Appendix B.1.

Figure 4.37 presents the implementation of three layers of electronic control and interface boards. The first layer is the first prototype of PRM control boards and the 12V power regulator module. The second layer is designed for placing the master control board, I²C multiplexer board, voltage level translator module, 5V power regulator board, displacement measurement module, key interface boards, and six-LA control boards, whereas the second prototype PRM control boards are mounted on the third layer.



(a)



(b)

Figure 4.37 Image of the electronic control system wiring: (a) expanded all electronic board layers and (b) three-layer integration of the electronic boards.

4.4 Summary

This chapter detailed the design of the mechanical components of the SE and PRM. The requirements of each element are analysed and calculated considering the required force for the SE and the rotational/braking force for the PRM. The required force for the SE was calculated considering pushing forces acting at the contact points in relation to the SE weight, compressive force, and COF of the contact point material. Furthermore, the required cable-pulling force for the unlocking stage of the PRM was calculated considering power spring specifications and minimum-required force to drag itself into the horizontal position. For the braking force analysis, a friction-based method was used to describe how to brake and release the rotational component for spooling and releasing the cable. This braking force defined the maximum force in the locking stage, which is related to the tension springs to produce pressing force between the braking and rotational components. Therefore, to overcome this pressing force for the unlocking stage, the actuator must produce high torques to overcome the pressing force to search for a proper actuator.

For the individual element implementations, the mechanical components for SE and PRM were designed based on the required force analysis, and several mechanical components were selected considering the off-the-shelf and small items rather than a custom design and manufacture due to the fast development and cost-effective development. For example, due to unknown parameters of power spring material specifications, a commercial retractable item that contained a power spring was used instead of a custom design. However, the required cable-pulling force of the power spring was calculated and then compared to the cable-pulling force of the selected power spring experimentally before integrating inside the PRM prototype. Similarly, after calculating the required pushing force for the SE, this component was used to search for the miniature LA. The force sensor (FSR) was also employed to measure and detect the pressing force of the LA end caps interacting with the environmental surface during locomotion. After designing a 3D model of the SE and PRM mechanism, 3D printing and CNC technologies were employed to manufacture each part of the SE and PRM. 3D printing technology was used for the non-frictional component and complex shape, which was difficult to manufacture with the CNC machine. The CNC machine was used to make frictional components that required long-life operations including rotational and braking components.

In order to control the SE and PRM, electronic control boards were designed and developed. I²C communication was chosen to communicate between a master control board and slave control boards. The master control board was used to

generate locking/unlocking stage procedures for PRMs and LA-slider lengths for robot configurations based on the control rules developed throughout this project.

To test the implemented SE and PRM, experiments are conducted in the following chapters to ensure that these components meet the requirements for developing a robot to perform locomotion tasks with the proposed actuation method.

Chapter 5 Individual Element Testing

This chapter describes demonstrations of individual elements, including the adjustable-length strut element (SE) and the passive-retractable joint with a cable locking mechanism (PRM). Henceforth, the SE is referred to as a linear actuator (LA). The LA-slider length and PRM-cable length are scaled compared to the standard measurements for reliable testing. The LA and PRM are tested individually to ensure that they provide suitable functions following force and torque requirements, as described in Chapter 4. The open and closed-loop position control for the LA-slider length and braking force for the PRMs are tested and evaluated before developing and demonstrating the structural configurations.

5.1 Strut Element Testing

The LA is the only active actuator used in a SE to exert two-directional forces (push and pull forces) for structural configurations. Therefore, to be able to control the structural shape, the overall length of the LA module, including the LA-base and LA-slider lengths, are scaled. The position control of the LA-slider with different payloads is then tested to determine the maximum payload allowance. Force sensors of the end caps are scaled and tested to measure the pressing forces to investigate wall pressing performance.

5.1.1 LA-Slider Length Feedback Scaling

To precisely control the slider displacement of a LA, the physical movement of the LA-slider length is calibrated and scaled. When the LA slider moves, the potentiometer sends output voltages (0 to 5V) to a control board through an analogue input pin of the controller module. The voltages are then converted to digital data 10 bits (0 to 1023) via an Analog to Digital Converter module (ADC), which is integrated into the microcontroller. However, this digital data is more extensive than the physical distance measured by the linear scale measurement (0 to 100mm). Therefore, the potentiometer voltage, the digital data, and the physical length of the LA slider are scaled, as detailed in Appendix C.1

To demonstrate slider displacement scaling accuracy, the displacement testing structure is made; it consists of six-LA modules mounted on aluminium bars, which are mounted onto a backplane. The commercial-linear-scale measurement is used to measure the LA-slider length and attached to a display unit. The linear scale sensor is attached to the LA-slider tip, which is able to move along the beam of

the linear scale placed between two parallel aluminium bars. The experimental setup is presented in Figure 5.1.

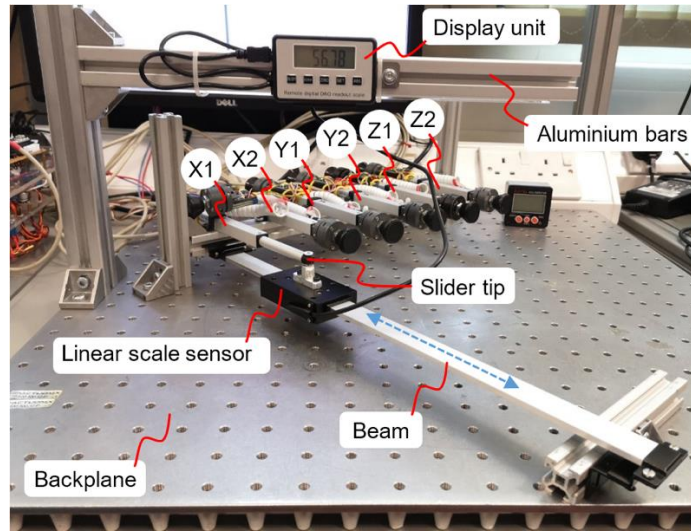


Figure 5.1 Experimental setup of six LA-slider scaling demonstrations.

After developing software to measure LA-slider length, slider movement accuracy is demonstrated and evaluated. LA sliders are moved manually by applying a control signal for a motor drive. The pulse width modulation (PWM) is employed to generate the control signal called the duty cycle (DT), which is between 0% (stop) and 100% (the highest speed). However, the duty cycle of the Arduino Nano provides the PWM function to generate the duty cycle, which is eight-bit data (0 to 255 values), as illustrated in Figure 5.2. Hereafter, the value of 0 duty cycle refers to 0% of the PWM, and the value of 255 duty cycle refers to 100% of the PWM.

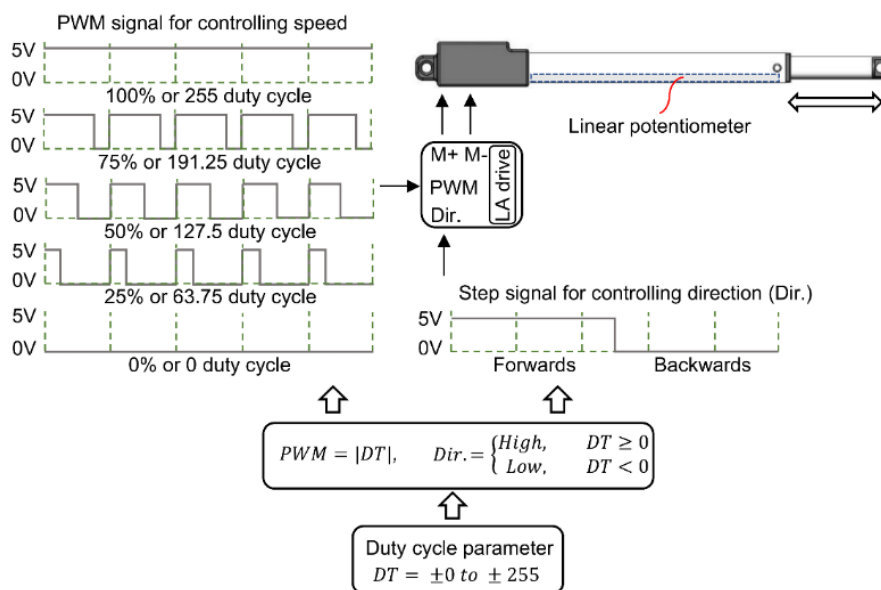


Figure 5.2 Pulse width modulation (PWM) signal and parameters to control LA slider speeds and directions

To change the direction of the LA-slider, the direction input signal (Dir.) must be applied to the motor drive separately apart from the PWM signal. If a logic “High” is applied, the LA slider will move in a forward direction. In contrast, if a logic “Low” is applied, the LA slider will move backwards. Both PWM (speed) and directional signals can perform two stages, namely open-loop control and closed-loop control. For the open-loop control system, speed and direction can be defined through a duty cycle parameter directly before sending to a PWM function. For the closed-loop control system, the duty cycle value and directional value of the LA slider can be generated by a controller module mathematically, and the directional value can be decoded from the value of the duty cycle parameter. If a value is higher than or equal to zero, the motor-directional signal will be a logic “high”. On the other hand, if the value is under zero, the motor direction signal will be a logic “low” (see Figure 5.2).

Two microswitches on an interface board are used to control the LA slider to move forwards and backwards manually. The small values of the duty cycle are applied to move the slider slowly, which increases five values for every sampling time (10 ms) while holding the bottom down. The different-slider-target lengths are defined by increasing every 5 mm, starting from 0 mm to 100 mm. Slider displacements are measured by the commercial-linear-scale measurement and the potentiometer data displayed on the serial monitor simultaneously, as shown in Figure 5.3.

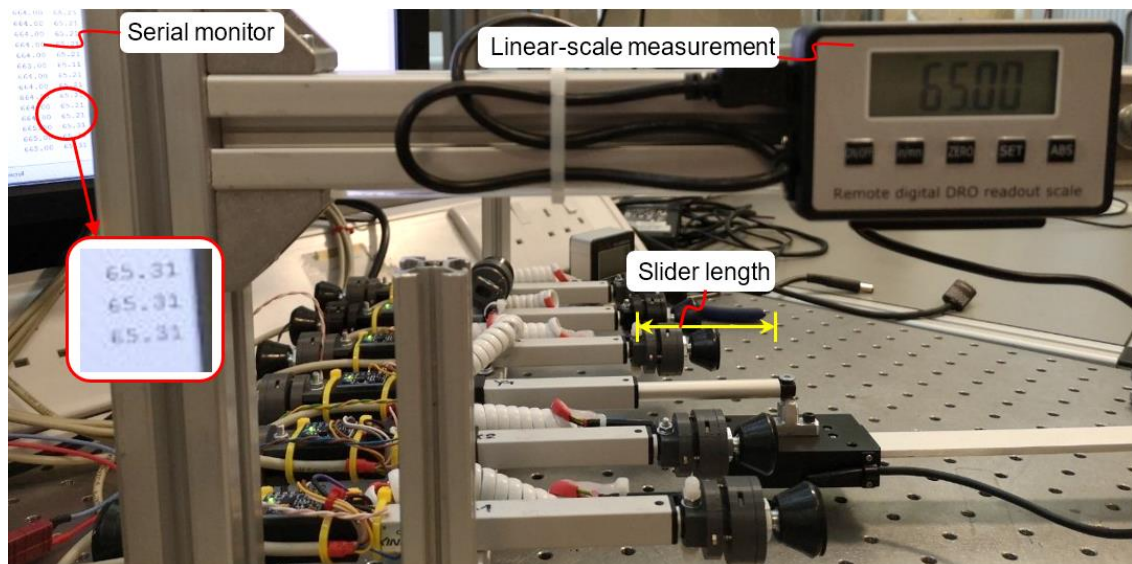


Figure 5.3 Example image to compare the LA-slider length data between the linear-scale measurement and the potentiometer displayed on the serial monitor provided with the Arduino programme.

Figure 5.4 presents the experimental results of the LA-X1 and LA-X2 slider accuracy; it is revealed that the LA-slider length error occurred within $\pm 1\text{mm}$.

However, this error is acceptable in this research, Similarly, for the experimental results of the LA-Y1, LA-Y2, LA-Z1, and LA-Z2, the displacement errors are under $\pm 1\text{mm}$, as presented in Appendix C2.

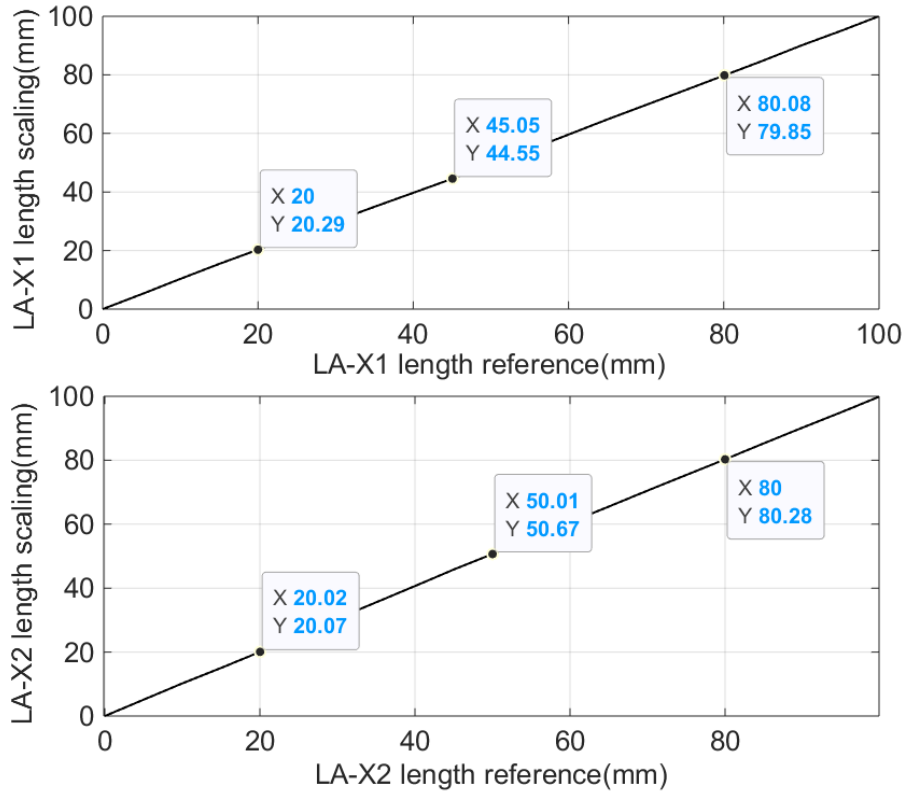


Figure 5.4 The LA-slider scaling accuracy experiments: (top) LA-X1 length scaling and (bottom) LA-X2 length scaling.

5.1.2 Open-Loop Control Experiments without Payloads

The open-loop control experiment is to test the step response of the LA-slider motion by defining the travelling time and duty cycle significantly related to the slider position. The block diagram of the open-loop control is presented in Figure 5.5

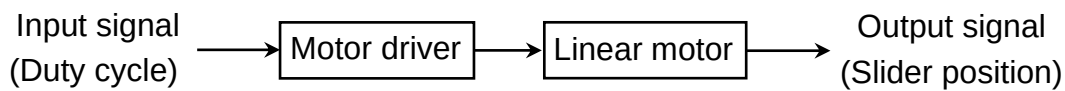


Figure 5.5 Block diagram of the open-loop control experiment.

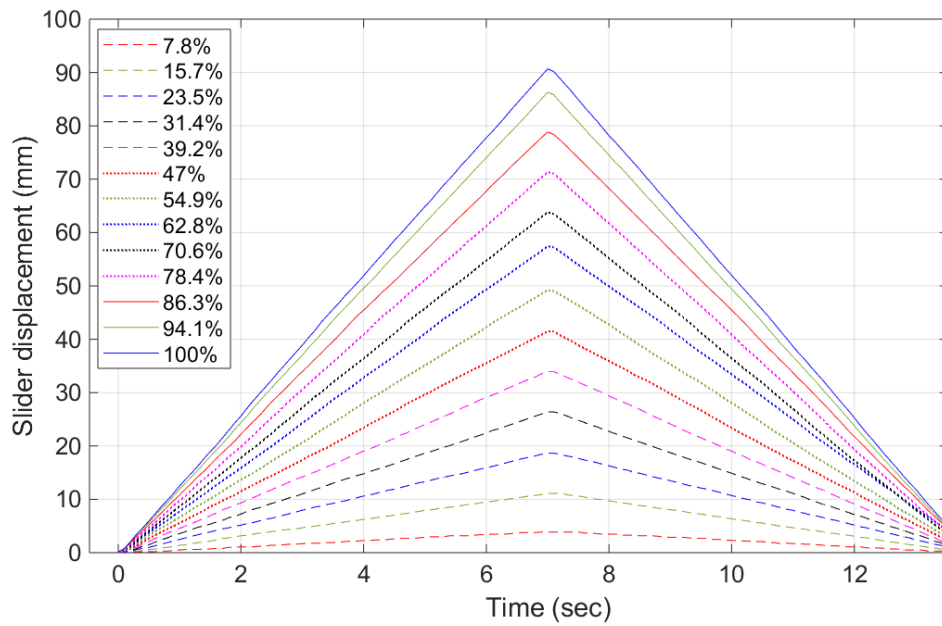


Figure 5.6 Step input response of the slider without payloads, applying 7.8% to 100% duty cycles.

Different step inputs are defined between 7.8% and 100% of duty cycles and run the time of 7 s downwards and 6.5 s upwards. The upwards time of 6.5 s is set to protect the slider mechanism from colliding with the original slider point in fast-speed movements. The 7.8% duty cycle is the first value due to the threshold of the duty cycle obtained from the motor's dead time finding experiment. The experimental results of the open-loop control are presented in Figure 5.6. The overall trend of the graph is a linear increase. The duty cycle directly relates to the powers applied for the LA drives also related to the speed movement of the LA slider. The more power applied, the higher the slider moving speed. The relationship between movement speeds and duty cycle is presented in Figure 5.7.

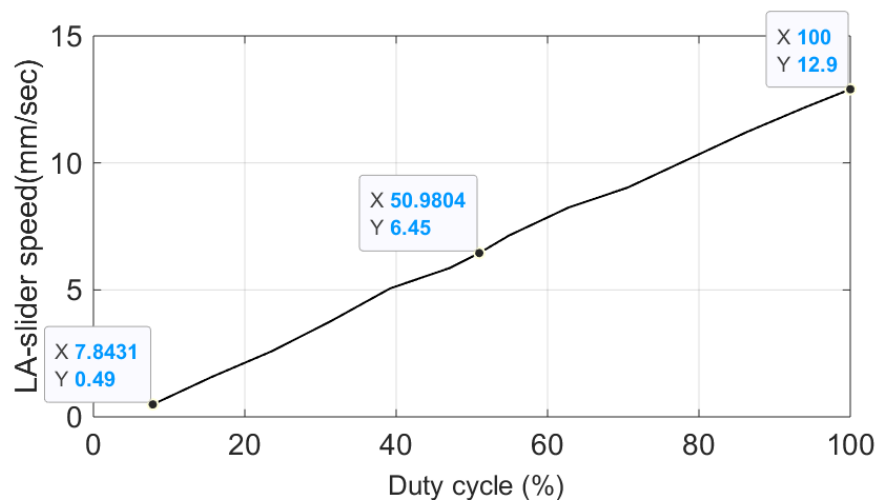


Figure 5.7 Relationship between duty cycle and the speed of the LA-slider without payloads in the open-loop system.

5.1.3 Open-Loop Control Experiments with Payloads

This experiment involves testing the effect of the payload while extending and retracting the LA slider on a vertical axis. This payload simulates the elastic cable or spring force against the slider movement.

From the load curves of the L12 specifications [102], the maximum slider speed without payload is 13 mm/s, and the minimum slider speed with a 40N payload is 4.8 mm/s. Therefore, the 100% duty cycle providing a maximum speed is applied to drive the LA slider, and the time for the slider extending is fixed as 7 s (downward) and the slider retracting is also fixed as 7 s (upward). The weights of the payloads are 100 g, 250 g, 500 g, 750 g, 1 kg, 1.25 kg, 1.5 kg, 1.75 kg, 2 kg, 2.25 kg, 2.5 kg, 2.75 kg, 3 kg and 3.25 kg, though the LA slider can carry payload weight up to 3.8kg experimentally. The maximum payload weight is set at 3.25kg to prevent the screw and gearbox of LA slider damage. The experimental setup is presented in Figure 5.8.

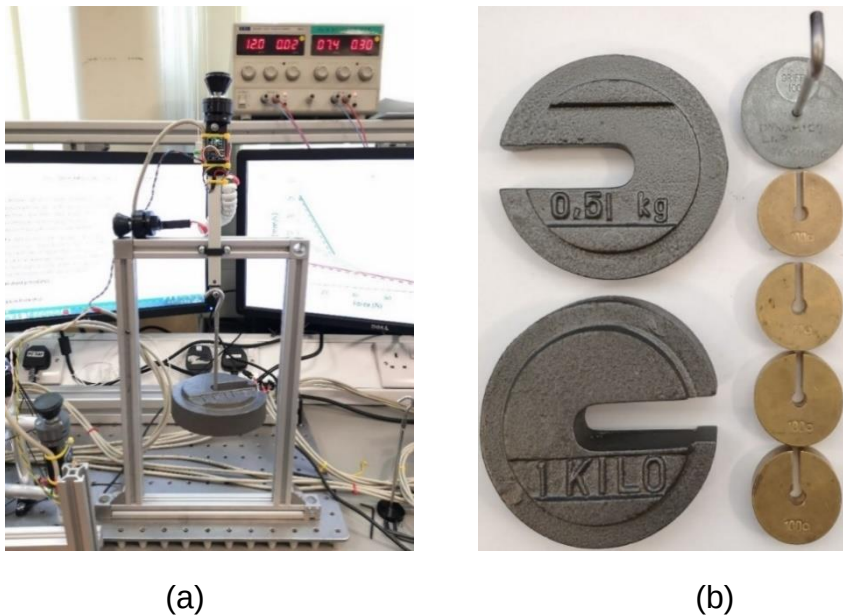


Figure 5.8 Payload carrying experimental setup: (a) opened-loop payload test platform and (b) payloads.

Figure 5.9 presents the experimental results of the LA-slider movements when carrying payloads. These results suggest that the payload weights slightly affect the slider speed compared to un-payload weight response. The payload weight slightly affects the slider speeds in the downward movements. For example, the maximum speed of the slider without payloads is 15.9 mm/s, and the slider speed slightly increased to 16 mm/s when carrying the 3 kg payloads. Differently, for the upward movements, the payload weights significantly affect the slider speeds compared to the downwards response. For example, the maximum speed of the

slider without payload was -14.9 mm/s, while the maximum speed of the slider reduced to -7.9 mm/s when carrying the 3 kg payloads.

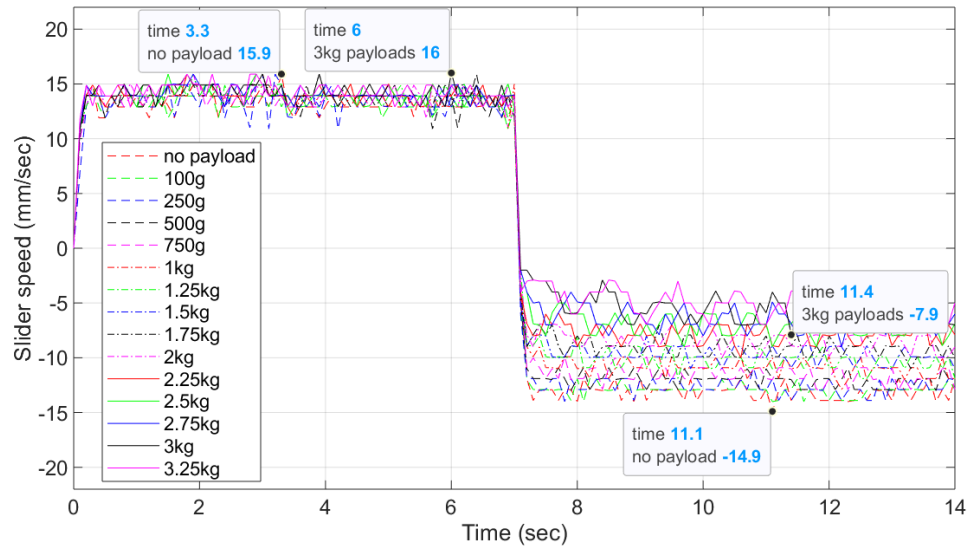


Figure 5.9 Experimental results of the LA-slider movements in the open-loop system where different payloads are carried, 100g to 3.25kg payloads

5.1.4 Closed-Loop Position Control

In order to control the LA-slider length accurately, the closed-loop position control is employed. The proportional controller (P-controller) is used to control the LA due to the functional simplicity and reliability controller, providing consistency and robust performance in a closed-loop control system [103]. The block diagram of the closed-loop control system is presented in Figure 5.10.

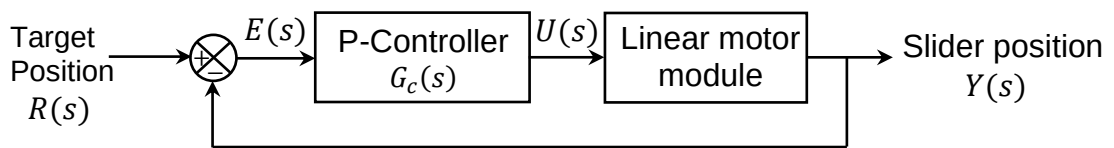


Figure 5.10 The closed-loop control with the P-controller block diagram.

Initially, the PI (Proportional-Integral) and PID (Proportional-Integral-Derivative) controllers are tested. However, the integral term makes the system overshoot because the LA-slider could not move fast enough to respond to the control signal, resulting in an integral windup effect. Although the derivative term may reduce the overshooting signal, it also produces noise that makes the system unstable. For this reason, the P controller is selected to control LA-slider length.

Using the second method of the Ziegler-Nichols tuning rule [104] and the trial-and-error method to find a suitable proportional gain that provides small steady-state error without per cent overshoot, parameter K_p of 450 can be experimentally

obtained as detailed in Appendix C.3. In order to evaluate controller performance, the LA-slider position control carrying payloads is demonstrated. The 1 kg, 2 kg and 3 kg payload weights are hung on the LA-slider tip travelling from 0 to 50 mm downwards and 50 mm to 10 mm upwards. The experimental setup is shown in Figure 5.11, and the results are presented in Figure 5.12.

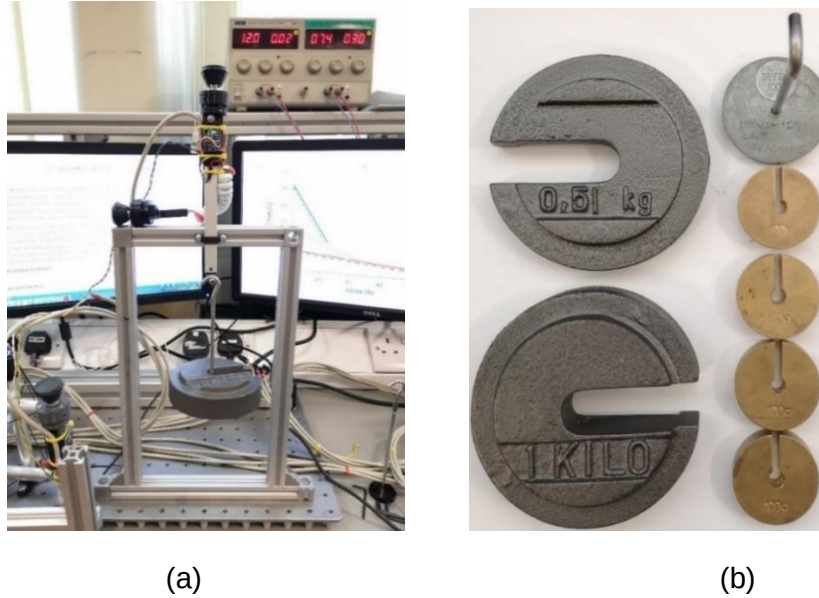


Figure 5.11 The payload carrying experimental setup: (a) payload-carrying procedure and (b) example of different weights of the payloads.

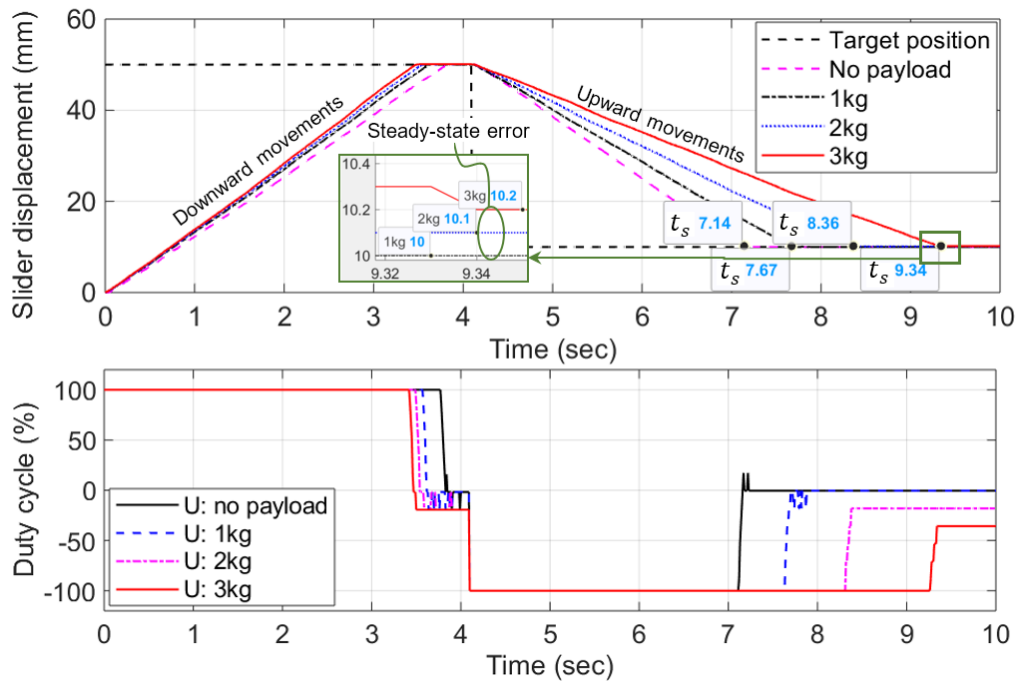


Figure 5.12 Closed-loop control with P-controller: (top) the LA-slider displacement and (bottom) control signals (u) or duty cycle applied for a LA drive; t_s is the settling time of the slider displacements.

The results suggest that the P-controller is able to produce control signals to control the LA-slider travelling to the target positions without overshoot. Small

steady-state errors of 0.1 mm and 0.2 mm occur when carrying payload weights of 2 kg and 3 kg, respectively. These small steady-state errors are acceptable in this research. Additionally, the weights of the payloads slightly affect the LA-slider motions in the downward movements and significantly affects the LA-slider motion in the upward movements in the same way as the previous demonstration. For example, in the upward movements, the settling time (t_s) of the LA-slider without payload is 7.14 s and significantly increases to 9.34 s when carrying 3 kg payload weights, as shown in Figure 5.12 (top).

In order to ensure that the P-controller can be used to control the LA-slider movements with carrying payloads over the whole length of the LA module, different target positions in upwards movement are tested, including 10mm, 20mm, 30mm, 40 mm, 50 mm, 60 mm, 70 mm, 80 mm and 90 mm. The 1 kg, 2 kg and 3 kg payloads are taken on the LA-slider tip. Experimental data are summarised in Table 5.1.

The experimental results show that the P-controller could control the LA slider travelling to different target distances without target overshooting; there were small steady-state errors of approximately 0.1mm when carrying 1 kg and 2 kg payloads, and 0.2mm–0.3mm when carrying a 3 kg payload; however, it is expected that the small error does not significantly affect the robot's structural configuration.

Table 5.1 Experimental results of the LA-slider displacement control with payloads travelling in upwards movement by using P-controller gain of 450.

Payload (kg)	Displacement error at different target positions					
	20mm to 10mm		30mm to 20mm		40mm to 30mm	
	t_s (sec)	$e_{s.s}$ (mm)	t_s (sec)	$e_{s.s}$ (mm)	t_s (sec)	$e_{s.s}$ (mm)
0	0.79	-0.03	0.81	-0.03	0.81	0
1	0.94	-0.03	0.93	-0.07	0.92	0.1
2	1.08	-0.13	2.33	-0.16	1.09	0.1
3	1.33	-0.23	1.33	-0.26	1.34	0.2
Payload (kg)	50mm to 40mm		60mm to 50mm		70mm to 60mm	
	t_s (sec)	$e_{s.s}$ (mm)	t_s (sec)	$e_{s.s}$ (mm)	t_s (sec)	$e_{s.s}$ (mm)
	t_s (sec)	$e_{s.s}$ (mm)	t_s (sec)	$e_{s.s}$ (mm)	t_s (sec)	$e_{s.s}$ (mm)
0	0.78	-0.03	0.72	-0.03	0.72	0
1	0.9	-0.03	0.83	-0.06	0.84	-0.1
2	1.07	-0.13	1.01	-0.16	1.01	-0.2
3	1.33	-0.23	1.26	-0.26	1.3	-0.3
Payload (kg)	80mm to 70mm		90mm to 80mm		95mm to 90mm	
	t_s (sec)	$e_{s.s}$ (mm)	t_s (sec)	$e_{s.s}$ (mm)	t_s (sec)	$e_{s.s}$ (mm)
	t_s (sec)	$e_{s.s}$ (mm)	t_s (sec)	$e_{s.s}$ (mm)	t_s (sec)	$e_{s.s}$ (mm)
0	0.67	-0.03	0.67	0.04	0.29	0
1	0.79	-0.03	0.76	-0.06	0.32	-0.1
2	0.95	-0.13	0.93	-0.16	0.37	-0.1
3	1.2	-0.23	1.29	-0.26	0.47	-0.2

Another experiment to evaluate the P-controller performance involves applying multiple-target distances and repeated-target distances of the LA-slider movement with and without payload. The first experiment involves applying multiple-step inputs to control LA-slider displacements. The target distances are defined as 0 to 15 mm, 15 mm to 45 mm, 45 mm to 85 mm downwards, and 85 mm to 65 mm, 65 mm to 35 mm and 35 mm to 5 mm upwards. These target distances are selected based on the short, medium, and long distances covering the LA-slider stroke. The experimental results are presented in Figure 5.13.

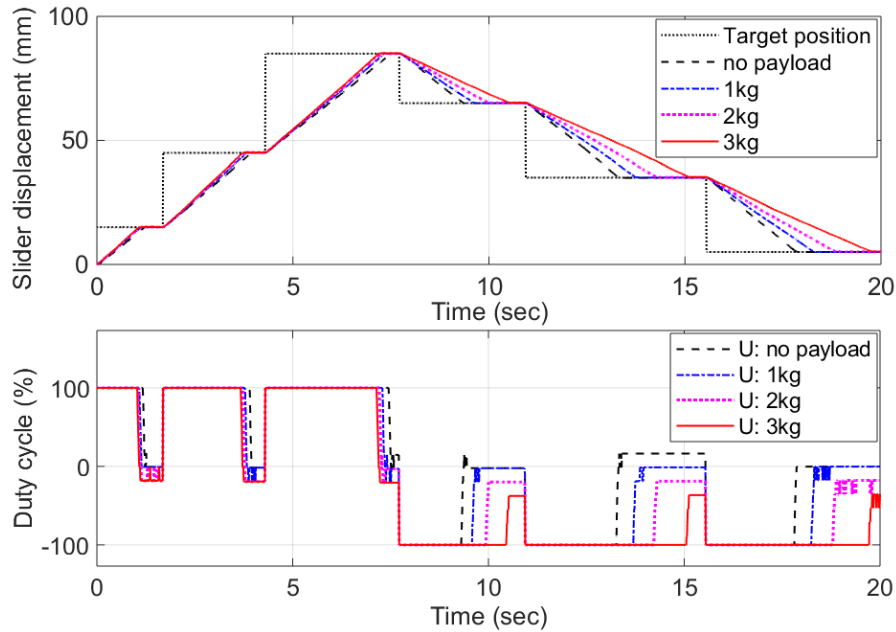


Figure 5.13 Multiple-step responses of the LA-slider movement with and without payloads: (top) the LA-slider position and (bottom) the control signal (u).

The experimental results show that the P-controller can control the LA-slider positions tracking the multiple-target positions without overshooting. However, the weight (1 kg, 2 kg, and 3 kg) of the payloads affects the settling time and steady-state error of the LA-slider movement, which is similar to the previous experimental results. The steady-state error of 0.2 mm only occurs in the upwards movement when the LA-slider carries a 3kg payload, as seen in the blue cells in Table 5.2.

Table 5.2 Summary of experimental results of the multi-step input of the LA slider movement with and without payloads.

Payload weight (kg)	Direction	Target distance (mm)	$p_{s.s}$ (mm)	t_s (sec)	$e_{s.s}$ (mm)
0	Downwards	0 to 15	15	1.2	0
1			15	1.11	0
2			15.1	1.08	-0.1
3			15.1	1.05	-0.1

Payload weight (kg)	Direction	Target distance (mm)	$p_{s.s}$ (mm)	t_s (sec)	$e_{s.s}$ (mm)
0	Downwards	15 to 45	45.01	2.19	-0.01
1			45.01	2.07	-0.01
2			45.11	2.02	-0.11
3			45.11	1.97	-0.11
0	Downwards	45 to 85	84.92	3.07	0.08
1			85.02	2.91	-0.02
2			85.02	2.84	-0.02
3			85.12	2.77	-0.12
0	Upwards	85 to 65	65.01	1.53	-0.01
1			65.01	1.79	-0.01
2			65.11	2.13	-0.11
3			65.21	2.64	-0.21
0	Upwards	65 to 35	34.91	2.31	0.09
1			35.01	2.75	-0.01
2			35.11	3.27	-0.11
3			35.21	4.1	-0.21
0	Upwards	35 to 5	5	2.3	0
1			5	2.76	0
2			5.1	3.33	-0.1
3			5.2	4.25	-0.2

The strut module confronts inconstant forces generated by tension elements during robot configurations and locomotion. Therefore, another experiment involves taking inconstant forces to the LA-slider in closed-loop position control. Three tension springs including 0.17, 0.4, and 0.83 N/mm (see Figure 5.15 (a)) are selected as the inconstant-force payload when the LA-slider is moved. These tension spring values are chosen based on maximum advisable extensions to cover a whole range of the maximum LA-slider stroke (short, medium, and long displacements) to produce compressive forces (F_{cs}) dynamically, which is the opposite-directional force of the payload weight used in previous experiments. The tension spring parameters and target positions of the LA slider are summarised in Table 5.3.

Table 5.3 Tension spring specifications and target positions.

Parameters	Tension spring 1	Tension spring 2	Tension spring 3
Wire diameter (mm)	0.7	1.22	0.8
Outside diameter (mm)	7.5	12.7	5.5
Free length (mm)	38.5	38.1	39
Maximum advisable extension (mm)	67.5	80	25.6
Load at minimum working length (N)	12.8	32.85	25.2
Rate (N/mm)	0.17	0.4	0.83
Maximum target position of the LA slider (mm)	60	80	25

Figure 5.14 presents the relationship between spring elongations and compressive forces, which are used to oppose the LA-slider movement. These compressive forces of three extension springs are measured experimentally using a commercial spring balance in the laboratory. The results show that the compressive forces increase while elongating the spring, producing inconstant forces to apply to the LA slider.

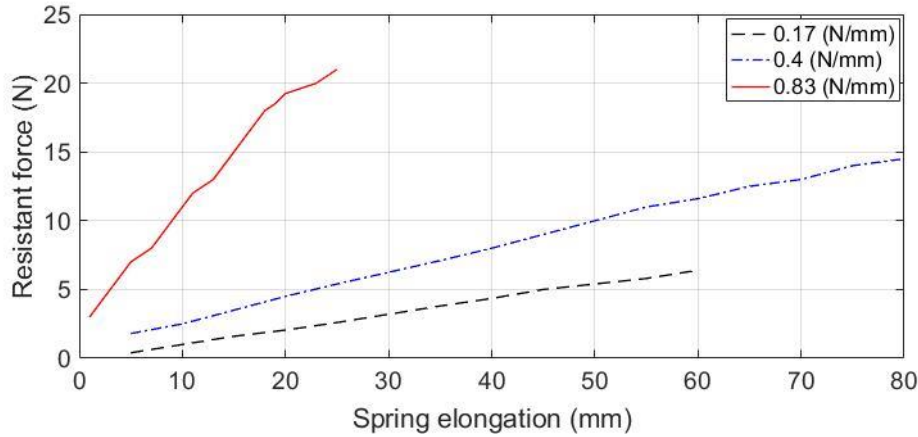


Figure 5.14 Relationship between the resistance force of the extension springs and the spring elongation.

For the experimental setup, one side of the spring is fixed to the aluminium bar, and another side is attached to the slider tip using nuts and screws, as illustrated in Figure 5.15(b), which is the initial stage. The different target positions are defined following the maximum advisable extensions of each spring, such as the 80 mm target position for the 0.4 N/mm spring.

For the experimental procedure, the multiple-target displacement is demonstrated to evaluate P-controller performance. Three target position groups are defined depending on each tension spring extension range. The initial length of the LA slider (p_{ini}) and target position of the LA slider (p_{ref}) of each group are summarised in Table 5.4.

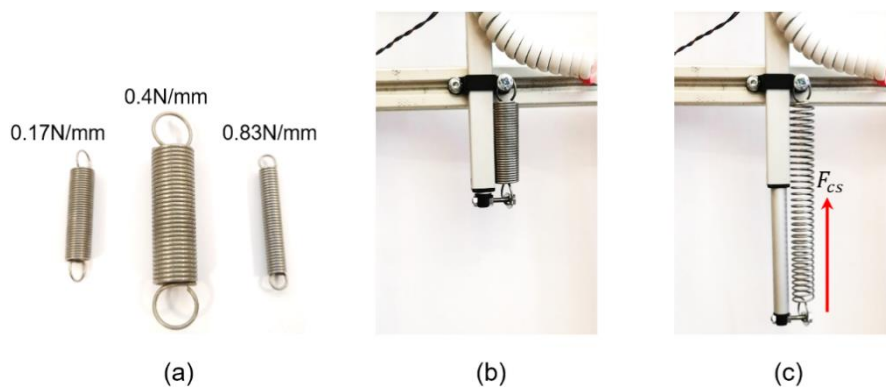


Figure 5.15 Spring payload experimentations: (a) 0.17N/mm, 0.4N/mm, and 0.83N/mm spring payload, (b) the initial LA-slider position, and (c) the compressive force direction and the example movement to elongate the tension spring.

Table 5.4 Summary of the multiple-target displacements of the three groups for the LA-slider movement carrying the inconstant payload experiment; the p_{ini} is the initial length of the LA-slider and the p_{ref} is the target length of the LA-slider.

Step No.	Spring rate					
	0.17N/mm		0.4N/mm		0.83N/mm	
	p_{ini} (mm)	p_{ref} (mm)	p_{ini} (mm)	p_{ref} (mm)	p_{ini} (mm)	p_{ref} (mm)
1	0	10	0	20	0	5
2	10	30	20	40	5	15
3	30	60	40	80	15	25
4	60	45	80	60	25	20
5	45	15	60	30	20	10
6	15	5	30	10	10	0

The experimental results of all target position groups, particularly time response of the LA-slider motions, are similar. Therefore, the experimental results of the multiple-target position control in the second group are selected to show the P-controller performance because the time responses for LA-slider motions between carrying the payloads and without payload are apparent, as shown in Figure 5.16. The experimental results of the first and third target groups are presented in Appendix C.4.

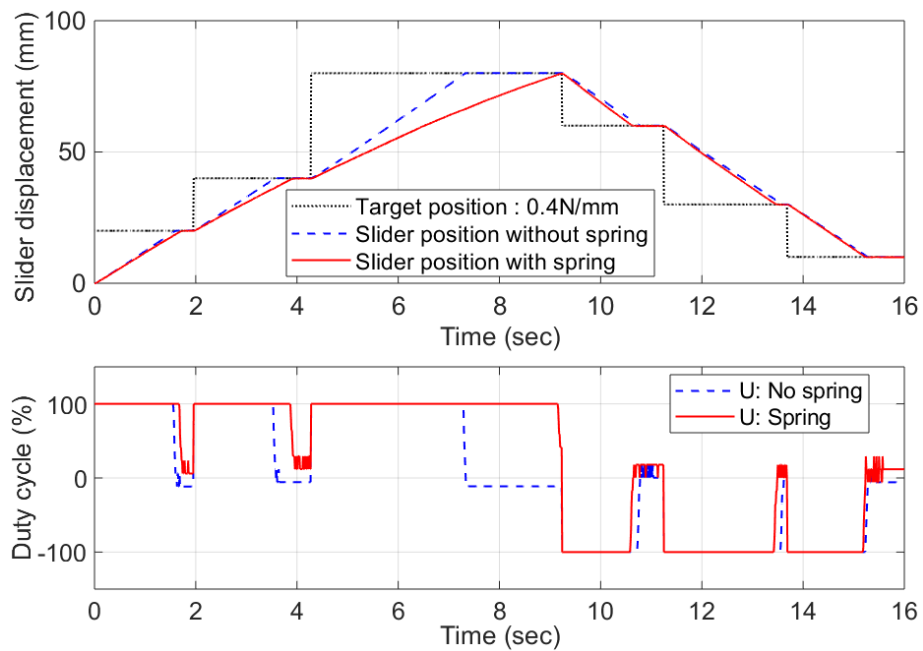


Figure 5.16 The multiple-target response of the LA-slider moving to the target positions with 0.4 N/mm tension spring payload: (top) the slider position and (bottom) the proportional control signal (u).

The experimental results suggest that the P-controller is able to control the LA-slider travelling to different target positions with small steady-state error within 0.1 mm and without target overshooting. The controller is able to adaptively generate

the control signal to compensate for irregular compressive forces varying on the spring elongation while extending and retracting LA-slider lengths. The inconstant compressive forces of the tension spring affect the rise time of the LA-slider movements, particularly when the direction of the LA-slider contrasts the direction of the compressive force in a downwards motion. For example, the rise time of the target positions travelling from 40mm to 80mm with payload is 4.73s, which is slower than the LA-slider movement without payload of 2.94s, as shown in the blue cells in Table 5.5.

Table 5.5 Experimental result summary of the multiple-step response of the LA-slider movement with 0.4 N/mm extension spring payload

Spring rate (N/mm)	Direction	p_{ref} (mm)	$p_{s.s}$ (mm)	t_s (sec)	$e_{s.s}$ (mm)
0	Downwards	0 to 20	20.07	1.57	-0.07
0.4			19.97	1.69	0.03
0		20 to 40	40.03	1.55	-0.03
0.4			39.93	1.89	0.07
0		40 to 80	80.06	2.94	-0.06
0.4			79.77	4.73	0.23
0	Upwards	80 to 60	60	1.44	0
0.4			59.9	1.3	0.1
0		60 to 30	30	2.3	0
0.4			30	2.17	0
0		30 to 10	10.03	1.57	-0.03
0.4			9.93	1.52	0.07

The results show that the P-controller is able to control the LA-slider displacement while carrying inconstant payloads durably, reliably, and accurately; therefore, it is adopted to control the six-LA modules in this project.

5.1.5 Force Sensor Scaling

This section discusses how to calibrate the pressing force of the selected force-sensitive resistor (FSR). The force-resistance characteristic of the FSR, which relates to the size and location of the pressing tip pressing on the circular active area, is first conducted. Then, FSR output voltages (v_{FSR}) is measured using different payload weights to calculate the theoretical pressing force (F_{p1}). The FSR output voltages are sent to the analogue to digital converter module to generate 10-bit data scaled by a matching function to generate a pressing force data (D_{dout}). However, the pressing force data are multiplied by an additional gain (K_F) to calibrate the calculated-actual pressing forces (F_{p2} and F_{p3}), matching the theoretical pressing force (F_{p1}). The block diagram of the force sensor scaling procedure is presented in Figure 5.17.

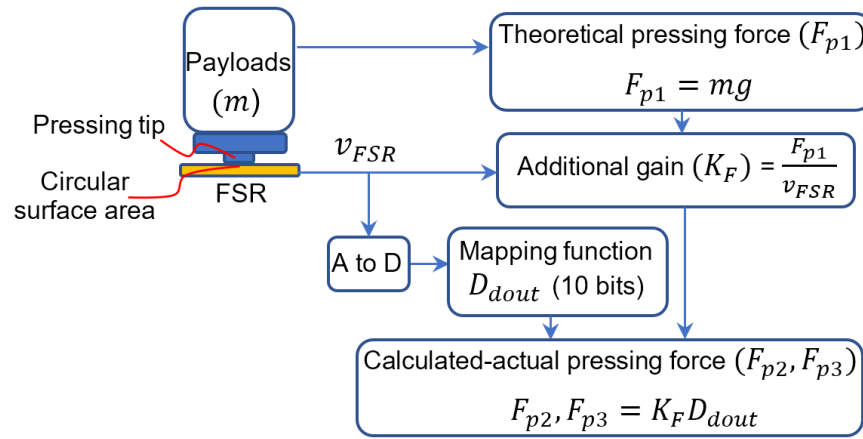


Figure 5.17 Block diagram of the force sensor scaling.

All experimental procedures and parameters of the force sensor scaling are described in Appendix C.5.

Table 5.6 presents the experimental data calculated by the force sensor scaling procedures. The results show that the calculated-actual pressing force F_{p2} and F_{p3} values (light-green highlighting) are similar to the theoretical pressing force F_{p1} (light-yellow highlighting). Therefore, it is expected that the selected FSR could be properly used to detect the pressing force of up to 19.6N acceptable for use in this project.

Table 5.6 The force sensor scaling experimental data.

Payload (m) (g)	Reference value and calculated data					Experimental data		
	V_{FSR} (V)	F_{p1} (N)	K_F	D_{dout}		D_{dout}	F_{p2} (N)	F_{p3} (N)
				Lower range	Upper range			
30	0.177	0.294	0.001661	0	190	179	0.29	0.25
40	0.342	0.392	0.001146	191	334	334	0.38	0.47
50	0.525	0.49	0.000933	335	518	518	0.48	0.6
60	0.735	0.588	0.0008	519	732	732	0.57	0.74
70	0.84	0.686	0.000817	733	842	842	0.69	0.76
80	0.92	0.784	0.000852	843	917	917	0.78	0.77
90	1.139	0.882	0.000774	918	1141	1141	0.88	0.82
100	1.225	0.98	0.0008	1142	1226	1226	0.98	0.92
200	1.54	1.96	0.001273	1227	1900	1550	1.97	2.05
300	1.946	2.94	0.001511	1901	2320	1949	2.95	2.98
400	2.5	3.92	0.001568	2321	2600	2522	3.96	4.01
500	2.73	4.9	0.001795	2601	2771	2771	4.97	4.8
600	2.86	5.88	0.002056	2772	2891	2891	5.94	5.75
700	2.924	6.86	0.002346	2892	2961	2961	6.95	6.78
800	2.988	7.84	0.002624	2962	3026	3026	7.94	7.81
900	3.022	8.82	0.002919	3027	3110	3056	8.92	8.95
1000	3.094	9.8	0.003167	3111	3160	3130	9.91	9.89
1500	3.223	14.7	0.004561	3161	3280	3270	14.91	15.13
2000	3.313	19.6	0.005916	3281	3360	3355	19.85	20.18

5.1.6 Wall Pressing Performance

The purposes of this experiment are to determine the strut module specifications and limitations, including accessible environment size, maximum strut module angle, and maximum payload weight allowance.

The first experiment determines the maximum extension length of the LA holding in a vertical direction and measures the pressing force between the end caps and a simple platform that imitates a climbing environment. A simple platform consists of two aluminium profiles (W30xD30xH390 mm) on a vertical axis called vertical poles, which are mounted on an aluminium profile placed on a horizontal axis called a horizontal pole mounted on a backplane. The two vertical poles can slide the horizontal pole to adjust the displacement between them to allow a pipe diameter adjustment. Two transparent acrylic sheets (3 mm thickness) are attached to the vertical pole surface to increase the COF between contact points. The simple platform of this experiment is presented in Figure 5.18.

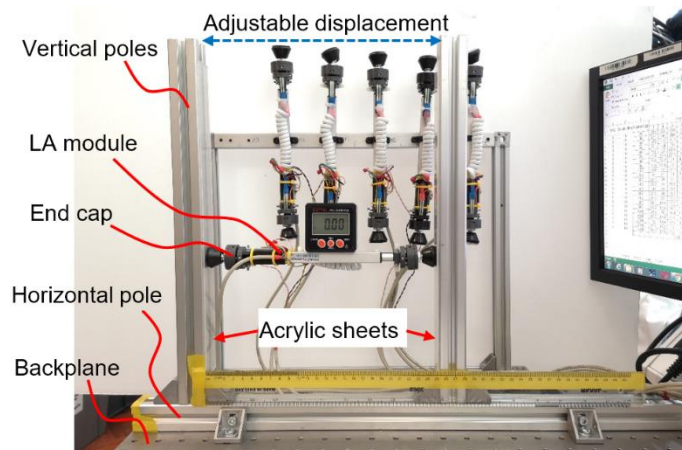


Figure 5.18 Experimental setup for the wall-press demonstration.

The maximum and minimum distance of the vertical poles, which relate to the strut module specification, are determined. Firstly, the minimum distance can be obtained by adjusting the maximum slope angle of both end caps (θ_E), which is approximately 29.5 degrees. The distances between the two poles are then adjusted until the acrylic plates touching the end caps (see Figure 5.19 (a)). Secondly, the maximum distance can be obtained using the same method. The LA length is extended to 93mm, which is the maximum slider length that can make the LA module rigid, with a maximum slope angle of the end caps (29.5 degrees). The LA module is then placed between the vertical poles, and the distance of both vertical poles is adjusted until touching the end caps (see Figure 5.19(b)).

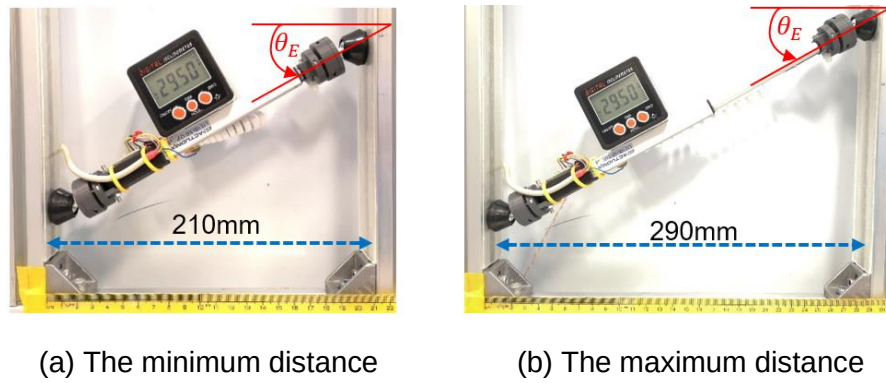


Figure 5.19 Maximum and minimum distance for holding the LA module.

The experimental results suggest that the minimum and maximum ranges that the LA module is able to hold to the vertical poles at the 29.5 degrees of the end cap slope, are 210 mm and 290 mm, respectively. Therefore, the proposed robot would be able to access a narrow environment that has inner diameters between 210 mm and 290 mm at the maximum end cap angle allowance. The maximum distance of the vertical poles is 330 mm. However, the holding capability of the LA module would be unstable at this distance because, if the end cap angle is slightly changed, the LA will fall due to the limitation of the LA-slider extension. Therefore, if the robot needs to access the narrow areas of diameters between 290mm to 330mm, the angle of the LA module should be restricted based on environmental requirements, as summarised in Table 5.7.

Table 5.7 End-cap-angle allowance (θ_E) for holding the LA module on the vertical poles with a distance between 290 mm and 330 mm

Distance between two poles (mm)	290	295	300	305	310	315	320	325	330
End-cap-angle allowance (degree)	29.5	27	25	23	20	17	14	11	0

For the wall pressing experiment, the relationship between the pressing force of the end caps, end cap angle, and the vertical pole width are demonstrated in order to examine for the wall pressing limitation of the LA module or strut module, leading to the design of robot configurations for locomotion.

In order to measure the pressing force between both end caps, the LA module is located between two vertical poles and extended until the end cap pushes the poles. In this experiment, the sewage pipe is chosen to define the environmental condition; therefore, the vertical pole distance is fixed as 300 mm based on the literature survey, and 60% of sewage pipes have an approximate 300 mm diameter [105]. In order to find the minimum pressing force for holding the LA module on the vertical poles, LA-slider lengths are slightly extended until the end caps touching the poles, and the LA module can also hold onto the poles without any payload.

The result suggest that a minimum pressing force is produced by three compressive springs rather than the LA-slider pushing force because the compressive springs (0.3 N/mm spring constant, 1.8N maximum load) integrated into the end cap module could exert a small compressive force (F_c) passively against the pressing plate, as presented in Figure 5.20. Therefore, the compressive spring force and the COF between friction areas is able overcome the gravity and overall weight of the LA module, which is approximately 176 g. However, the LA module slips from the vertical poles when putting 500 g payloads on the LA module. Based on this result, it is assumed that the minimum pressing force that the LA module is able to hold its body to the vertical poles was 0.9N, which is the spring rate of the three compressive springs pressed over a 1 mm length.

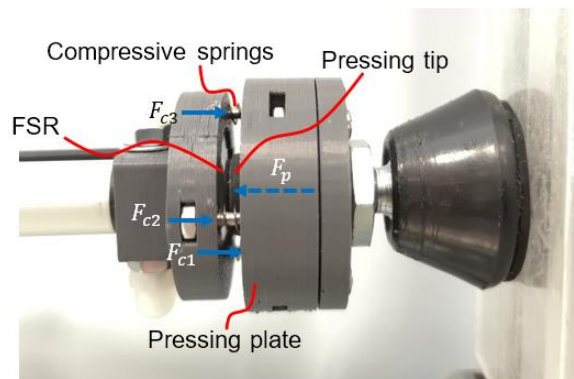


Figure 5.20 Passive-compressive force of the end cap produced by three compressive springs.

The pressing forces also relate to the power applied to the LA slider. This power also directly relates to the pressing speed of the end caps. The more power that is applied, the larger the pressing force produced. The experimental results are presented in Figure 5.21. These results are beneficial for designing an appropriate pressing force safe for an environmental surface.

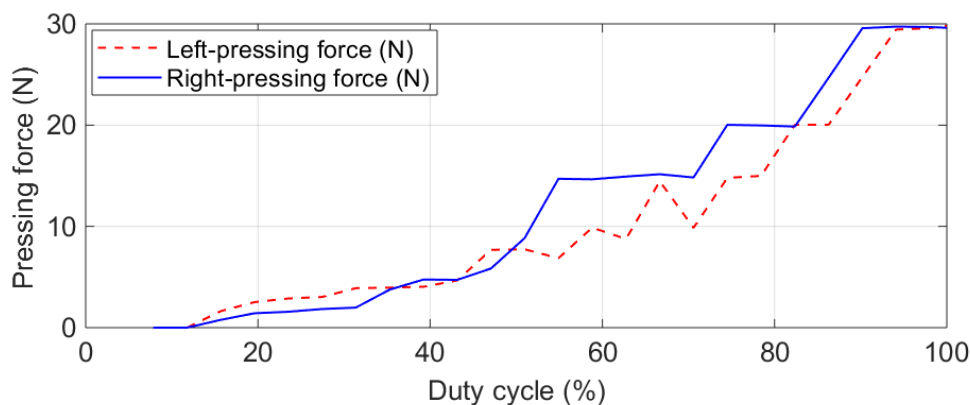


Figure 5.21 Relationship between the control signal (duty cycle) and the pressing forces of the left and right end caps against the vertical pole surfaces.

To investigate the maximum payload allowance, payloads are placed into the payload holder, which is hung on an inelastic cable fastened between the left and right sides of ball joints, as illustrated in Figure 5.23. The payload weights are increased by 1 kg until the LA module cannot hold on to the vertical poles for one minute. The maximum pressing force is generated by applying the continuous 100% duty cycle leading to produce the maximum speed of the LA slider, which is perpendicular to the poles. The 290 mm distance of the vertical poles is selected to test maximum payload allowance. The results show that the maximum payload weight that the LA module can hold between two vertical poles for one minute is 4 kg.

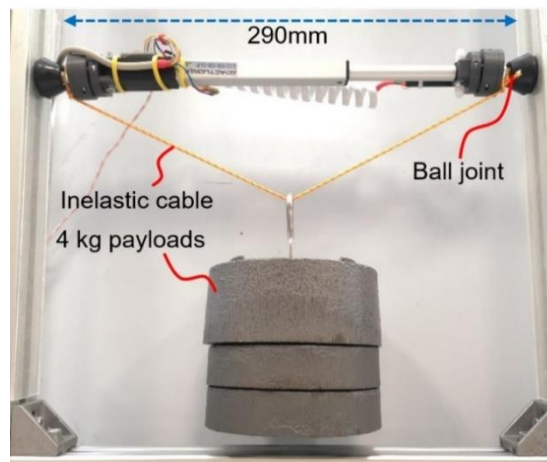


Figure 5.22 Maximum payload weight experimental setup.

Another experiment investigates the relationship between the end cap angle (θ_E) and the pressing force between the end caps (left and right side) and the vertical poles through the pressing plates to gain an understanding of how the end cap angle affects the pressing force of both end caps. This experiment would be beneficial in designing the robot gait for locomotion, particularly when accessing a curve, where end cap angles are changed. For the experimental setup, the 100% duty cycle is applied to the LA module placed on the 290mm vertical pole distance, and end cap angles are adjusted every five degrees for each experiment (see Figure 5.23). The maximum payloads are also taken with the LA module to observe how the payload affects the pressing force occurring between the vertical poles and end caps. The experimental results are summarised in Table 5.8.

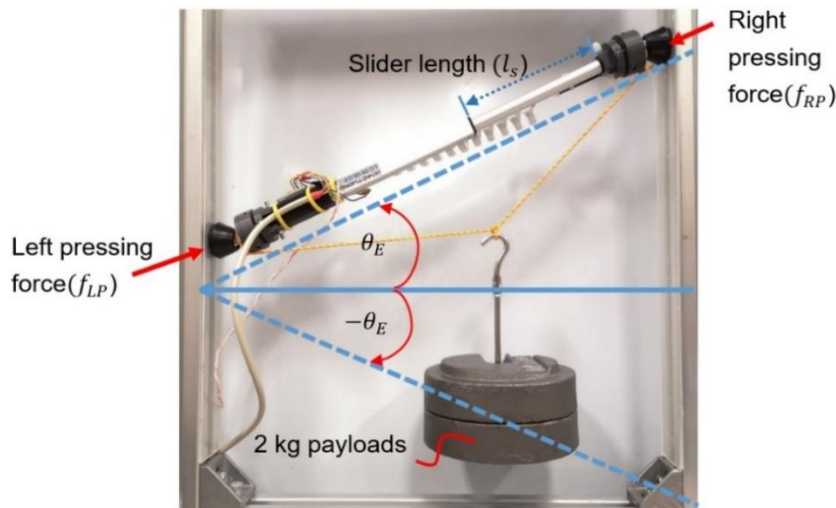


Figure 5.23 Experimental setup for the pressing force of the end caps while carrying different payload weights.

The experimental results show that the end cap angle slightly affects the maximum payload allowance when carrying a 4kg payload. The LA module with the angle of $\pm 20^\circ$ could carry the 4kg payload, whereas the angle of $\pm 25^\circ$ could not, as shown in Table 5.8 (green and red numbers).

In addition, end cap levels affect the pressing forces while carrying payloads. For instance, the pressing forces of the left end cap (F_{LP}) are higher than the right end cap (F_{RP}) if the position of the left end cap is lower than the right end cap, as illustrated in Table 5.8. Similarly, the pressing forces of the right end cap (F_{RP}) are higher than the left end cap (F_{LP}) if the position of the right end cap is lower than the left end cap, as shown in Table 5.8.

Table 5.8 Experimental results of the pressing force of the end caps related to the payload weights and LA angles. Yellow cell indicates the lower level of an end cap.

l_s (mm)	θ_E ($^\circ$)	no payload		1kg		2gk		3kg		4kg	
		f_{LP} (N)	f_{RP} (N)	f_{LP} (N)	f_{RP} (N)	f_{LP} (N)	f_{RP} (N)	f_{LP} (N)	f_{RP} (N)	f_{LP} (N)	f_{RP} (N)
87	-25	6.74	8.76	6.86	8.95	7.72	9.8	7.81	9.88	-	-
81	-20	8.92	14.8	9.82	14.9	14.3	15.1	14.4	19.9	14.6	20.1
72	-15	14.8	19.9	9.88	24.6	14.2	29.5	14.3	29.6	14.6	30
65	-10	29.5	29.6	29.6	29.8	24.8	29.7	19.8	19.9	14.8	15.1
64.6	-5	29.8	30.2	29.9	30.2	30.1	30.3	29.8	30.3	15.2	29.4
64	0	31.2	30.2	31	30	30.8	24.8	15.2	14.2	15.1	14.3
64.9	5	30.6	29.9	31.1	29.4	30.2	9.89	14.8	9.89	14.8	14.3
66	10	29.5	24.6	30.5	14.7	29.6	8.81	14.8	9.78	15	14.3
72.5	15	24.7	9.82	29.5	8.78	29.9	9.78	19.9	14.3	19.9	14.7
81.5	20	6.76	4.66	9.86	6.77	15	8.81	24.7	9.86	31	14.5
87.8	25	14.7	4.85	15.2	5.76	20	6.8	19.8	6.72	-	-

5.2 Passive-Retractable Joint with a Cable Locking Mechanism

This section describes the experimentation of the passive-retractable joint with the cable locking mechanism (PRM) to examine the element specifications and limitations, such as cable forces and maximum braking force. The evaluation of the PRM is also discussed.

5.2.1 Cable Length Feedback Scaling

In order to measure the cable length of a PRM, the small non-contact rotary encoder model RM08 [99] is used to generate 512 CPR. This encoder resolution is used to calculate cable length using the circumference equation of the cable storage, as presented in Equation (5.1). In this case, the circumference of the cable storage is fixed by neglecting the cable diameter for each turn.

$$C = 2\pi r, \quad (5.1)$$

where C represents the circumference of the cable storage, π is 3.141592653 and r represents the radius of the cable storage (12.25mm). Therefore, the circumference of cable storage is 76.93mm. The encoder count per revolution can then be calculated by using the gear ratio between a driving gear (46 teeth) and a driven gear (8 teeth), which is 5.75. This number is multiplied by a small non-contact rotary encoder 512 CPR. Therefore, the encoder count per revolution (E_{CPR}) becomes 2944 CPR. Eventually, the cable length per count (L_E) initially is

$$L_E = \frac{C}{E_{CPR}} = \frac{76.93}{2944} = 0.026131 \frac{mm}{count}. \quad (5.2)$$

This cable length per count value is multiplied by encoder count per one revolution, gathered by the encoder. However, the cable length per count value must be finely tuned using a trial-and-error method due to mechanical errors such as gear teeth and rotational parts. Therefore, the final values of the L_E parameters of six PRMs are different, as presented in Table 5.9. The experimental setup and results of the cable length measurement for six PRMs are presented in Figure 5.24 and Figure 5.25, respectively.

Table 5.9 the cable length per count value of six PRMs.

Restrictor Mechanism (PRM)	Cable length per count (mm/count)
A	0.0262
B	0.0264
C	0.0264
D	0.0264
E	0.0262
F	0.0262

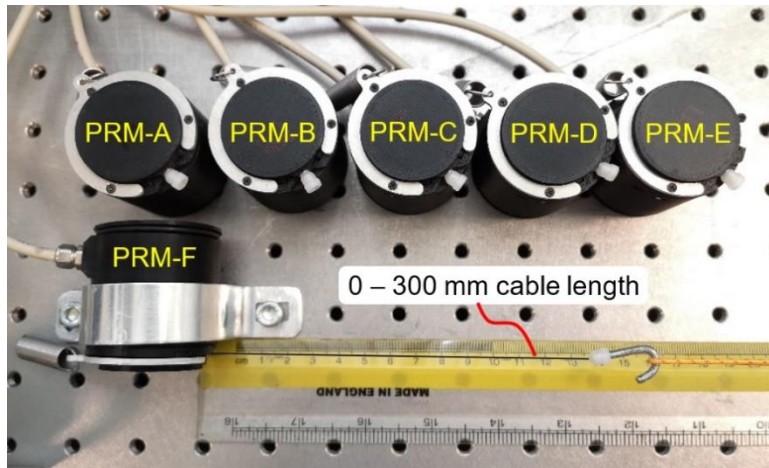


Figure 5.24 Experimental setup for the cable length calibration for six restrictor mechanisms (PRM-A, PRM-B, PRM-C, PRM-D, PRM-E and PRM-F).

The results suggest that the encoder module of six PRMs could generate cable length data, providing ± 1 mm cable length error acceptable in this research.

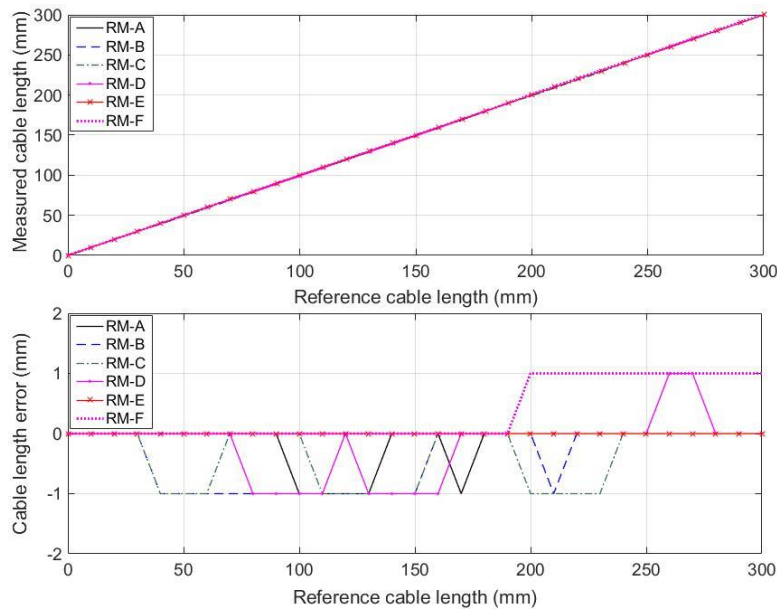


Figure 5.25 Experimental results of the cable length calibration for the PRMs: (top) the calculated cable length by using encoder data and (bottom) the cable length error of the computed cable length comparing to the reference cable length.

5.2.2 Cable Force Calibrations

This experiment involves measuring the cable forces of six PRMs using spring balances and commercial digital force measurement. The primary purpose of this experiment is to determine the relationship between the cable length and cable forces that spool the cable keeping inside cable storage and calibrate the cable forces of each PRM equally by adjusting the power spring turn before starting to roll a cable.

For the experimental procedure, the PRM is mounted on a platform. A spring balance is attached to the cable tip of the PRM to then spool the cable. The lengths of the cable are increased every 10 mm until the cable length reaches 300 mm. Cable forces are measured simultaneously using a commercial-standard ruler with a 1 mm resolution. Although both the spring balance and standard ruler used in this experiment are not effective for measuring cable forces and cable length accurately, they are good enough to measure cable length and cable-pulling forces of all PRMs related to the lengths of their cables. The experimental setup is presented in Figure 5.26, and the experimental results are presented in Figure 5.27.

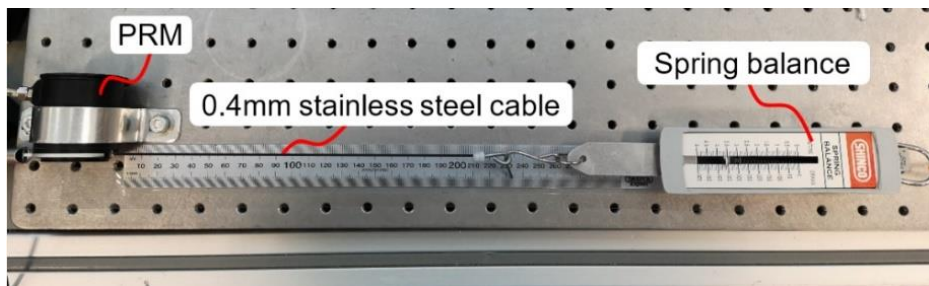


Figure 5.26 Experimental setup of cable-pulling force calibrations.

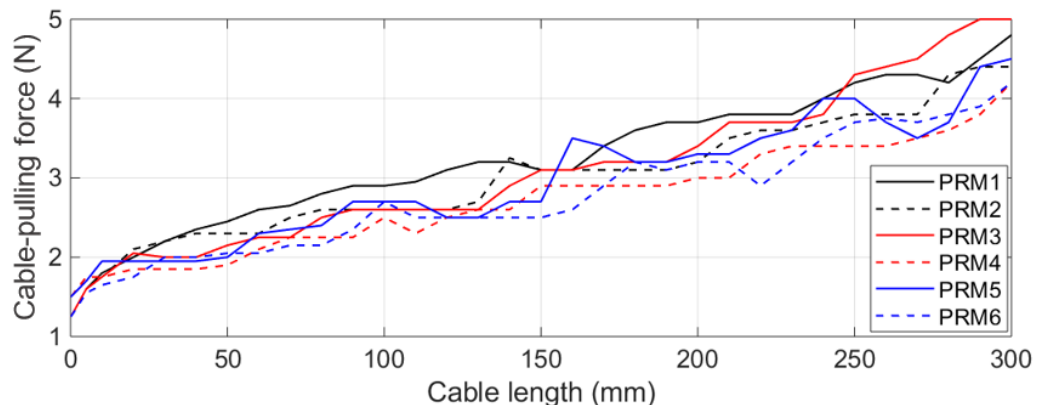


Figure 5.27 Relationship between the cable-pulling force and the cable length of the PRM1 to PRM6.

The results showed that the cable-pulling forces increased when cable length increased. The cable forces of the six PRMs were not similar to each other, which might be caused by several factors, such as the mechanical frictions between rotational and fixed components, measurement errors, and the cable-pulling angle. However, the cable-pulling forces of all PRM had the same trend. The more that the cable length is spooled, the more cable-pulling force occurred. The minimum cable-pulling force of the PRMs falls in the range of 1.25 and 1.5N. On the other hand, the maximum cable-pulling force of the six PRMs is in the range of 4N and 5N.

5.2.3 Maximum Braking Force

Another experiment involves finding the maximum braking force of each PRM in order to determine the force limitations of the braking mechanisms. This experiment also observes the spooling forces generated by LA modules for structure configurations. For the experimentation procedure, the PRM is mounted on the platform. The digital force gauge, AMETEK model DFE-500 with 1N resolution, is used to measure the braking force by attaching the force gauge tips to the PRM cable tip. The target cable lengths are then defined for the locking stages, which are 0, 50, 100, 150, 200, 250 and 300 mm. Following this procedure, the locking stage is applied when a cable is spooled by the force gauge until reaching the target length. At this stage, the force gauge continuously spools the PRM cable and slightly increases spooling force until the braking components cannot lock the cable. The maximum braking force can then be obtained by reading the spooling force value from the force gauge display. These experimental procedures are demonstrated repeatedly at all cable target lengths in order to test the braking performance between rotational and braking components. The example images of the maximum braking force demonstrated at 0mm and 200mm cable lengths are shown in Figure 5.28 (a) and (b), respectively. The experimental result details are summarised in Table 5.10.

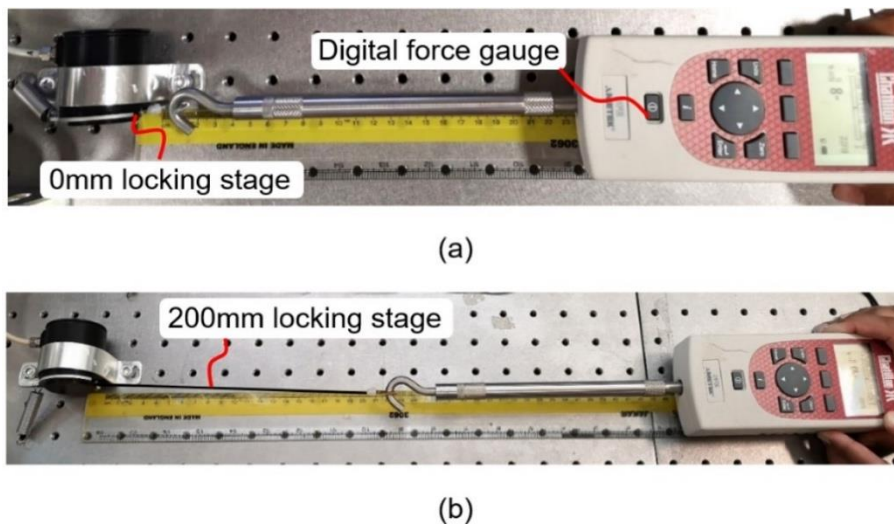


Figure 5.28 The maximum braking force demonstration: (a) the 8N maximum spooling force allowance at 0mm locking stage and (b) the 10N maximum spooling force allowance at 200mm locking stage.

The experimental results suggest that there are different values in the maximum braking forces depending on cable lengths. For example, at the initial length (0mm), the maximum braking force is 8 N. This force increases to 10N and 11N when the locking stage is performed between 200 mm and 300 mm cable lengths, respectively. These results anticipate that, at the long cable length, the power

spring might exert a high coil force against the spooling force produced by hand, resulting in an increase in the maximum braking force.

Table 5.10 Experimental results of the maximum braking force.

Cable length (mm)	Maximum braking force (N)					
	PRM-A	PRM-B	PRM-C	PRM-D	PRM-E	PRM-F
0	8	8	8	8	8	8
50	8	8	9	8	8	9
100	9	8	9	9	8	9
150	9	9	9	9	9	9
200	10	9	10	9	10	10
250	10	10	10	10	10	11
300	10	11	10	10	10	11

5.2.4 Locking and Unlocking Delay Time Experiments

This section describes the delay time between locking and unlocking command for the braking component of the PRM to investigate that the PRM could possibly provide high speeds for structural configurations.

The experimental setup is presented in Figure 5.29. PRM-B and LA-X1 are selected to demonstrate this experiment. The PRM-B cable tip is attached to the LA-slider tip in order to adjust the length of the PRM-B cable. The LA base and another side of the PRM are mounted on an aluminium profile.



Figure 5.29 The experimental setup of the locking and unlocking delay time.

The experimental procedure is described. Firstly, different target lengths of the PRM-B cable are defined as 5 mm, 10 mm, 15 mm, 20 mm, 25 mm and 30 mm, and the LA-slider speed is set as 12.9 mm/sec or applied as a 100% duty cycle. Secondly, the control signal 100% duty cycle is applied to the LA slider to spool the PRM-B cable. If the cable reaches the target length, the locking stage is applied to PRM-B. Then, the time for sending the locking command is compared to the physical cable restriction. Eventually, the locking delay time is obtained. The unlocking delay time (t_{ld}) can be measured by subtracting actual-cable

unlocking time from unlocking command time. The experimental result is presented in Figure 5.30.

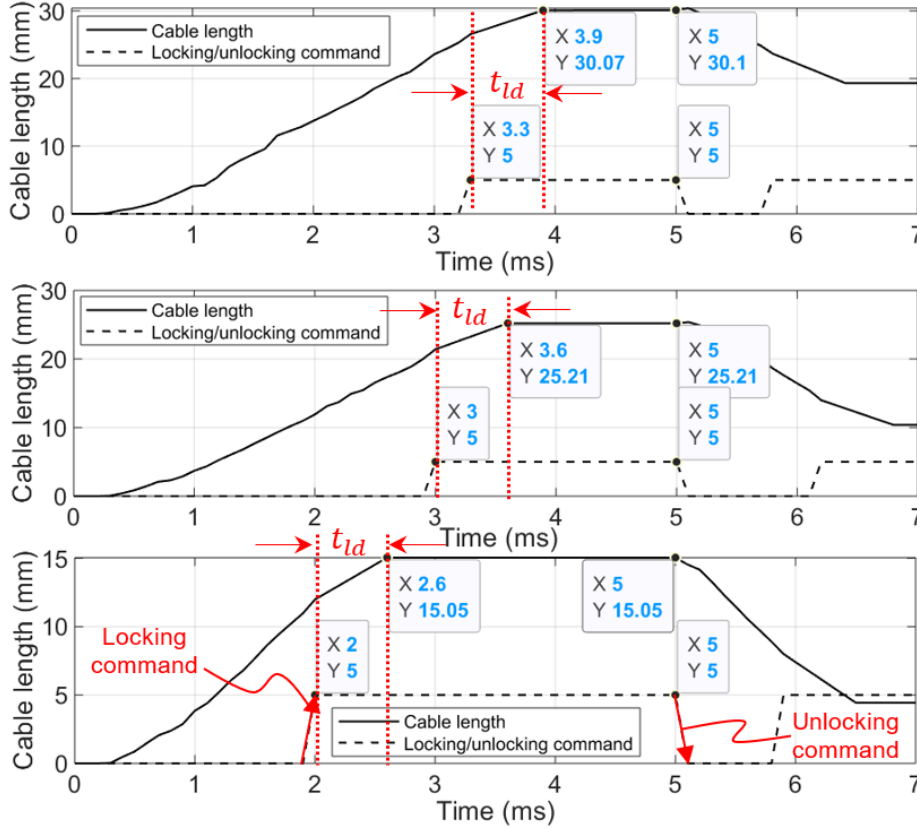


Figure 5.30 Experimental results of the locking and unlocking delay time (t_{ld}) experiment: (top) 30mm target length, (middle) 25mm target length and (bottom) 15mm target length. The duty cycle of the LA slider is 100% (12.9mm per sec); t_{ld} represents locking delay time.

The results illustrate that the braking component of the PRM-B could restrict the cable within 0.6 seconds after applying the locking command. Therefore, the locking delay time (t_{ld}) of the PRM-B was 0.6 seconds. In contrast, after applying the unlocking command, the braking component could perform within 0.1 s to allow the cable to adjust. For reliable experimental results, different LA-slider speeds and PRM-B target lengths were tested, and the results showed that, after applying the locking command, the PRM could restrict its cable length within 0.6 seconds at all target lengths and LA-slider speeds. Furthermore, the PRM can release its cable length within 0.1 s at all target lengths and LA-slider speeds.

Therefore, it is expected that the proposed actuation method, including PRM and LA, may be used to build a tensegrity robot that possibly provides high speed for structural configurations, particularly when swapping between soft and hard structures, 0.6 s to swap from a soft to hard structure and 0.1 s to swap from a hard to soft structure. Moreover, the locking delay time of 0.6 s can be reduced by utilising a faster speed and higher torque actuator.

5.3 Summary

After demonstrating the LA module and passive-restrictor joint with a cable locking mechanism (PRM), suitable specifications were provided to meet the requirements, compared to the SE and PRM property requirements mentioned in Chapter 4. The specifications of the LA and PRM are summarised in Table 5.11 and Table 5.12, respectively.

Table 5.11 Strut element (SE) or linear actuator (LA) module specifications.

Specifications	Value	Unit
Initial strut length	236	mm
Maximum stroke	100	mm
Weight	170 - 180	g
Pushing force range	0.25 - 20.18	N
Strut length error	± 1	mm
Pressing-force detection range	0.3 - 20	N
Maximum vertical lifted payload	3.8	kg
Maximum horizontal payload for wall pressing stage	4	kg
End-cap diameter (frictional surface area)	22	mm

Table 5.12 Passive-retractable joint with cable locking mechanism (PRM) specifications.

Specifications	Value	Unit
Dimensions (height and diameter)	48 x 43	mm
Weight	125-135	g
Encoder resolution	512	CPR
Cable length error	± 1	mm
Maximum cable length	300	mm
Rotational force range	0.5 – 5	N
Maximum braking resistance	11	N
Cable length control	Lock/Unlock	Stage
Maximum retractable-cable speed (no load)		
50 mm	710	mm/s
100 mm	760	
150 mm	1150	
200 mm	1420	
250 mm	4160	
300 mm	4285	
Locking delay time	0.6 – 0.8	s
Unlocking delay time	0.1	s

To demonstrate the proposed structural deformation method, LAs and PRMs are employed to construct the proposed 3- and 5-DOF structures to test the fundamental motions using new control rules to generate control signals for reconfigurable structural configurations in Chapter 6.

Chapter 6 Control and Structural Deformation Validations

This chapter describes the different structural configurations of the strut element (SE) and linear actuator (LA) modules cooperating with a passive-retractable joint with a locking mechanism (PRM) to deform the structure to control end-effector and robot locomotion. Various degrees of freedom systems are employed to investigate the fundamental movements, including straight and rotational movements using the locking/unlocking stage of the RMs while extending or retracting the LA-slider length. 3- and 5-DOF systems are constructed based on a passive-retractable-cable structure to demonstrate linear and rotational movements. New control rules for LAs and RMs to control end-effector positions are designed and implemented.

6.1 3-DOF System Experiments

To demonstrate the fundamental motions of the proposed structural deformation concept presented in Chapter 3, physical 3-DOF systems are constructed. New control rules are then designed and implemented to evaluate control system performance. The cooperation between LA and PRMs to move an end-effector position of the 3-DOF structure are also evaluated.

6.1.1 3-DOF Structure

The 3-DOF structure consists of one LA module and two PRMs (PRM-A and PRM-B), as presented in Figure 6.1. The LA module is mounted on a miniature linear bearing, model GS02740-02, to reduce friction between LA module contact points and backplane surfaces. The design aims to minimise friction because this research aims to investigate PRM performance for structural configurations without inconstant factors that affect the movement of the LA module. Two PRMs are placed on both sides of the LA module. PRM-A is placed on the right, and PRM-B is placed on the left. Stainless steel cables are used to connect the LA module and the RMs, which can adjust its length passively, and two tension springs connect the PRM anchor and screw, which is fixed on the panel. The tension springs 0.16 N.mm are used to prevent cables damage in case of over tension during locking.

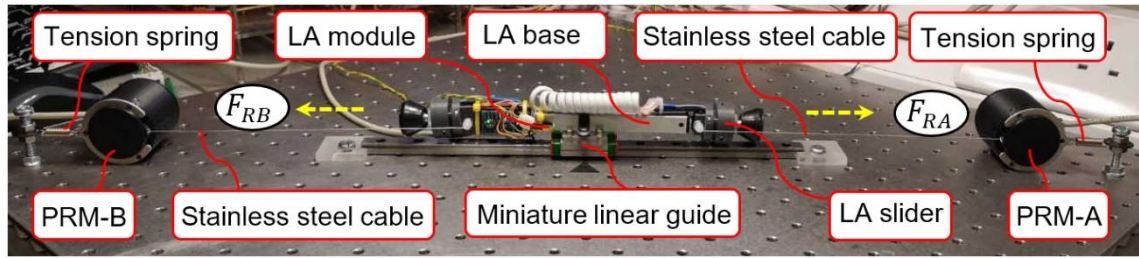


Figure 6.1 Experimental setup of the 3-DOF structure.

6.1.2 LA-Base Position Control Demonstrations

To demonstrate the motion control of the 3-DOF structure, three experiments are designed. The first experiment involves demonstrating a fundamental motion of a straight path for the LA-base position by applying the LA-slider target length after applying the locking and unlocking stages of the PRMs. The second experiment involves demonstrating the closed-loop control of the LA-base positions travelling in a straight direction along the X-axis, and the third experiment involves demonstrating the fundamental motion of a triangle structure that shows angular control of the LA module.

For the first experiment, all parameters and target positions of the LA slider are defined, considering the maximum length of the linear guide bar (300mm maximum length). The LA module is placed in the middle of said linear guide bar. Therefore, the rest length of the linear guide bar on the left and right remains at 140 mm. Consequently, the LA-slider target lengths are defined to move the LA-base position to the left and right of the linear guide bar and then move to the initial position. The applied LA-slider target lengths in each control procedure are summarised in Table 6.1.

Table 6.1 Control procedures of the LA-slider lengths and locking/unlocking stages of the PRM-A and PRM-B.

Step	LA-slider target length (mm)	Locking procedure	
		PRM-B	PRM-A
A	0	U	U
B	60	U	L
C	0	L	U
D	60	U	L
E	0	L	U
F	90	L	U
G	0	U	L
H	90	L	U
I	0	U	L
J	60	L	U
K	0	U	L
L	90	U	L
M	0	L	U
N	30	U	L
O	0	L	U

Regarding the delay time for the locking/unlocking mechanism of the PRM, the controller sends the locking/unlocking command to each PRM module before applying the extending and retracting stages of the LA slider. The constant speed of 12.6 mm/s is applied to the LA-slider movements in each stage. The control procedure of the locking/unlocking stages of the PRM-A and PRM-B are summarised in Table 6.1, and the video frames of the LA-base movement demonstrations are presented in Figure 6.2.

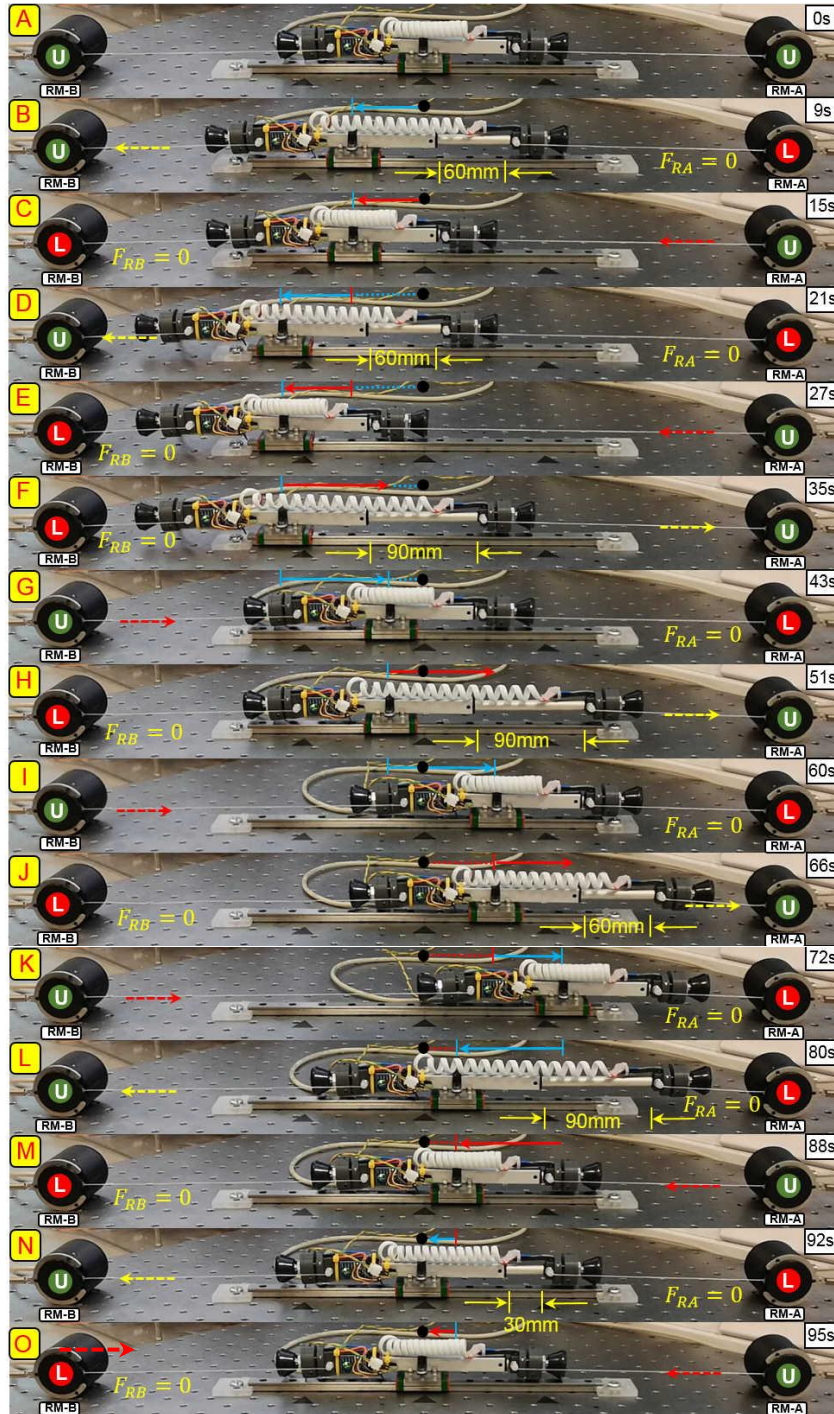


Figure 6.2 Video frames of the closed-loop LA-base position control by using the control procedures of the LA module, PRM-A and PRM-B

The experimental results suggest that the LA module can be moved using the control procedure generated by the locking/unlocking stages of the PRM-A and PRM-B and the extending/retracting stages of the LA-slider length. There were 15 stages for the LA-base motions, as described in Algorithm3, and the time responses of the LA-base movements and locking/unlocking command procedure are presented in Figure 6.3.

Algorithm 3: LEFT AND RIGHT MOTIONS

Input: Motion step // Motion step A to O are motion steps 0 to 14

Output: PRM-A, PRM-B, and LA-slider target length

Target length [14] = {0,60,0,60,0,90,0,90,0,60,0,90,0,30} // Define Slider target lengths

PRMA [14] = {U,L,U,L,U,U,L,U,L,U,L,L,U,L} // Define locking (L) and unlocking (U)

PRMB [14] = {U,U,L,U,L,L,U,L,U,L,U,U,L,U}

Motion step = 0 // Define initial motion step as 0 or A

```

1  while Motion step < 15 do
2      PRM-A = PRMA [Motion step]
3      PRM-B = PRMB [Motion step]
4      if (PRM-A and PRM-B = Finished) then // Check PRM-A and PRM-B status
5          LA-slider target length = Target length [Motion step]
6          if (LA-slider target length = Finished) then //Check LA-slider status
7              Motion step ++ // Do the next motion step
8          end if
9      end if
10 end while

```

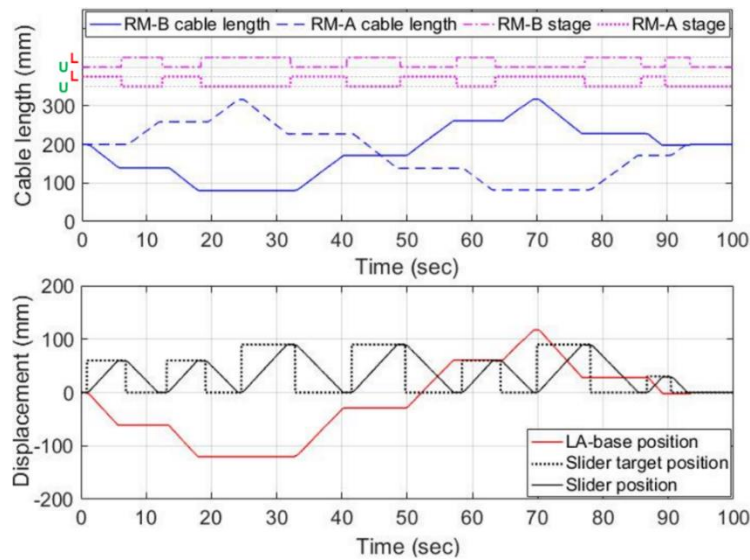


Figure 6.3 Experimental results of the 3-DOF system: (top) cable lengths and the locking/unlocking procedures of the PRM-A and PRM-B and (bottom) LA-slider length and LA-base or end-effector position.

This experimental result suggests that the 3-DOF system could be used to move the LA-base travelling to different positions covering the whole length of the linear guide effectively. PRM-A and PRM-B could restrict the cable to enable and disable pulling forces F_{RA} and F_{RB} providing with the desired movements of the LA-base.

For the second experiment, the closed-loop control of the LA-base positions is demonstrated. The slider length target function is designed to generate LA-slider target lengths to move LA-base positions. This function cooperates with the control procedures of the locking and unlocking stages of the PRM-A and PRM-B to restrict and release two cables, which attach to the left and right of the LA module. In order to identify the LA-base directions, the sign of the LA-base target position is used. For example, if the LA-base target positions (LA_{ref}) are greater than zero, the LA-base will be moved to the right. In contrast, if the LA-base target position is less than zero, the LA-base will be moved to the left. A block diagram of the closed-loop control of the LA-base position is presented in Figure 6.4.

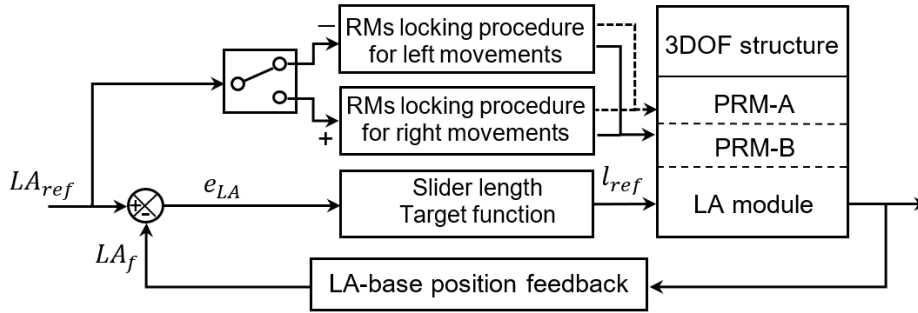


Figure 6.4 Block diagram of the closed-loop LA-base position control.

The design of control procedures between left and right movements are slightly different in one movement cycle. The movement cycle comprises two main steps, namely the LA slider extension step and the LA-slider retraction step.

Based on the left movement procedure, the first step is to apply the locking stage for the PRM-A and unlocking stage for PRM-B and then apply the LA-slider extension moving to the target length, which is defined as 50 mm for the example, as illustrated in Figure 6.5 (first step). In this step, the pulling force of the PRM-A is equal to zero ($F_{RA} = 0$), while the PRM-B exerts a pulling force to pull the LA-base position on the left-hand side (yellow arrow direction). The LA-base distance is equal to the LA-slider length. For the second step, the locking stage is applied for the PRM-B, the unlocking stage is applied for the PRM-A, and the LA-slider is retracted to the initial length in preparation for the next cycle. The video frames of the initial, first, and second steps for the left movement cycle are shown in Figure 6.5.

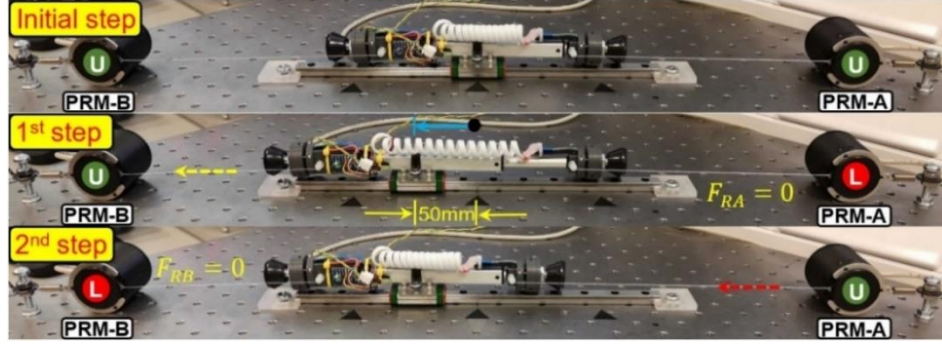


Figure 6.5 Left movement cycle of the LA-base; the first step is the LA slider extension, and the second step is the LA-slider retraction.

Differently, for the right movement procedure, the LA-slider extension must be applied in the first step to provide the free LA-slider length and prepare for the LA-base movements. This step can be completed by applying the locking stage for the PRM-B and unlocking stage for the PRM-A and then extending the LA-slider on the right-hand side, as illustrated in Figure 6.6 (first step). In the second step, the unlocking stage is applied for the PRM-B, allowing the PRM-B cable to release; the locking stage is applied to the PRM-A to restrict the LA-base to only moved to the right. After this process, the LA-base is dragged to the right while retracting the LA-slider to the initial length (see Figure 6.6 (second step)).

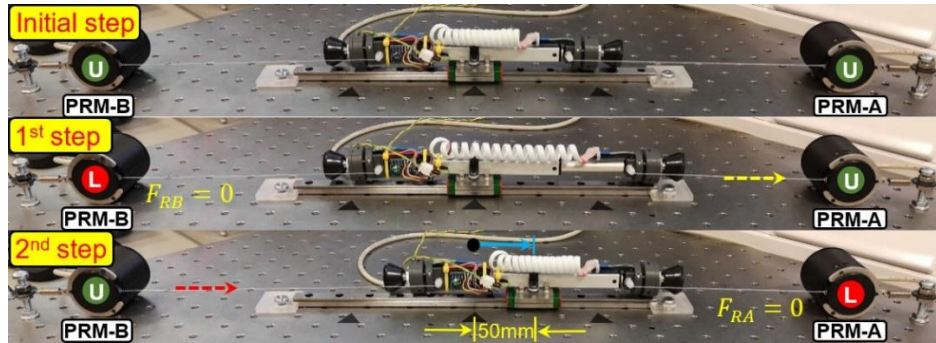


Figure 6.6 Right movement cycle of the LA-base; The first step is the LA slider extension, and the second step is the LA slider retraction.

There are different control rules for the slider target function to calculate the LA-slider target length to make the LA-base travelling to the target position. The first control rule is used if the LA-base target position (LA_{ref}) is less than or equal to the maximum LA-slider stroke (Stk_{max}), the LA-base can be moved to the target position in one movement cycle by defining LA-slider target length (l_{ref}) being the absolute value of the LA-base target position, as presented in Equation (6.1).

$$l_{ref} = |LA_{ref}|, \quad \text{if } |LA_{ref}| \leq Stk_{max} \quad (6.1)$$

The LA-slider target length is an absolute value because the LA-slider extends only in the positive direction (greater than zero). However, if the LA-base position

error (e_{LA}) still occurs in the system, another movement cycle will be applied by defining the next LA-slider target position (l_{refn}). This value is defined as the absolute value of the LA-base position error ($|e_{LA}|$) if the error is higher or equal to the LA-base position error allowance (e_{min}) of ± 2 mm. However, if the error is higher or equal to the LA-base position error allowance and lower than the elongated-coil spring compensation (S_c), which is 5 mm, experimentally, the LA-slider target position is increased to compensate for the unexpected tension spring elongation mounted between the PRMs and backplane. The next LA-slider target position (l_{refn}) is calculated with the following formula:

$$l_{refn} = \begin{cases} |e_{LA}|, & \text{if } |e_{LA}| \geq e_{min} \\ |e_{LA}| + |e_{LA}| - 1, & \text{if } |S_c| \geq e_{min} \end{cases} \quad (6.2)$$

The LA-base position error can be calculated as a subtraction between the LA-base target position (LA_{ref}) and the current position feedback (LA_f) of the LA-base, as shown in Equation (6.3):

$$e_{LA} = LA_{ref} - LA_f \quad (6.3)$$

For the second control rule, if the LA-base target position is higher than or equal to the maximum LA-slider stroke (Stk_{max}) and less than the maximum length of the PRM cables (CRM_{max}), the LA-slider target length for the first movement cycle (l_{ref1}) is defined as a maximum LA-slider stroke as shown in Equation (6.4):

$$l_{ref1} = Stk_{max}, \text{ if } |LA_{ref}| \geq Stk_{max} \text{ and } |LA_{ref}| < CRM_{max} \quad (6.4)$$

The LA slider target length for the second-movement cycle (l_{ref2}) is given as equal to the LA-base position error (e_{LA}). However, the position error should not be higher than the maximum stroke of the LA-slider. In this case, the LA-slider target length should be equal to the maximum stroke length, as shown in Equation (6.5). The calculated process of the LA slider target length continues and will run another movement cycle until the LA-base position error becomes zero. In other words, the LA-base reaches the target position:

$$l_{ref2} = \begin{cases} e_{LA}, & \text{if } |e_{LA}| < Stk_{max} \\ Stk_{max}, & \text{if } |e_{LA}| \geq Stk_{max} \end{cases} \quad (6.5)$$

and the control rule for the locking and unlocking stages for the PRMs can be generated by the following formula:

$$PRMs = \begin{cases} \text{Left movement procedure, if } LA_f > LA_{ref} \\ \text{Right movement procedure, if } LA_f < LA_{ref} \end{cases} \quad (6.6)$$

In order to evaluate the closed-loop control of the LA-base positions using the proposed first and second control rules, two experiments are designed and conducted.

The first demonstration is the closed-loop position control of the LA-base by applying multiple-target positions, which are less than the maximum LA-slider stroke ($LA_{refn} < |100\text{mm}|$) at -30 mm, -60 mm, -90 mm, -60 mm, -30 mm, 0 mm, 30 mm, 60 mm, 90 mm, 60 mm, 30 mm and 0 mm. These target positions are selected by considering the short, medium, and long lengths covering the LA-slider stroke. LA-slider target lengths are calculated using Equations (6.1) to (6.3), and the control procedure of the locking stage of both PRM-A and PRM-B are applied by verifying the LA-base target position sign. If the LA-base target position sign is the plus sign, the right movement cycle is performed. On the other hand, if the LA-base target position sign is the minus sign, the left movement cycle is performed. These PRM-A and PRM-B locking procedures are done before processing the LA-slider movements. The time response of the multiple-step inputs is presented in Figure 6.7, and the experimental result data are summarised in Table 6.2.

The experimental results suggest that the proposed control method could calculate LA-slider length and generate the locking and unlocking stage of the PRM-A and PRM-B effectively. It could control the LA-base position travelling to all target positions, as shown in Figure 6.7 (top). Moreover, the left and right movement cycles could be used to send the locking and unlocking stages for the PRM-A and PRM-B (see Figure 6.7 (middle)) before extending and retracting the LA-slider lengths (see Figure 6.7 (bottom)).

The small steady-state error ($LA_{e_{s.s}}$) occurred in the system at approximately $\pm 2\text{mm}$ (see Table 6.2). The settling time of the LA-base movement (LA_{t_s}) between the left and right were different. The left movement was approximately two times faster than the right movement because the LA-base immediately moves when changing the LA-slider length to the left. Furthermore, to the right, the LA-slider length must be extended to provide a free length before retracting the LA slider to pull the LA-base to target position.

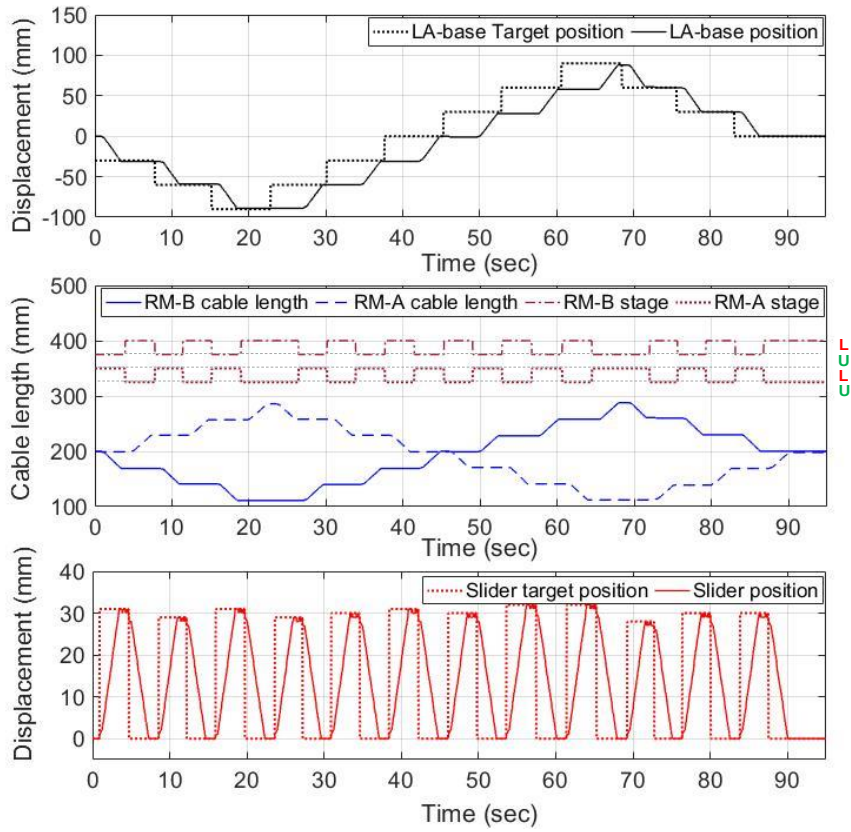


Figure 6.7 Experimental results of the LA-base travelling by applying the continuous-multiple inputs of the target positions: (top) the LA-base displacement, (middle) the locking/unlocking stage and cable length of both PRM-A and PRM-B, and (bottom) LA-slider target position and displacement.

Table 6.2 Experimental data results of the multiple-step input response.

Movement direction	LA_{ref} (mm)	$LA_{s.s}$ (mm)	LA_{t_s} (s)	$LA_{e_{s.s}}$ (mm)	$LA_{e_{s.s}}$ (%)
Left	-30	-31	3.22	1	3.3
Left	-60	-59	3.11	-1	-1.67
Left	-90	-89	3.24	-1	-1.1
Right	-60	-60	6.67	0	0
Right	-30	-31	6.94	-1	-3.3
Right	0	0	7.01	0	0
Right	30	28	6.99	-2	-6.67
Right	60	58	6.55	-2	-3.3
Right	90	88	7.31	-2	-2.2
Left	60	60	3	0	0
Left	30	30	3.21	0	0
Left	0	0	3.06	0	0

The second demonstration involves testing the LA-base position control when applying target positions greater than the maximum LA-slider stroke. The 210 mm LA-base target distance, which is two times longer than the LA-slider length, is defined. Equations (6.4) and (6.5) are used to generate the LA slider target length in each cycle movement to move the LA-base travelling to the desired target positions, and the locking stages of the PRM-A and PRM-B are used.

Initially, the initial position of the LA-base ($LA_{ini.}$) is shifted to the right of the linear slide guide. The LA-base is then moved to the target position on the left and then return to the initial position (0mm). The time response of the closed-loop control system is presented in Figure 6.8.

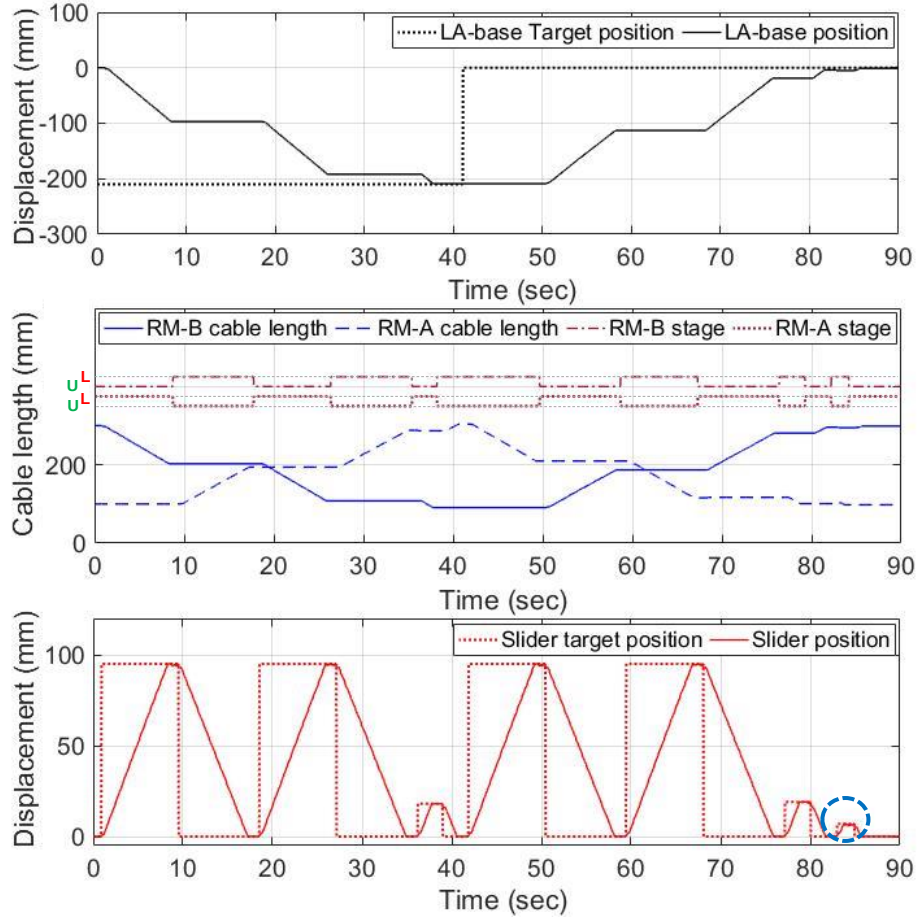


Figure 6.8 Experimental result of the closed-loop LA-base position control: (top) the LA-base displacement, (middle) the locking/unlocking stage and cable length of both PRM-A and PRM-B and (bottom) the LA-slider target position and displacement.

The results show that the proposed control method and control procedure of the locking stage of the PRM-A and PRM-B could control the LA-base moving to the desired target positions properly, as presented in Figure 6.8 (top). Three LA-slider target lengths (l_{ref}) are calculated as 95 mm, 95 mm and 18 mm and used for the LA-slider extension stages in the left movement cycles, resulting in the movement of the LA-base travelling from 0 to -210 mm. For LA-slider safety, the maximum LA-slider length was limited to 95 mm. Therefore, the maximum calculated LA-slider was 95 mm, and the proposed control method could compute the LA-slider target lengths to move the LA-base to the right-hand side, returning to the initial position. However, the movement cycle to the right is more than the left direction of one step because the system has a small steady-state error higher than the maximum position error allowance ($\pm 2\text{ mm}$). Then, the additional

movement cycle with a short target length (7mm) of the LA-slider is produced (see inside circle in Figure 6.8 (bottom)). Consequently, the LA-base position reached the target point within the steady-state error of 1 mm. The settling time of both left and right movements are similar, as shown in Table 6.3 because, although the movement behaviours of the LA-based between the left and right movement cycle are different, the total time for running the cycle are similar due to the same process of the LA-slider retraction and extension.

Table 6.3 Experimental data results when defining the LA-base target position higher than the maximum LA-slider stroke.

Movement direction	$LA_{ini.}$ (mm)	LA_{ref} (mm)	l_{ref} (mm)	LA_{ref} (mm)	$LA_{s.s}$ (mm)	$LA_{e.s.s}$ (mm)	$LA_{e.s.s}$ (%)
Left	0	-210	95	-97	37.5	-1	-0.476
			0	-97			
			95	-192			
			0	-192			
			18	-209			
			0	-209			
Right	-209	0	95	-209	40.56	-1	-0.476
			0	-113			
			95	-113			
			0	-19			
			19	-19			
			0	-4			
			7	-4			
			0	-1			

These experiments suggest that the proposed control rules can be used to accurately calculate LA-slider target lengths. Furthermore, the proposed left and right movement cycle can be performed to operate the locking and unlocking stage of the PRM-A and PRM-B to restrict and release the cable effectively in order to move the LA-base to different target positions. The results suggest the fundamental linear movement of the 3-DOF structure by using the proposed deformation technique. However, the end-effector of the 3-DOF can move only along the X axis.

The third demonstration involves testing the angular control capability by using locking and unlocking stage procedures while changing LA-slider lengths. The triangular-shaped structure, including one LA module and two PRMs, is constructed for the experimental setup, as presented in Figure 6.9.

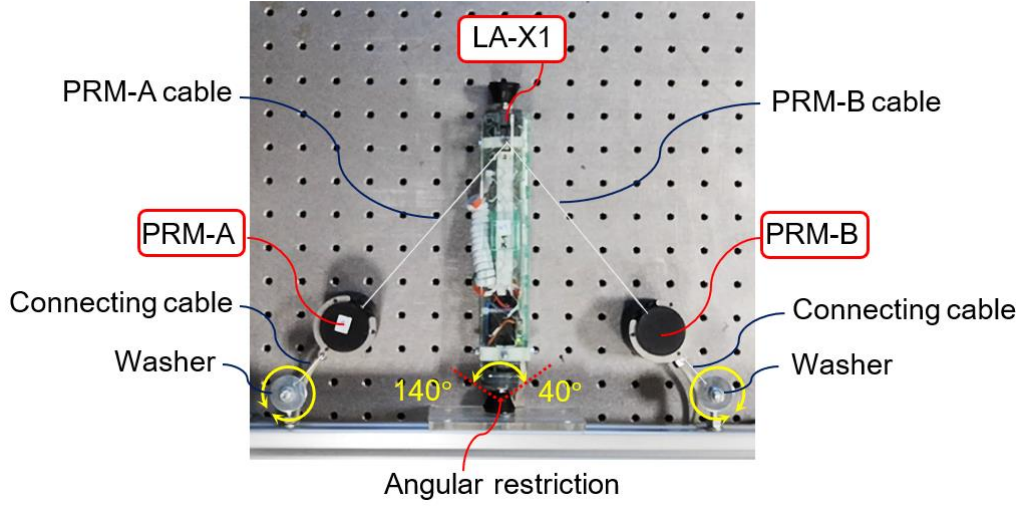


Figure 6.9 Experimental setup of the angular control demonstration.

The triangular-shaped structure comprises one LA module (LA-X1) placed in the middle between PRM-A and PRM-B. The bottom end of the LA module attaches to an acrylic plate fixed with an aluminium frame. However, the bottom pivot of the LA-X1 is restricted in order to limit the LA-X1, tending between 40° and 140° due to the physical constraint of a ball-joint foot. The PRM-A and PRM-B cables are connected to the top of the LA slider, and the opposite sides of the PRMs are connected to washers via connecting cables, which rotate freely surrounding two fixed screws mounted on the left and right sides of the LA module.

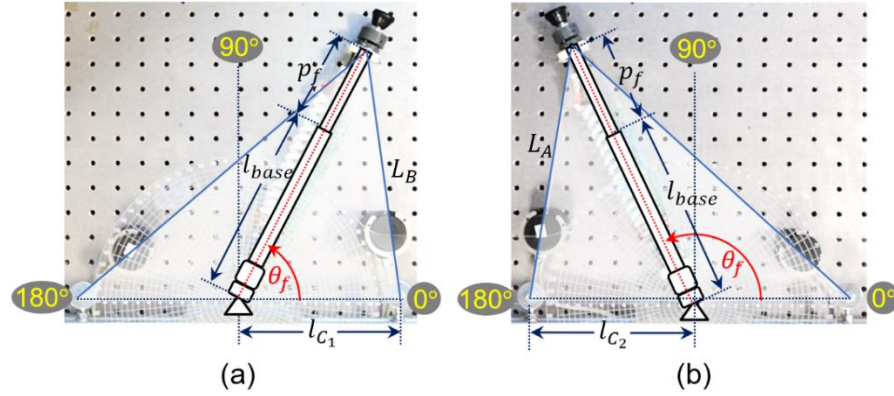


Figure 6.10 Kinematic diagram of the LA-X1 angle: (a) first kinematic equation and (b) second kinematic equation.

To identify the LA-X1 angle, the forward kinematic equation is solved using the Cosine rule. The cable length of the PRM-A and PRM-B must be tight while changing the LA-X1 length to provide angular measuring accuracy. Therefore, two kinematic equations are used to calculate LA-X1 angles (θ_f) feeding back to a control module to generate the locking/unlocking stages of the PRMs while changing the LA-X1 slider length. The first kinematic equation is adopted when a reference angle (θ_{ref}) is less than or equal to 90° , where the PRM-A cable is tight

constantly, and the second kinematic equation is adopted when a reference angle is more than 90° when the PRM-B cable is tight all time. Both kinematic diagrams of the LA-X1 angle are presented in Figure 6.10 (a) and (b), respectively. The kinematic equations of the LA-X1 angle are shown in the following formulas.

$$\theta_f = \begin{cases} \cos^{-1} \left(\frac{(l_{base}+p_f)^2 + l_{c1}^2 - L_B^2}{2(l_{base}+p_f)l_{c1}} \right), & \text{if } \theta_{ref} \leq 90^\circ \\ 180 - \cos^{-1} \left(\frac{(l_{base}+p_f)^2 + l_{c2}^2 - L_A^2}{2(l_{base}+p_f)l_{c2}} \right), & \text{if } \theta_{ref} > 90^\circ \end{cases}, \quad (6.7)$$

where L_A is the PRM-A cable length, L_B is the PRM-B cable length, l_{base} is the LA-base length that is 180mm, p_f is the LA-slider length, and l_{c1} , l_{c2} are the distance between the centre of the ball joint foot and the centre of the screw on the right and left-hand side (150mm equally).

These kinematic equations are programmed in a control module to calculate the current angle (θ_f) and compare it to a reference angle (θ_{ref}) to find the LA-X1 angular error (e_θ). This error value is used to design control rules to lock and unlock both PRM-A and PRM-B cables while changing the LA-X1 slider length (p_f) in order to rotate the LA module to the reference angle. A block diagram of the closed-loop control of the LA-X1 angle is presented in Figure 6.11.

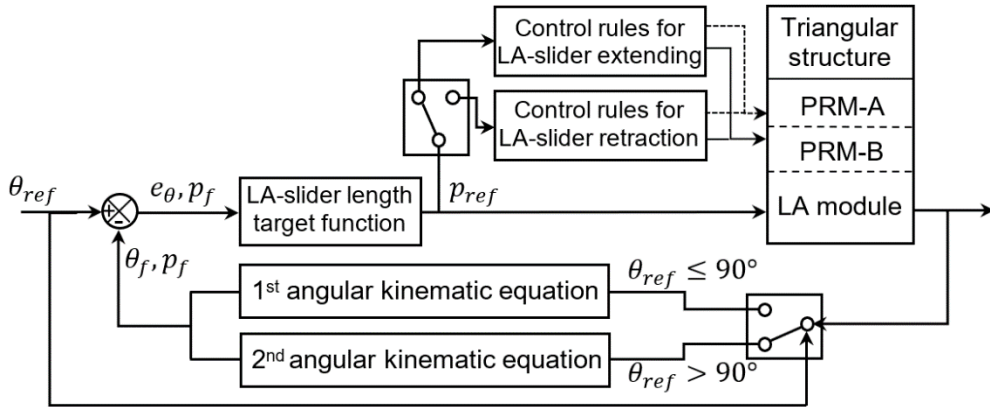


Figure 6.11 Closed-loop control of the LA-X1 angle for the triangular structure; LA-X1 angle (θ_{ref}) is controlled in this experiment using proposed control rules to determine locking/unlocking procedures for the PRM-A, PRM-B, PRM-C, and PRM-D when changing the LA-X1 length.

The concept of the control rules is to extend and retract the LA-X1 slider length travelling between the maximum and minimum values to produce different cable tensions. When changing the LA-X1 slider length, the current angle of the LA-X1 module is compared to the reference angle to force the LA-X1 to rotate to the reference angle by applying locking and unlocking stages for the PRMs to create cable tension caused by the change in LA-X1 slider length.

Therefore, the control rules are divided into two sections, namely LA-slider target function and locking and unlocking stage procedures of PRM-A and PRM-B. The LA-slider target function is designed based on an On-Off controller. The maximum slider length is defined for the LA-slider extending stage, and the minimum slider length is defined for the LA-slider retracting stage. Both slider stages perform alternately until the angular error is lower than 0.1° . For the PRMs' control procedure, the simple concept to tend the LA-X1 module in the extending stage is to control cable tension of the PRM-A and PRM-B, which can be achieved by restricting the PRM cable on the same side of the target angle and release the PRM cable at the opposite side of the target angle, as shown in the following formulas:

$$\text{PRM-A} = \begin{cases} \text{Locking stage,} & \text{if } \theta_f < \theta_{ref} \\ \text{Unlocking stage,} & \text{if } \theta_f \geq \theta_{ref} \end{cases} \quad (6.8)$$

$$\text{PRM-B} = \begin{cases} \text{Unlocking stage,} & \text{if } \theta_f < \theta_{ref} \\ \text{Locking stage,} & \text{if } \theta_f \geq \theta_{ref} \end{cases} \quad (6.9)$$

In contrast, to ensure that all cables remain in tension during the retracting stage of the LA-X1 slider, the unlocking stage is applied to all PRMs to enable spooling forces to pull the cables. These PRM control rules perform until the LA-X1 angle is tended to the target angle.

Before this demonstration, all parameters are initialised; the maximum length of the LA-X1 slider is as 90 mm, and the minimum length is as 0 mm, which is the initial length of the LA-X1 slider. All PRMs are defined as being in the unlocking stage. The initial angle (θ_{ini}) of the LA-X1 is set to 90° , and the initial lengths of the PRM-A and PRM-B cables are set as 233 mm and 234 mm, respectively. Both initial cable lengths are slightly different due to the unequal lengths of the connecting cables that connect the PRMs and washers (see Figure 6.9).

For the angular control experimentations, two experiments are conducted. The first experiment involves controlling the LA-X1 angle tending to 45° and 135° , while the slider target lengths (p_{ref}) of the LA-X1 are defined as 90 mm for the slider extension stage. Each target angle is repeatably demonstrated three times for reliable results. The video frames of the 45° angular control of the LA-X1 module are shown in Figure 6.12, and the experimental results are shown in Figure 6.13.

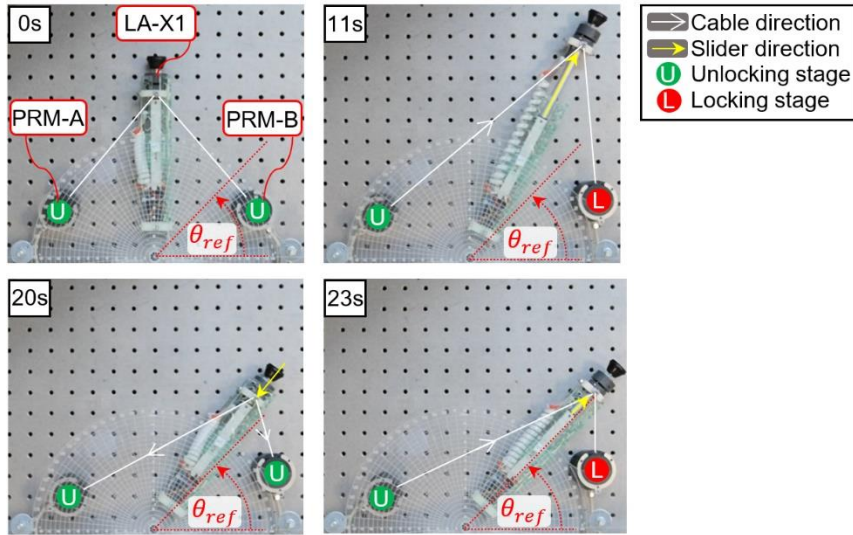


Figure 6.12 Video frames of the 45° angular control demonstration.

The results showed that all locking and unlocking stages of the PRMs, cable lengths, LA-X1 slider length, and LA-X1 angle in the first, second, and third experiments are similar. The simple control rules could control the LA-X1 angle tending to a steady-state angle ($\theta_{s.s}$) of 44.96°, which has a very small steady-state error ($\theta_{es.s}$) of 0.1°. The experimental data are summarised in Table 6.4.

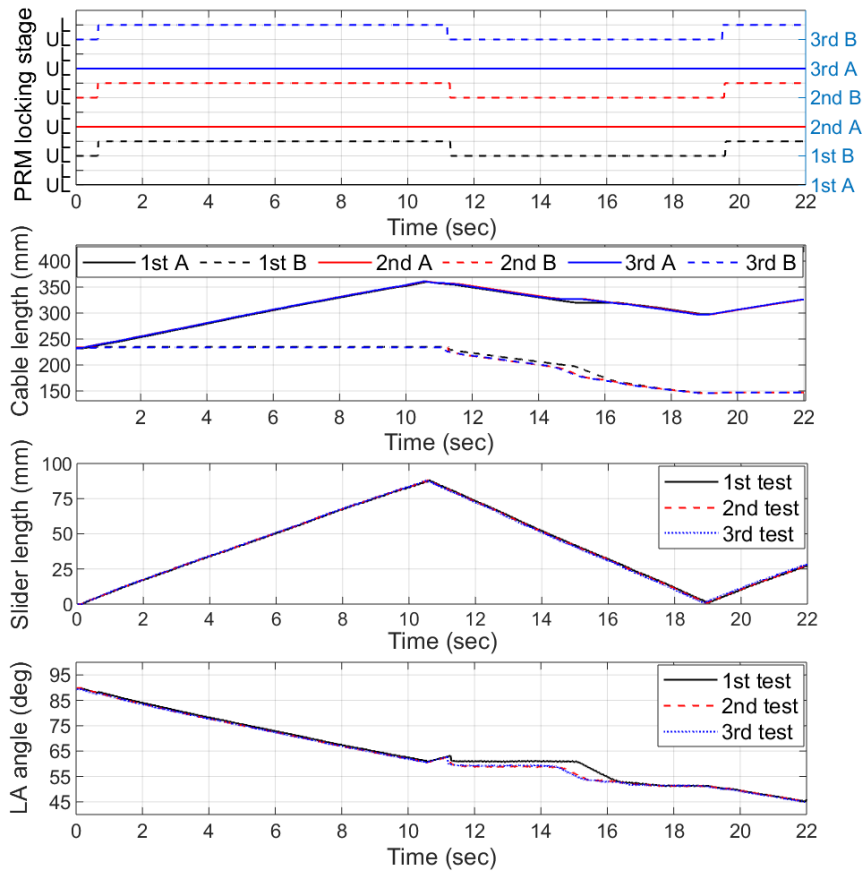
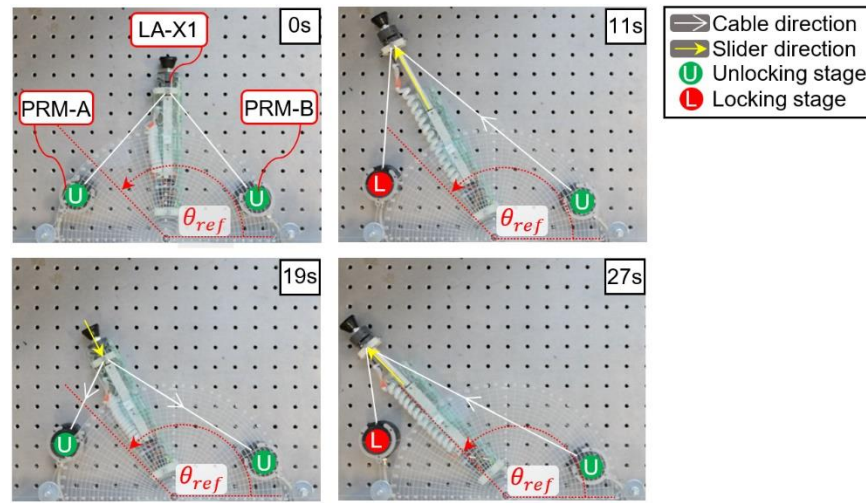
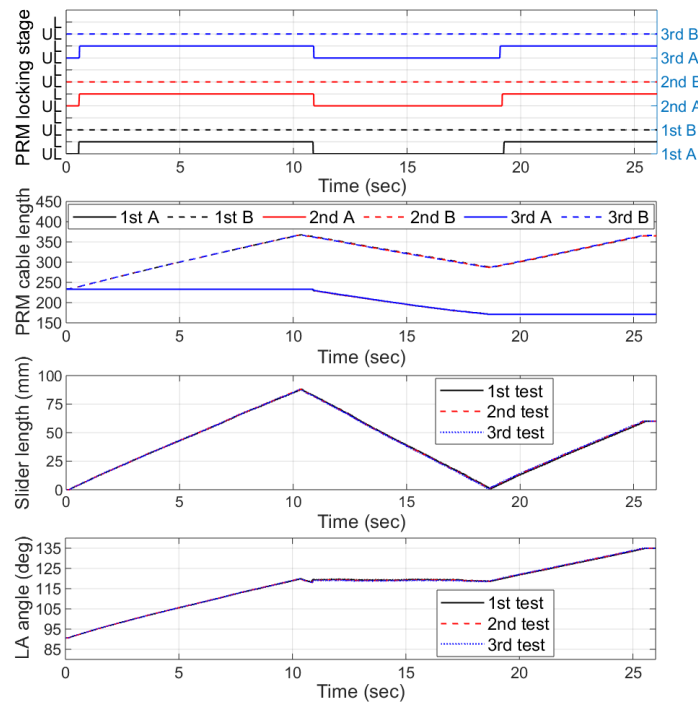


Figure 6.13 45° angular control experimental results: (top) the locking stage of PRM-A and PRM-B, (middle-top) LA-X1 cable length, (middle-bottom) LA-X1 slider length, and (bottom) LA-X1 angle.

Table 6.4 Experimental result summary of the 45° angular control.

Test order	θ_{ini}	$\theta_{s.s}$	$t_{\theta.s}(\text{sec})$	$\theta_{es.s}$
1	90	44.96	21.66	0.04
2	90	44.96	21.65	0.04
3	90	44.96	21.54	0.04

Another experiment involves controlling the LA-X1 angle rotating to 135°, where the LA-X1 module is tended on the left side of the triangular structure. The video frames of the demonstration are shown in Figure 6.14, and experimental data are shown in Figure 6.15.

**Figure 6.14** Video frames of the 135° angular control demonstration**Figure 6.15** 135° angular control experimental results: (top) the locking stage of PRM-A and PRM-B, (middle-top) LA-X1 cable length, (middle-bottom) LA-X1 slider length, and (bottom) LA-X1 angle.

The results suggest that the LA-X1 module could be rotated to the target angle effectively with a very small steady-state error, as presented in Table 6.5. In addition, the experimental data results of the first, second, and third demonstrations are almost identical.

Table 6.5 Experimental results summary of the 135° angular control.

Test order	θ_{ini}	$\theta_{s.s}$	$t_{\theta.s}(\text{sec})$	$\theta_{es.s}$
1	90	134.94	24.54	0.06
2	90	134.94	24.46	0.06
3	90	134.94	24.41	0.06

Therefore, the proposed structural deformation method not only can control the end-effector position in a straight path, but also can control the end-effector angle, which is the basic motion of general robot needs for locomotion tasks.

However, to demonstrate the further capability to control the end-effector positions on both the X and Y axis and control the end-effector angle simultaneously, the 5-DOF structure, including one LA module and four PRM modules, are constructed and demonstrated, as presented in the following subsections.

6.2 5-DOF System Experiments

This section describes 5-DOF system experimentation to demonstrate the fundamental movements of end-effector positions. The end-effector can be moved along the X and Y-axis using four PRMs cooperating with an LA module. Forward kinematics of the end-effector are investigated to identify the end-effector position of the structure. New control rules for the closed-loop position control of the end-effector are then introduced.

6.2.1 5-DOF Structure

The 5-DOF structure consists of four PRMs (PRM-A, PRM-B, PRM-C, and PRM-D) and one LA module, as presented in Figure 6.16. The LA module is placed in the middle of the structure. The PRM-A and PRM-C are placed on the top-left and top-right of the LA, and their cable tips are attached and screwed at the middle top of the LA-module represented as P_2 position. A connecting cable connects the PRM connector and a washer that can rotate freely around a 6 mm screw. On the bottom of the structure, the PRM-B and PRM-D are placed on the bottom left and right sides of the LA, and their cable tips connected and screwed into the middle bottom of the LA module, represented as P_1 position. In this structure, the end-effector position of the structure is in the middle of the LA module at the initial length represented as P_e .

In this experiment, the fundamental motions of the end-effector using the proposed actuation method are demonstrated without unstable factors such as frictions that affect end-effector motions. Therefore, the rotary and linear components are created and attached to the LA module to minimise friction between the LA-module surfaces and the backplane. The rotary parts, including ball-bearing and supporter, are connected to the end-effector to allow the end-effector to rotate smoothly; they are mounted on the bracket of the X axis linear part, including linear bearing providing the movement in the X direction. The X axis' linear bearing is attached to the bracket of the Y axis' linear bearing to allow the end-effector to move along the Y axis. Therefore, the end-effector can rotate and move in X and Y directions smoothly. The installations of the three additional parts are presented in Figure 6.16 (zoomed-in image).

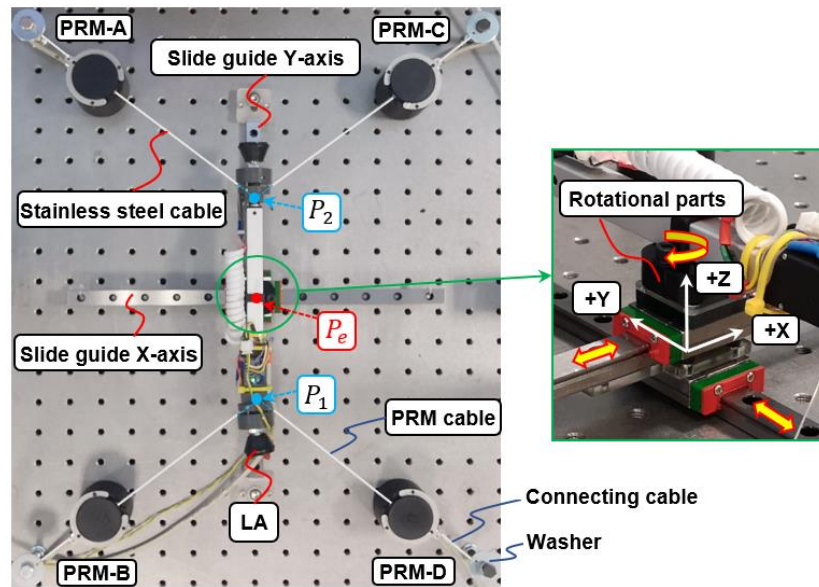


Figure 6.16 5-DOF structure, including four PRMs and one LA. Red dot indicates the end-effector of the structure.

Before demonstrating the end-effector position control, the forward kinematic equations of the end-effector derived in Chapter 3 are evaluated, which is achieved by programming all forward kinematic equations into the master control module. The calculated positions generated by the kinematic equations are then compared to the custom-circular scale (see Figure 6.17) to ensure that the forward kinematic equation is effectively used to identify the end-effector positions, as detailed in Appendix E1.

Figure 6.17 presents the experimental setup of the forward kinematic equations for the proposed 5-DOF structure. The custom-circular scale is placed above the structure. The left and right sides of the custom scale are mounted on the brackets attached to the aluminium profiles to highlight the custom-circular scale accurately. A 3 mm screw with a sharp tip of 0.2 mm is mounted in the middle of

the end-effector, and the tip is turned up to the custom scale to indicate the end-effector position, as presented in Figure 6.18.

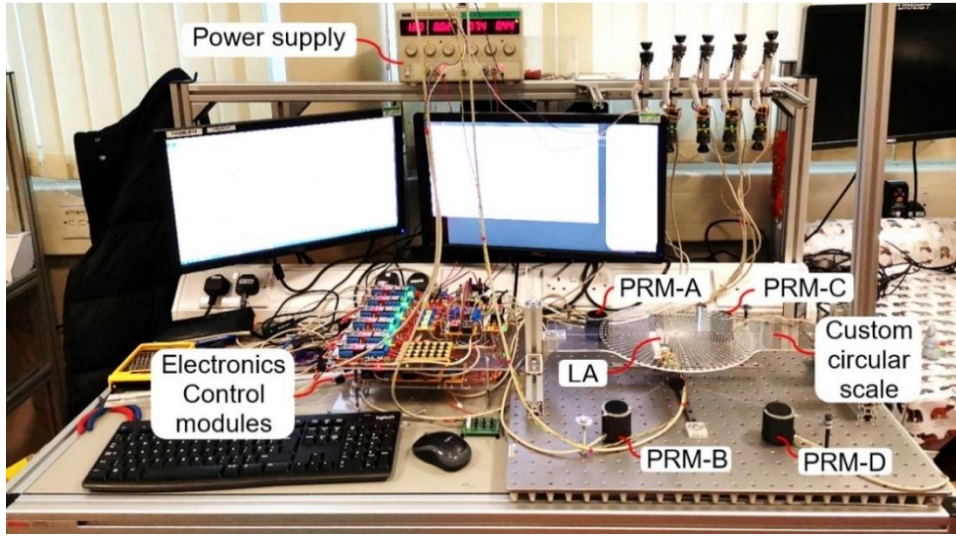


Figure 6.17 Experimental setup of the kinematics equations accuracy evaluation.

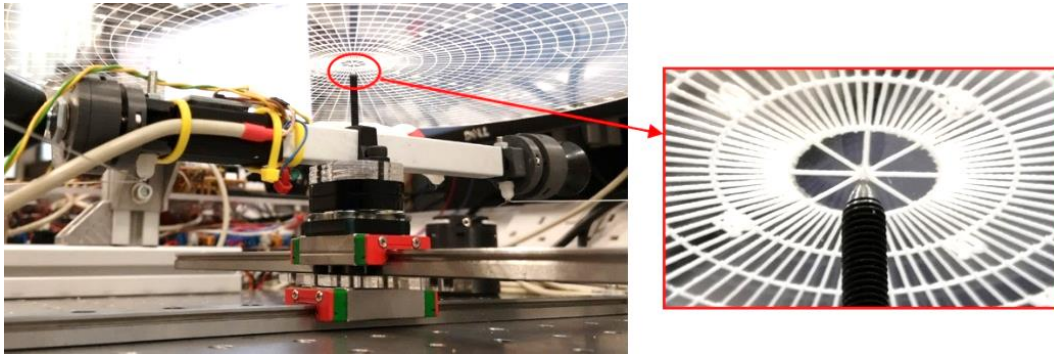


Figure 6.18 Sharp tip installation for pointing out the custom circular scale.

The cable length of the four PRMs is determined by placing the end-effector position in the middle of the structure, which is the initial position. The PRM cable lengths are then measured and combined with the summation of the PRM diameter and the connecting cable length (see Figure 6.16). These combination lengths of the PRM-A to PRM-D are called L_A , L_B , L_C and L_D . All parameters used for substituting the kinematics equations (see section 3.3.2 C) are summarised in Table 6.6.

Table 6.6 Initial parameters for the kinematics equations.

Parameters	L_A	L_B	L_C	L_D	L_W	L_H	l_b
Length (mm)	219	221	222	221	350	425	156

End-effector position measurements are implemented by defining the four target positions of the end-effector. The end-effector is then moved manually and held

in the target position. At this time, the end-effector angle and distance are calculated to compare with the custom scale. All data are sent to the PC via serial communication with a baud rate of 9600 bits per second.

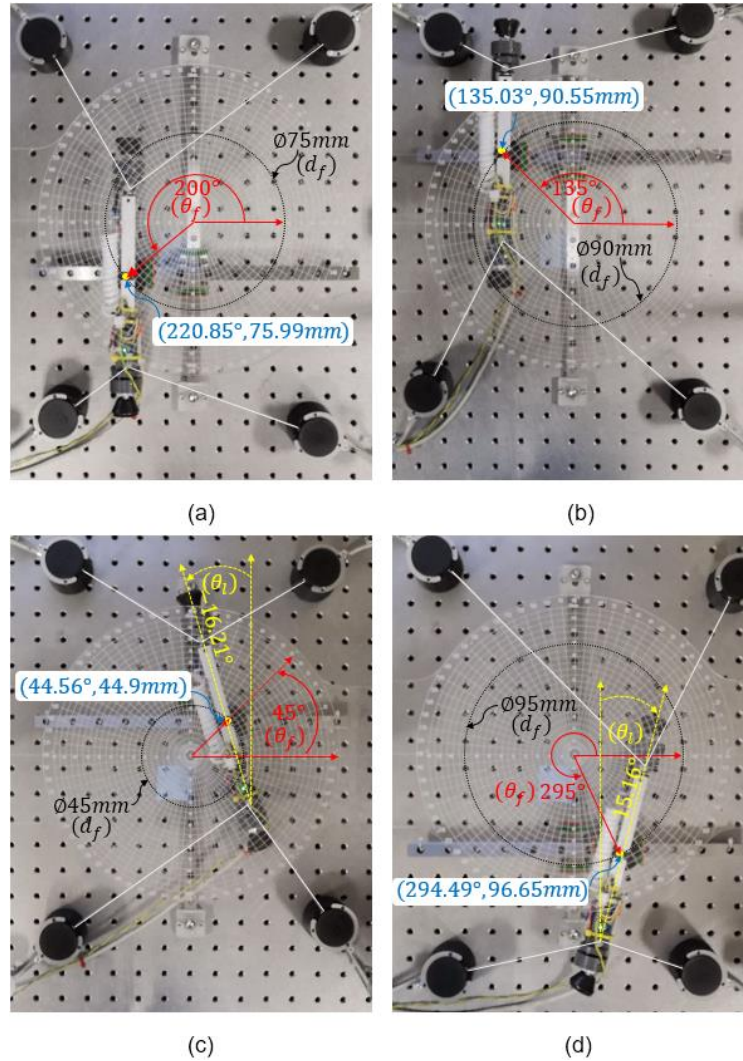


Figure 6.19 Example video frames of the kinematic equation accuracy experiments by comparing the end-effector angle (θ_f) and distance (d_f) values to the custom scale: (a) $\theta_f = 200^\circ$, $d_f = 75\text{mm}$, (b) $\theta_f = 135^\circ$, $d_f = 90\text{mm}$, (c) $\theta_f = 45^\circ$, $d_f = 45\text{mm}$ and (d) $\theta_f = 295^\circ$, $d_f = 95\text{mm}$.

Figure 6.19 presents the four different positions of the end-effectors. The red arrow and text indicate the physical end-effector angle measured by the custom scale, whereas the black circle line, arrow, and text indicate the radius or distance of the end-effector measured by the custom scale, and the blue arrow and text indicate the end-effector angle and distance calculated by the forward kinematic equations. The results show that the forward kinematic equations could be used to calculate the end-effector positions properly. Although the LA-base angle (θ_l) was rotated as -16.21° (see Figure 6.19, bottom-left image) and 15.16° (see Figure 6.19 bottom-right image), the calculated angle and distance are still similar

to the custom scale values. The accuracy of the forward kinematic equations is also tested by adjusting the different LA-base angles at the same target position. The end-effector target position on the custom scale is defined as 235° and 50 mm distance and then moved manually to that position. The experimental result data are summarised in Table 6.7. In addition, 108-target positions are tested to evaluate the forward kinematic equations to identify the end-effector position, as detailed in Appendix E2.

The results suggest that the calculated angle and distance of the end-effector position at all LA-base angles are similar to the target position. The angle and distance errors are in the range of $\pm 2^\circ$ and ± 2 mm, respectively. The LA-base angle slightly affects the end-effector angle and distance accuracy. However, it is acceptable to use these forward kinematic equations to calculate the end-effector position in closed-loop control system.

Table 6.7 Experimental results of the calculated angle and distance of the end-effector when adjusting the LA-base angle.

End-effector target position (235° angle and 50 mm distance)				
$\theta_l (^\circ)$	$\theta_f (^\circ)$	d_f (mm)	$e. e_{\theta_f} (^\circ)$	$e. e_{d_f}$ (mm)
21.46	235.93	51.69	0.93	1.69
13.17	235.39	50.94	0.39	0.94
7.92	235.78	51.99	0.78	1.99
3.29	235.75	51.83	0.75	1.83
1.95	236	51.35	1	1.35
-2.66	236.42	51.88	1.42	1.88
-7.98	236.03	51.19	1.03	1.19
-13.04	236.23	51.09	1.23	1.09
-21.53	235.23	50.16	0.23	0.16

6.2.2 End-Effector Position Control Demonstrations

In order to control the end-effector position in this structure, the definitions of reference inputs and initial position are designed. Initially, the end-effector position is arranged in the middle of the structure, where the end-effector angle and distance are set to zero (x_0, y_0). Two parameters are defined as the reference inputs for movements, namely the angle between the end-effector subjected to X-axis called target or reference angle (θ_{ref}) and the distance between the initial position to target position, which is called the target or reference distance (d_{ref}).

The control rule of the end-effector position of this structure is challenging because it cannot be controlled by adjusting each cable length directly, which is simply achieved by calculating the forward kinematic of the four-cable cable-direct-driven robot (CDDR) [86]. On the other hand, the proposed structure has only one active LA to generate dynamic forces to manoeuvre the end-effector

positions. The LA cooperates with four PRMs. These PRMs can spool the cable passively via rotational mechanisms driven by a power spring and are able to restrict cable length by locking the rotational mechanisms. Therefore, while extending and retracting the LA-slider length, PRMs are used to disable and enable the spooling forces to move the end-effector to desire positions. Therefore, based on the structural configuration analysis and previous experimental results, new control rules for locking/unlocking state procedures of four PRMs and the extending/retracting stage of the LA are designed.

The movement behaviour of the end-effector to achieve a target position is unique; it consists of two movement behaviours, namely a straight path and a zigzag path. For example, in case of the LA module placed in the vertical orientation and the target position defined as 90 or 270 degrees at any distances, the movement behaviour of the end-effector will be straight because the end-effector moves in the same direction as the LA-slider movement. Therefore, the end-effector can be moved to the target distance by extending or retracting the LA-slider length using only one step for the locking or unlocking stage of the PRMs. On the other hand, if the target position is defined as 180 or 0 degrees at any distance, the movement behaviour of the end-effector is a zigzag path because the direction of the target position is different from the LA-slider direction. Therefore, the need to move the end-effector to other locations with multiple LA-slider extension and retraction is required. The examples of the straight and zigzag path are presented in Figure 6.20.

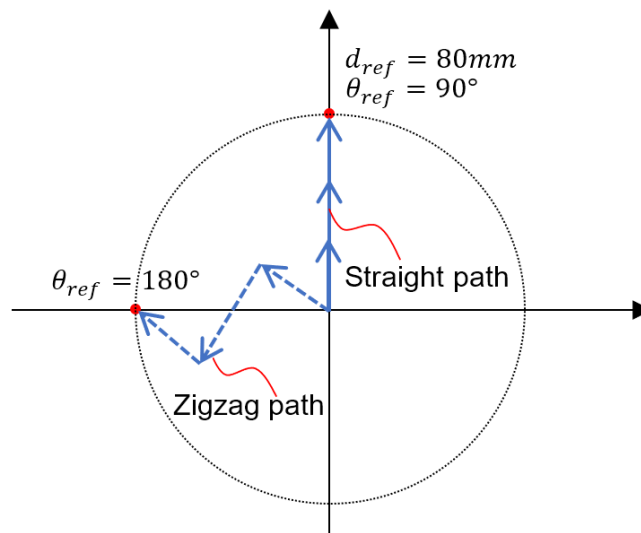


Figure 6.20 Movement behaviours of the end-effector. The end-effector is able to move like straight and zigzag paths to reach target points.

For these end-effector movement concepts, the control rules for the closed-loop control system are proposed. The block diagram of the closed-loop position control of the end-effector is presented in Figure 6.21.

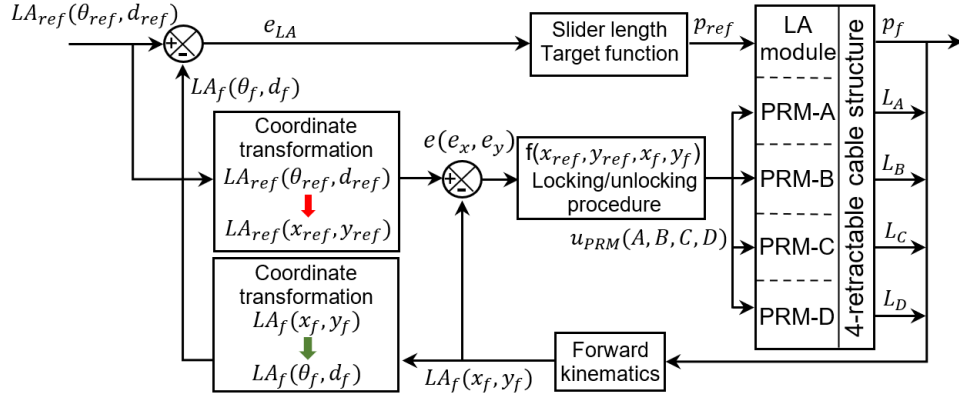


Figure 6.21 Block diagram of the closed-loop position control of the end-effector of the 5-DOF system structure; two variables (θ_{ref}, d_{ref}) are controlled simultaneously in this experiment using the new control rule to determine LA-slider target lengths and locking/unlocking procedures for the PRM-A, PRM-B, PRM-C, and PRM-D.

The control rule consists of two parts, namely LA-slider target length (p_{ref}) and locking/unlocking control procedure of the PRMs. Both control rules produce the control signals to control the 5-DOF structure. The output signals of this structure are LA-slider length (p_f), the PRM-A cable length (L_A), PRM-B cable length (L_B), PRM-C cable length (L_C), and PRM-D cable length (L_D). These parameters are sent to the forward kinematic equations to calculate the current end-effector positions ($LA_f(x_f, y_f)$) calculated by Equation 3.12 and 3.13), which are compared to the target position ($LA_{ref}(x_{ref}, y_{ref})$) and sent to the PRM control rule to produce the locking and unlocking procedure for the four PRMs. The current end-effector position is also transformed to angle and distance values ($LA_f(\theta_f, d_f)$), calculated by Equation 3.14 and 3.15), which are compared to the end-effector target point ($LA_{ref}(\theta_{ref}, d_{ref})$) to calculate the position error (e_{LA}) and calculate the LA-slider target length to move the end-effector to the target point.

In real-world robot development, there are two levels for using and controlling the robot. The first level is the user level, in which the user interface must be designed in a way that is user-friendly, and second level is the computing level, which controls signals and data that must be designed for simple programming and developments. Therefore, in this project, the end-effector target point variables $LA_{ref}(\theta_{ref}, d_{ref})$ are designed on a user level and transformed to X-Y coordinates as the computing level in order to calculate and generate control signals.

In this experiment, the first control rule for calculating the LA-slider target length (p_{ref}) may be achieved by designing the LA-slider length target function, which is the combination of the displacement error (e_{LA}) and the distance compensation constant (d_{cp}), as shown in the following formulas:

$$e_{LA} = (d_{ref} - d_f), \quad (6.10)$$

$$p_{ref} = (e_{LA} + d_{cp}), \quad (6.11)$$

where d_{ref} is the end-effector distance target, d_f is the end-effector distance feedback, and d_{cp} is the distance compensation value.

Distance compensation (d_{cp}) is defined as 15 mm experimentally using the trial-and-error method. Therefore, the minimum length of the LA-slider target is 15 mm. The distance compensation (d_{cp}) is crucial in preventing the oscillating movements of the end effector in case of a small displacement error occurrence. For example, if a 5 mm displacement error (e_{LA}) occurs in the system, the LA-slider target length (p_{ref}) for the next movement will be 5 mm, excluding the distance compensation constant (d_{cp}). After applying the locking and unlocking stage of each PRM and extending the LA-slider length of 5 mm, only PRM cable angles are changed instead of moving the end-effector position due to the cable angle error, caused by cable slacking during the locking stage. Therefore, the stroke length compensation needs to be added to the control rule to change the LA-slider length, which can move the end-effector to target points.

The second control rule is the locking and unlocking control procedures of four PRM modules. This control rule is designed considering the target and current end-effector position in X-Y planes. Therefore, the end-effector target position (LA_{ref}), which consists of angle (θ_{ref}) and distance (d_{ref}), need to be transformed to the X-Y planes $LA_{ref}(x_{ref}, y_{ref})$. The diagram of the coordinate transformation is present in Figure 6.22, and the target position in the X-Y axis is calculated using Equations (6.12) and (6.13), respectively.

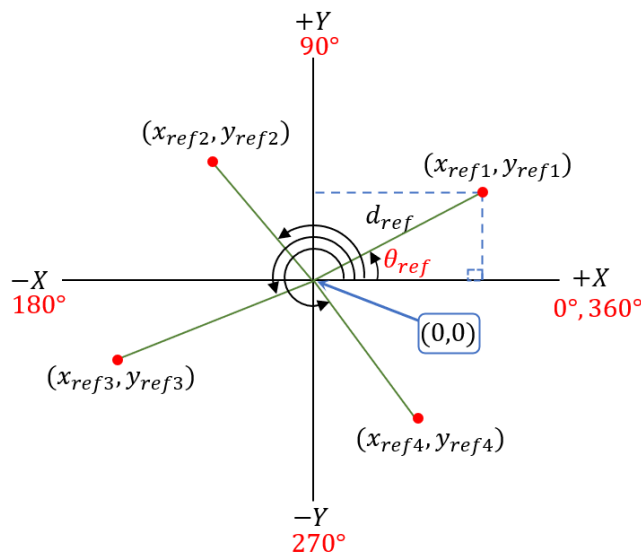


Figure 6.22 Diagram of the end-effector target angles and target distances $LA_{ref}(\theta_{ref}, d_{ref})$, converting to the X-Y plane; the red dots are example target positions of the end-effector $LA_{refn}(x_{refn}, y_{refn})$ for $n = 1$ to 4.

$$x_{refn} = d_{ref} \cos \theta_{ref} \quad (6.12)$$

$$y_{refn} = d_{ref} \sin \theta_{ref} \quad (6.13)$$

The control rule for the locking and unlocking procedure of four PRMs is divided into two states, namely extension and retraction states. The extension state involves extending the LA slider to a target length in order to move the end-effector or prepare for movement in the next state, depending on end-effector target directions. For example, if the end-effector target is defined under the beginning position, the end-effector will be moved suddenly in the extension state by applying the locking stage of both PRM-A and PRM-C and the unlocking stage of both PRM-B and PRM-D. On the other hand, if the target direction is defined above the beginning position, the end-effector will not be moved at the extension state because the end-effector does not directly connect to the LA slider. The need for the extension state should be determined before doing the retraction state to move the end-effector. Therefore, the control rule significantly relates to the end-effector target positions. The new control algorithm to generate locking and unlocking procedures for all PRMs is summarised in Table 6.8.

Table 6.8 Control rule for locking/unlocking procedures.

Control rule	PRM Locking/unlocking stage (u_{PRM})			
LA-extension state	A	B	C	D
$y_{ref} > y_f$				
$x_{ref} > x_f$	L	L	U	L
$x_{ref} < x_f$	U	L	L	L
$x_{ref} = x_f$	U	L	U	L
$y_{ref} < y_f$				
$x_{ref} > x_f$	L	L	L	U
$x_{ref} < x_f$	L	U	L	L
$x_{ref} = x_f$	L	U	L	U
LA-retraction state	A	B	C	D
$y_{ref} > y_f$				
$x_{ref} > x_f$	L	U	L	L
$x_{ref} < x_f$	L	L	L	U
$x_{ref} = x_f$	L	U	L	U
$y_{ref} < y_f$				
$x_{ref} > x_f$	U	L	L	L
$x_{ref} < x_f$	L	L	U	L
$x_{ref} = x_f$	U	L	U	L

This new control algorithm is implemented to evaluate the closed-loop position control performance. Software implementation was developed using the LA-slider target function and control rules to calculate the locking and unlocking stage procedures of the PRMs (A to D). This algorithm is programmed into a high-level controller to generate locking and unlocking command patterns and LA-slider

target lengths sent to each low-level controller, including one LA and four PRM electronic control boards.

In order to demonstrate the proposed control rule, four target positions of the end-effector are selected. The target positions are chosen from one point of each quarter of the custom circular scale, which are $(45^\circ, 40 \text{ mm})$, $(120^\circ, 50 \text{ mm})$, $(255^\circ, 30 \text{ mm})$ and $(355^\circ, 65 \text{ mm})$. Each target position $(LA_{ref}(\theta_{ref}, d_{ref}))$ is demonstrated three times for reliable testing. However, the LA-base angle (θ_l) is not controlled in this experiment. The steady-state error allowance for both end-effector angle and distance are defined as $\pm 2^\circ$ and $\pm 2 \text{ mm}$, respectively. The maximum duty cycle of the LA-slider is defined as 50% to observe the movement behaviour of the end-effector.

Figure 6.23 shows the video frames of the end-effector moved to the first target position $(45^\circ, 40 \text{ mm})$. In the initial position (0s), the end-effector is placed in the middle between four PRMs. The red-dash line indicates the end-effector target distance, whereas the yellow-dash line indicates the end-effector target angle. The unlocking stage (green circular) was applied for all PRMs to make all cables remaining in tension. After starting the closed-loop position control, the locking stage is applied to the PRMs (A to D) and then extended to the LA-slider length. In the stage at the sixth second, the LA-slider tip is pulled on the right-hand side due to the pulling force of the C. The final step (11 s) is to apply the locking stage for A, C, and D and the unlocking stage for B to release the cable, which is spooled by the LA-base while retracted its length. Consequently, the end-effector is moved to the target position (red dot).

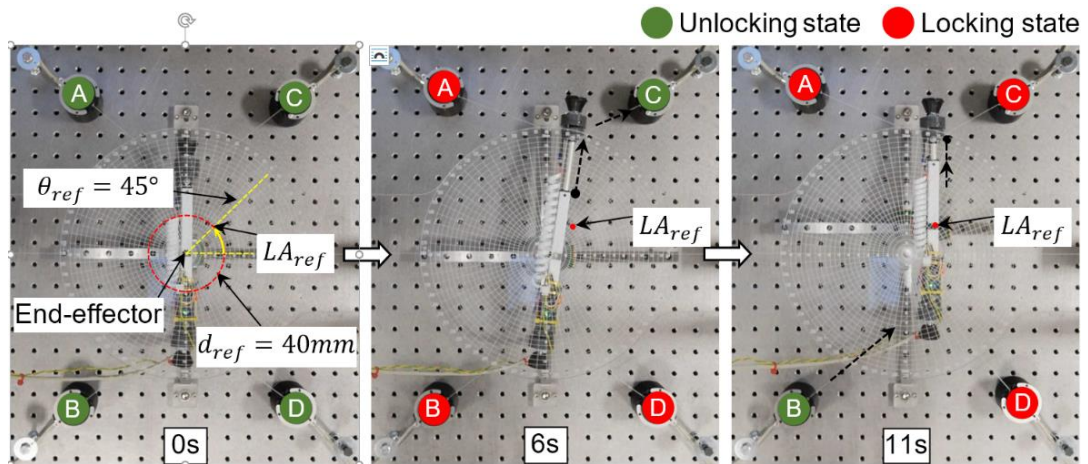


Figure 6.23 Video frames of the end-effector position control experiments ($LA_{ref}(45^\circ, 40 \text{ mm})$)

A three-repetitive test is performed to evaluate controller performance. The experimental results and the control signals generated by the proposed control rules are shown in Figure 6.24 and Figure 6.25, respectively.

The results show that the end-effector of the three experiments could be moved to the same target position effectively. The control rule could produce the LA-slider extension and retraction procedures while locking and unlocking four PRMs, as shown in Figure 6.25.

Figure 6.24 (top) illustrates the end-effector motions along with the X-Y plane and is plotted using the coordinate transformation function from the current end-effector angle (middle graph) and displacement (bottom graph). Although the route of the end-effector is not the shortest distance travelling to the target point due to the movement behaviour limitations, the steady-state value of the end-effector angle ($\theta_{f.s.s}$) and end-effector displacement ($d_{f.s.s}$) are closed to the target values. Furthermore, the settling time, $\pm 2\%$ of the target value, of the end-effector ($t_{s\theta}$ and t_{sd}) of the three experiments is similar, and the steady-state error of the target angle and target displacement of the end-effector occur within the desire values of $\pm 2^\circ$ and $\pm 2\text{mm}$. All experimental parameters and results are summarised in Table 6.9.

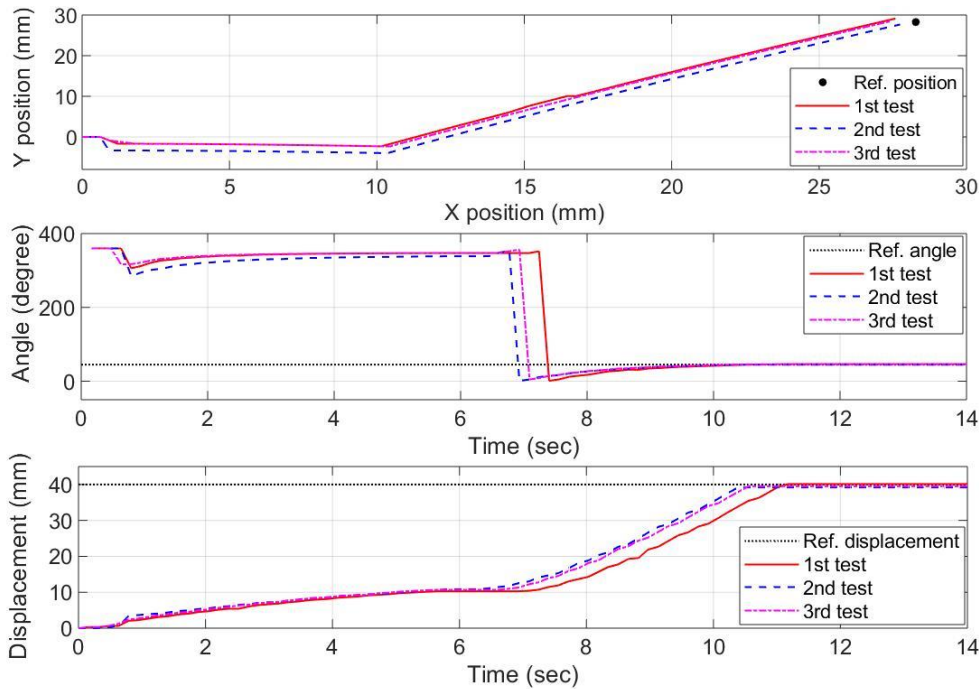


Figure 6.24 Experimental results of the end-effector position control $LA_{ref}(45^\circ, 40\text{mm})$: (top) the end-effector movements in X-Y plane, (middle) the end-effector moving to the target angle, and (bottom) the end-effector moving to the target position.

Table 6.9 Repetitive experimental result summary ($LA_{ref}(45^\circ, 40\text{mm})$).

θ_{ref} ($^\circ$)	d_{ref} (mm)	Repetitive test	$\theta_{f.s.s}$ ($^\circ$)	$t_{s\theta}$ (sec)	$e.e_{\theta_{ref}}$ ($^\circ$)	$d_{f.s.s}$ (mm)	t_{sd} (sec)	$e.e_{d_f}$ (mm)
45	40	first	46.55	10.39	-1.55	40.12	11.02	-0.12
		second	44.91	10.23	0.09	39.19	10.39	0.81
		third	46.07	10.08	-1.07	39.5	10.55	0.5

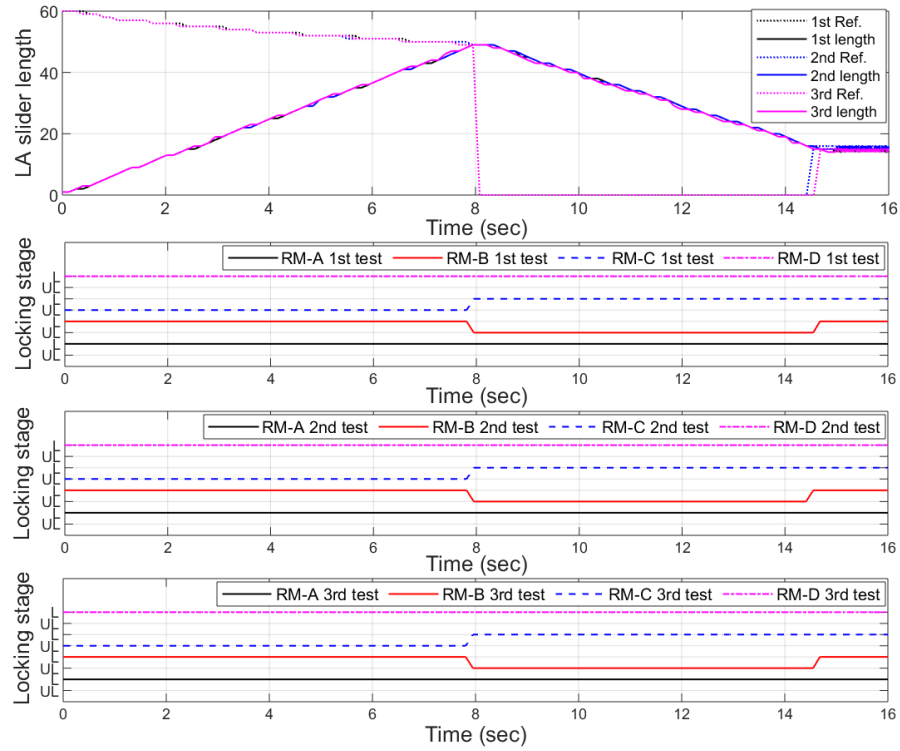


Figure 6.25 Control signal comparison of the three repetitive experiments generated by the proposed control rule for moving the end-effector to the target position ($LA_{ref}(45^\circ, 40mm)$): (top) the LA-slider targets and movement, (three-bottom) the first, second, and third locking and unlocking control procedures of the PRMs or RMs (A to D).

The second target position involves moving the end-effector to the point where the target angle (θ_{ref}) is 120° and the target distance (d_{ref}) is 50 mm . The video frames of this experiment are presented in Figure 6.26.

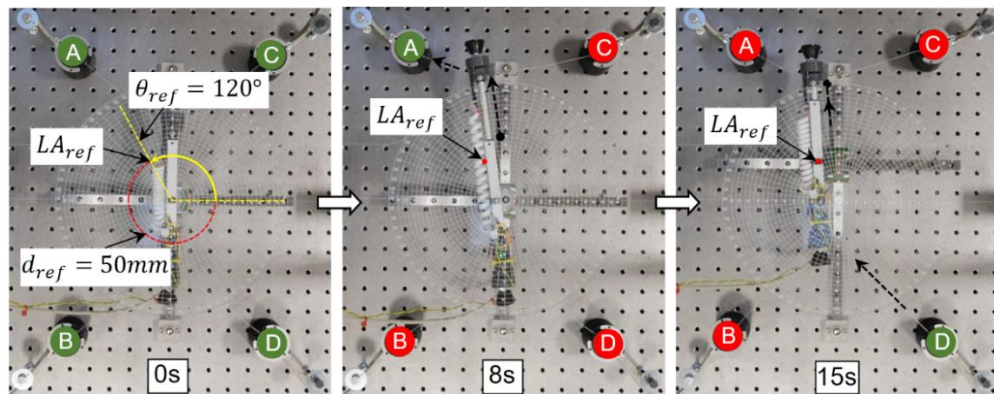


Figure 6.26 Video frames of the end-effector position control experimentations ($LA_{ref}(120^\circ, 50mm)$).

The video frames show that the control rule could produce the LA-slider target length that cooperates with the locking and unlocking procedure of four PRMs in order to move the end-effector travelling to the target position. The end-effector reaches the target position using only one step of the LA-slider extension (see

the eighth second) and one step of the LA-slider retraction (see 15th second). The time responses of the three-repetitive experimental results are shown in Figure 6.27.

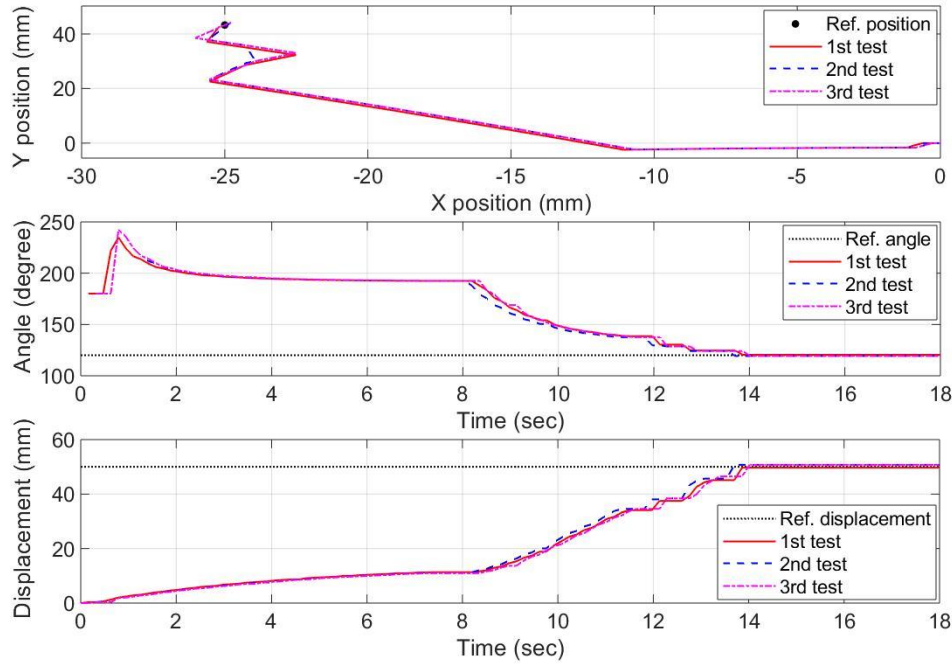


Figure 6.27 Experimental results of the end-effector position control($LA_{ref}(120^\circ, 50\text{mm})$): (top) the end-effector movements in X-Y plane, (middle) the end-effector moving to the target angle, and (bottom) the end-effector moving to the target position.

The time response graph of the three repetitive experiments shows that the movement behaviours of the end-effector are different compared to the first experiment. The motion path of the end-effector is of a zigzag style because the motion angle in the first stage between the second and eighth second cannot move the end-effector to the target point. After detecting the angular and displacement error, the control rule calculates the new LA-slider target length and locking/unlocking stage of all PRMs until the end-effector moves to the target position, as presented in Figure 6.27 (top). The control rule could generate different LA-slider target lengths (see Figure 6.28 (top)) and the locking and unlocking procedures of the PRMs (A to D) effectively in the first, second, and third experiments, as shown in Figure 6.28 (three bottom graphs). These results lead to providing a small steady-state error, under $\pm 1^\circ$ of the end-effector target angle and under $\pm 1\text{mm}$ of the end-effector target distance, in the closed-loop control system, as shown in Table 6.10.

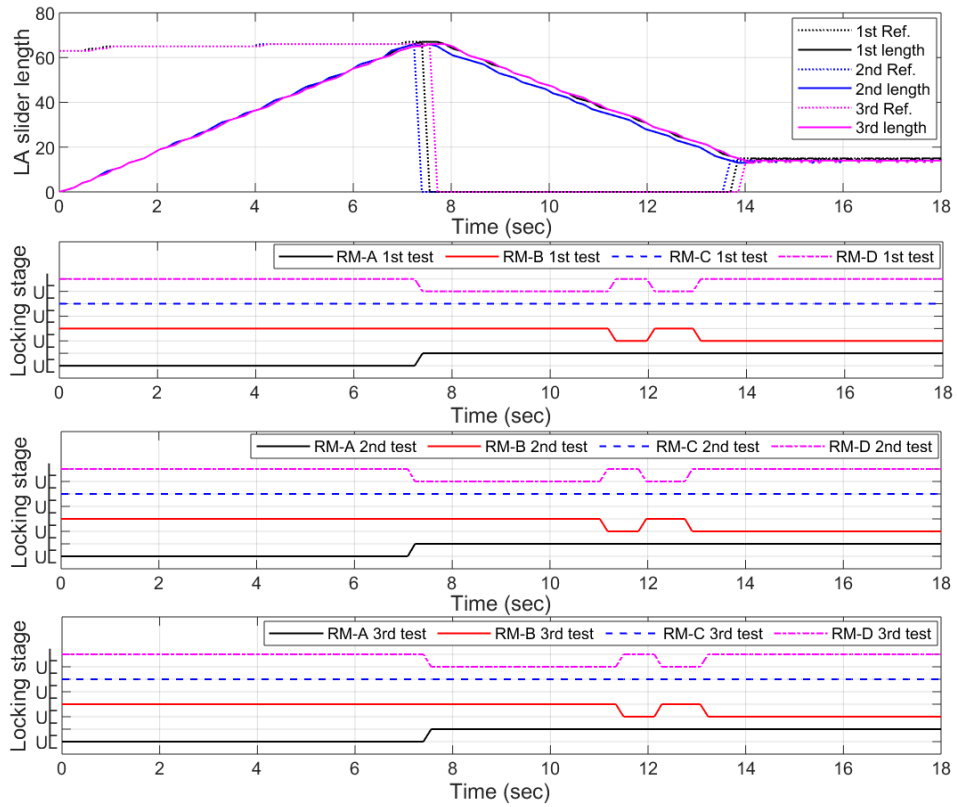


Figure 6.28 The control signal comparison of the three repetitive experiments generated by the proposed control rule for moving the end-effector to the target position ($LA_{ref}(120^\circ, 50mm)$): (top) the LA-slider targets and movement, (three-bottom) the first, second, and third locking and unlocking control procedures of the PRMs or RMs (A to D).

Table 6.10 Repetitive experimental result summary($LA_{ref}(120^\circ, 50 mm)$).

θ_{ref} ($^\circ$)	d_{ref} (mm)	Repetitive test	$\theta_{f.s.s}$ ($^\circ$)	$t_{s\theta}$ (sec)	$e.e_{\theta_{ref}}$ ($^\circ$)	$d_{f.s.s}$ (mm)	t_{sd} (sec)	$e.e_{d_f}$ (mm)
120	50	first	120.45	13.86	-0.45	49.69	13.86	0.31
		second	119.25	13.7	0.75	50.73	13.7	-0.73
		third	119.25	14.02	0.75	50.73	14.02	-0.73

For the third and fourth target positions, the control rule could calculate control signals to control the end-effector motions to reach target positions with small steady-state error, offering the same results as the first and second target position control experiments. The results are summarised in Table 6.11.

Table 6.11 Third and fourth repetitive experimental result summary.

θ_{ref}	d_{ref}	Test order	$\theta_{f.s.s}$	$t_s(\theta_{ref})$	$e.e_{\theta_{ref}}$	$d_{f.s.s}$	$t_s(d_f)$	$e.e_{d_f}$
255	30	first	254.84	5.35	0.16	29.38	7.09	0.62
		second	255.33	5.35	-0.33	29.35	7.4	0.65
		third	255.81	5.35	-0.81	29.31	7.4	0.69
310	55	first	309.86	11.65	0.14	54.16	14.01	0.84
		second	310.44	11.18	-0.44	54.73	13.85	0.27
		third	310.38	11.34	-0.38	56.07	17.01	-1.07

Another experiment involved controlling both end-effector position (including end-effector angle (θ_f), displacement (d_f)), and LA-base angle (θ_l) simultaneously. Thus, the end-effector reference point (LA_{ref}) can be modified as $LA_{ref}(\theta_{ref}, d_{ref}, \theta_{l_{ref}})$. This experiment explores a new control algorithm to control both the end-effector position and the LA-base angle simultaneously, which is beneficial in controlling the strut module angle in the robot structure for rotating and turning. The block diagram of the closed-loop position and angle controls of the end-effector is presented in Figure 6.29.

The block diagram of the control system is slightly different from the previous demonstrations. The LA-base target angle ($\theta_{l_{ref}}$) is added in the end-effector target point, and the LA-base angle (θ_l) is added in the locking/unlocking procedure functions to generate locking and unlocking procedures for the four PRMs. Forward kinematics are used to identify current points of the end-effector position and angle ($LA_f(x_f, y_f, \theta_l)$) in the X-Y plane, compared to the end-effector target point ($LA_{ref}(x_{ref}, y_{ref}, \theta_{l_{ref}})$) that is the coordinate transformation of $LA_{ref}(\theta_{ref}, d_{ref}, \theta_{l_{ref}})$. Position errors ($e(e_x, e_y, e_{\theta_l})$) are the input of the locking/unlocking procedure functions that are the control rule to produce locking and unlocking stages for the four PRMs ($u_{PRM}(A, B, C, D)$).

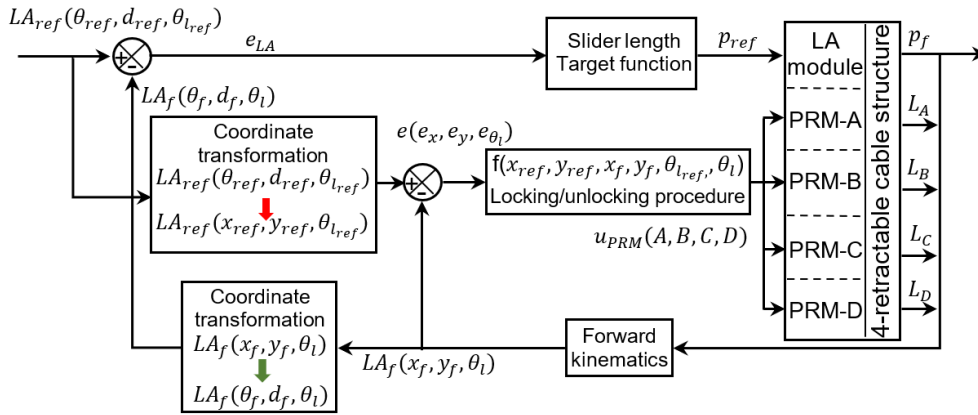


Figure 6.29 Closed-loop position and angle control of the end-effector; three variables (θ_{ref} , d_{ref} , $\theta_{l_{ref}}$) are controlled simultaneously in this experiment using the new control rule to determine LA-slider target lengths and locking/unlocking procedures for the PRM-A, PRM-B, PRM-C, and PRM-D.

The control rules for generating the LA-slider target length are solved by Equations (6.10) and (6.11) in the same way as the previous demonstration. However, the control rules for the extension and retraction stages of the four PRMs are different. The LA-base angle (θ_l) and the LA-base target angle ($\theta_{l_{ref}}$) are added to the locking/unlocking conditions of the four PRMs. For the LA-extension state, both LA-base current angle (θ_l) and target angle ($\theta_{l_{ref}}$) are used to check the end-effector conditions when the current-X-position error (e_x) is

smaller or equal to the minimum-X-position error allowance (e_{xmin}), which is defined as $\pm 2\text{ mm}$. It is observed that the LA-base target and current angle are checked with four conditions in the LA-extension state because, for the extension stage, the priority is moving the end-effector close to the target position and a lesser priority is controlling the LA-base angle. In contrast, in the retraction stage, the LA-base angle is defined as the priority in order to turn the end-effector to reach the LA-base target angle rather than focusing on the end-effector target position. The priority of the end-effector position and the LA-base angle (end-effector body angle) is set differently because the control of the end-effector position and the angle cannot be achieved simultaneously due to the restricted number of active actuators, which cannot spool four cables attached to the end-effector at the same time. The locking/unlocking control rules to control the end-effector positions and angles are summarised in Table 6.12.

Table 6.12 The control rules of the position and angle control of the end-effector of the 5-DOF structure

Condition	PRM Locking/unlocking stage (u_{RM})			
LA-extension state	A	C	B	D
$y_{ref} > y_f$				
$e_x \leq e_{xmin}$				
$\theta_l < \theta_{lref}$	L	U	L	L
$\theta_l \geq \theta_{lref}$	U	L	L	L
$x_{ref} > x_f$	L	U	L	L
$x_{ref} < x_f$	U	L	L	L
$y_{ref} < y_f$				
$e_x \leq e_{xmin}$				
$\theta_l < \theta_{lref}$	L	L	U	L
$\theta_l \geq \theta_{lref}$	L	L	L	U
$x_{ref} > x_f$	L	L	L	U
$x_{ref} < x_f$	L	L	U	L
LA-retraction state	A	C	B	D
$y_{ref} > y_f$				
$e_x \leq e_{xmin}$				
$\theta_l = \theta_{lref}$	L	L	U	U
$\theta_l < \theta_{lref}$	L	L	L	U
$\theta_l > \theta_{lref}$	L	L	U	L
$(x_{ref} > x_f) \&\& (e_x > e_{xmin})$				
$\theta_l = \theta_{lref}$	L	L	U	U
$\theta_l < \theta_{lref}$	L	L	L	U
$\theta_l > \theta_{lref}$	L	L	U	L
$(x_{ref} < x_f) \&\& (e_x > e_{xmin})$				
$\theta_l = \theta_{lref}$	L	L	U	U
$\theta_l < \theta_{lref}$	L	L	L	U
$\theta_l > \theta_{lref}$	L	L	U	L
$y_{ref} < y_f$				
$(x_{ref} = x_f) \parallel (e_x \leq e_{xmin})$				

$\theta_l = \theta_{l_{ref}}$	L	U	L	L
$\theta_l < \theta_{l_{ref}}$	U	L	L	U
$\theta_l > \theta_{l_{ref}}$	L	U	U	L
$(x_{ref} > x_f) \&\& (e_x > e_{xmin})$				
$\theta_l = \theta_{l_{ref}}$	L	U	L	L
$\theta_l < \theta_{l_{ref}}$	U	L	L	L
$\theta_l > \theta_{l_{ref}}$	L	U	L	L
$(x_{ref} < x_f) \&\& (e_x > e_{xmin})$				
$\theta_l = \theta_{l_{ref}}$	L	L	L	L
$\theta_l < \theta_{l_{ref}}$	U	L	L	L
$\theta_l > \theta_{l_{ref}}$	L	U	L	L

Regarding the control rule implementation, the end-effector target position and end-effector-base angle ($LA_{ref}(\theta_{ref}, d_{ref}, \theta_{lref})$) are selected and demonstrated. The end-effector-base angle and target angle are defined as 45° , 40 mm , and 10° , respectively. The maximum duty cycle of the LA-slider is 50%. Three repetitive implementations are performed to evaluate control performance. The video frames of the end-effector moved to the selected target point with the end-effector base angle control are presented in Figure 6.30.

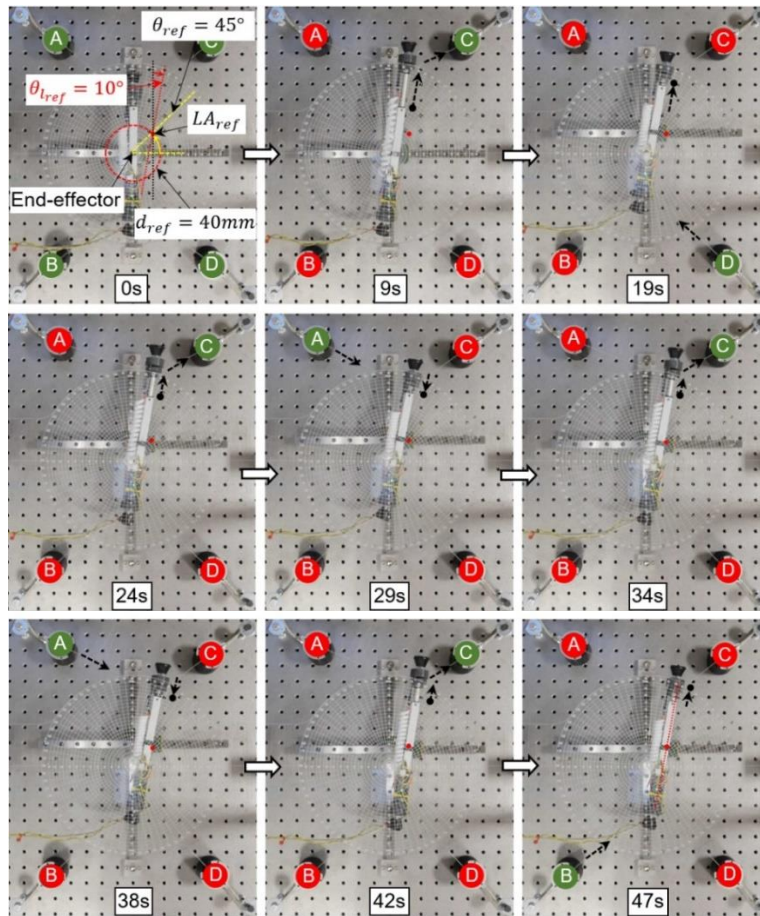


Figure 6.30 Video frames of the end-effector position and angle control experiments ($LA_{ref}(45^\circ, 40\text{mm}, 10^\circ)$).

The video frames show that the proposed control rules could calculate the LA-slider target length and the locking/unlocking procedure for the four PRMs to move the end-effector to the target point. Furthermore, the end-effector base angle was controlled at the desired angle. The movement behaviours of the end-effector position in the first, second, and third experiments are shown in Figure 6.31 (top). These end-effector positions are calculated and plotted by using the experimental data, including the current end-effector angles (second graph from the top) and the current end-effector positions (third graph from the top) via the forward kinematic equations, while the end-effector-base angle is shown in Figure 6.31 (bottom). The control signals for the three repetitive experiments are shown in Figure 6.32.

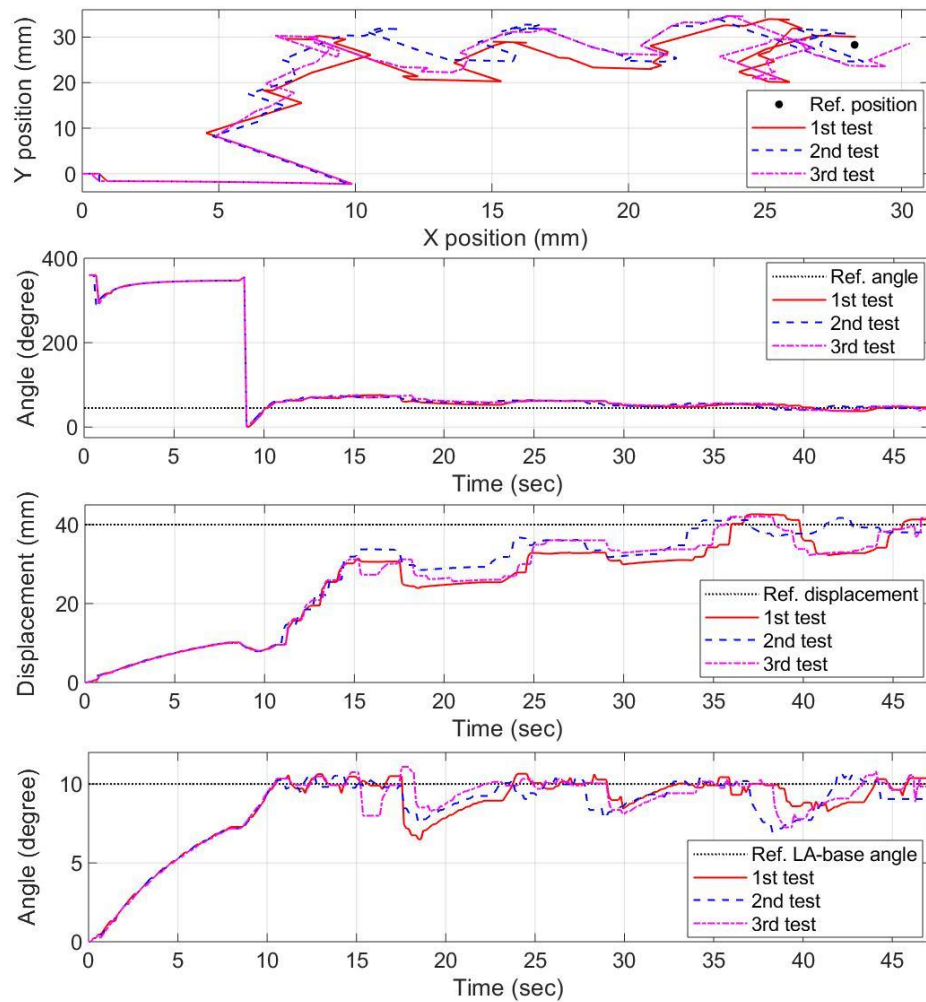


Figure 6.31 The experimental results of the end-effector position (45° , 40mm) and end-effector-base angle control (10°): (top) the end-effector movements in X-Y plane, (second graph) the end-effector moving to the target angle, (third graph) the end-effector moving to the target position and (bottom) the end-effector-base rotating to the target angle.

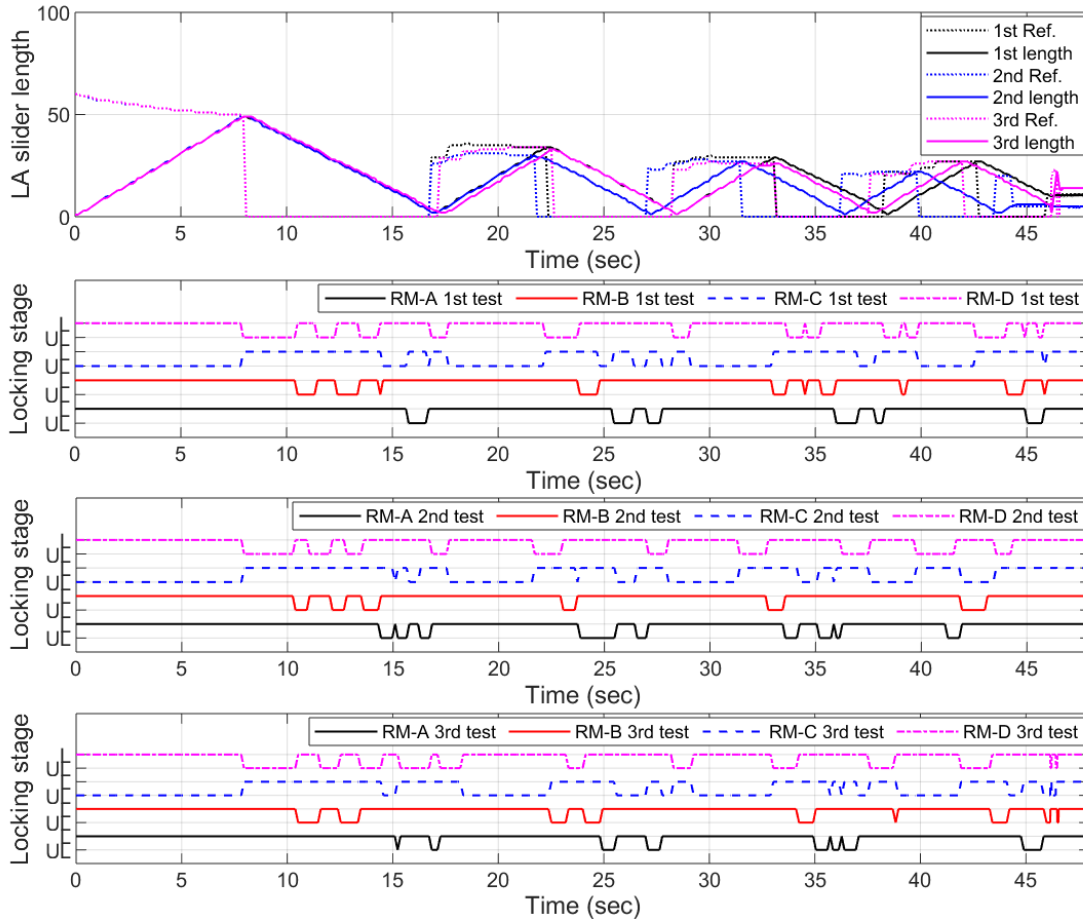


Figure 6.32 Control signal comparison of the three repetitive tests generated by the proposed control rule to move the end-effector to the target position ($LA_{ref}(45^\circ, 40mm, 10^\circ)$): (top) the LA-slider targets and movement, (three-bottom) the first, second, and third locking and unlocking control procedures of PRMs or RMs (A to D)

Another experiment involves changing the end-effector-base target angle while using the same end-effector target position to observe the movement behaviour of the end-effector controlled by the proposed control rules. The end-effector-base target is determined as -10° , and the end-effector target angle and distance are 45° and 40 mm , respectively. The video frames of the experiment are shown in Figure 6.33.

The video frames show that the end-effector could be moved to the target point (see red dot in Figure 6.33) at a time of 39 seconds. The end-effector-base angle is finally stopped at an angle of -10° approximately. Three repetitive tests are performed to obtain the same results. However, the movement behaviour of the end-effector is different to that of the 10° target angle.

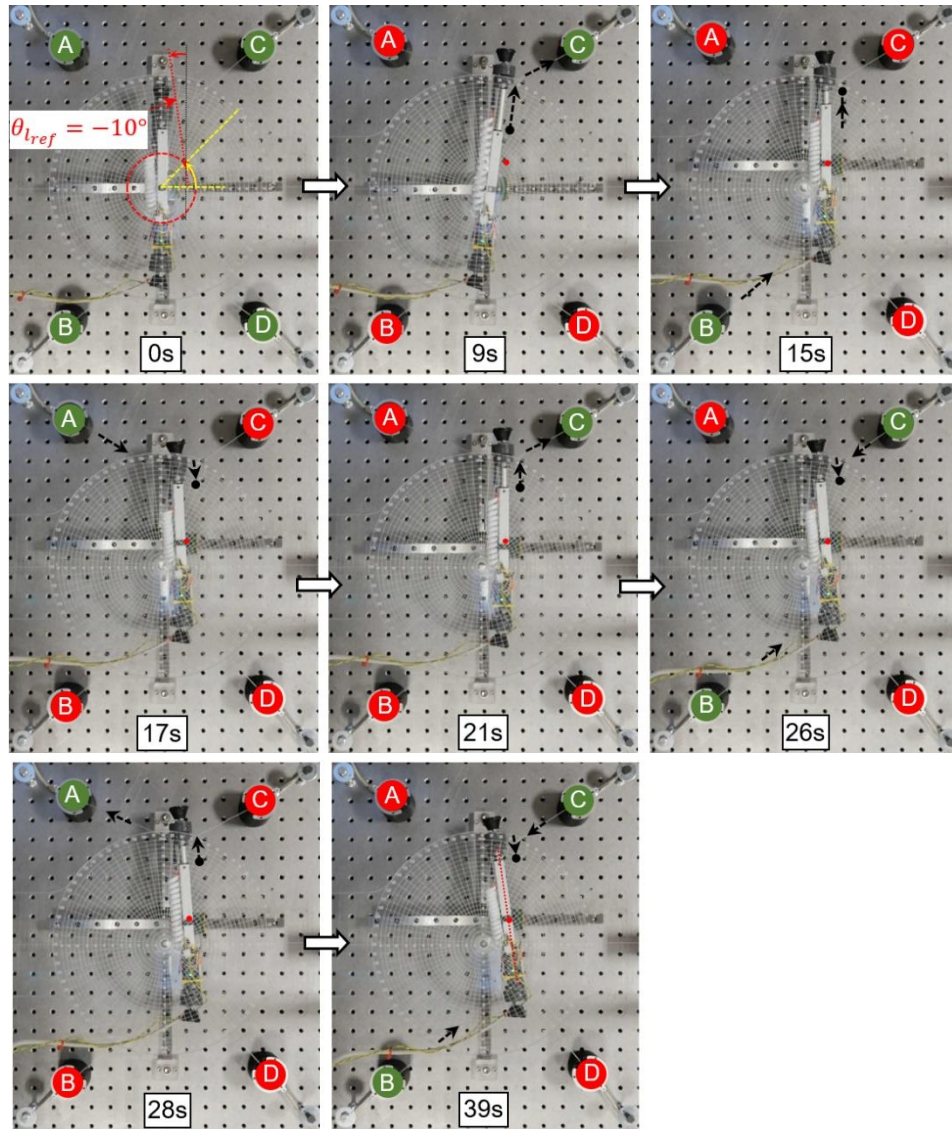


Figure 6.33 Video frames of the end-effector position and angle control experiments ($LA_{ref}(45^\circ, 40mm, -10^\circ)$).

The end-effector moves around the target point before reaching the target point at a time of 75 seconds, as presented in Figure 6.34 (top). In this result, unexpected movement behaviour of the end-effector occurred is found when the end-effector moves over the target point. The control rule detects the position error of the end-effector. The unlocking stage is then applied to the PRM-C to unlock the cable in order to move the end-effector down to the target point. The PRM-C cable is released quickly following the pulling force of the PRM-B and PRM-D cables, dragging the end-effector position under the target point. This movement occurs many times during, adjusting the end-effector-base angle until reaching the target value (-10°), which requires more locking and unlocking procedures compared to the 10° target angle. However, this unexpected motion happens inevitably to control the end-effector position by using only one LA. The control signals of the LA-slider target length and PRM locking/unlocking procedure are presented in Figure 6.35.

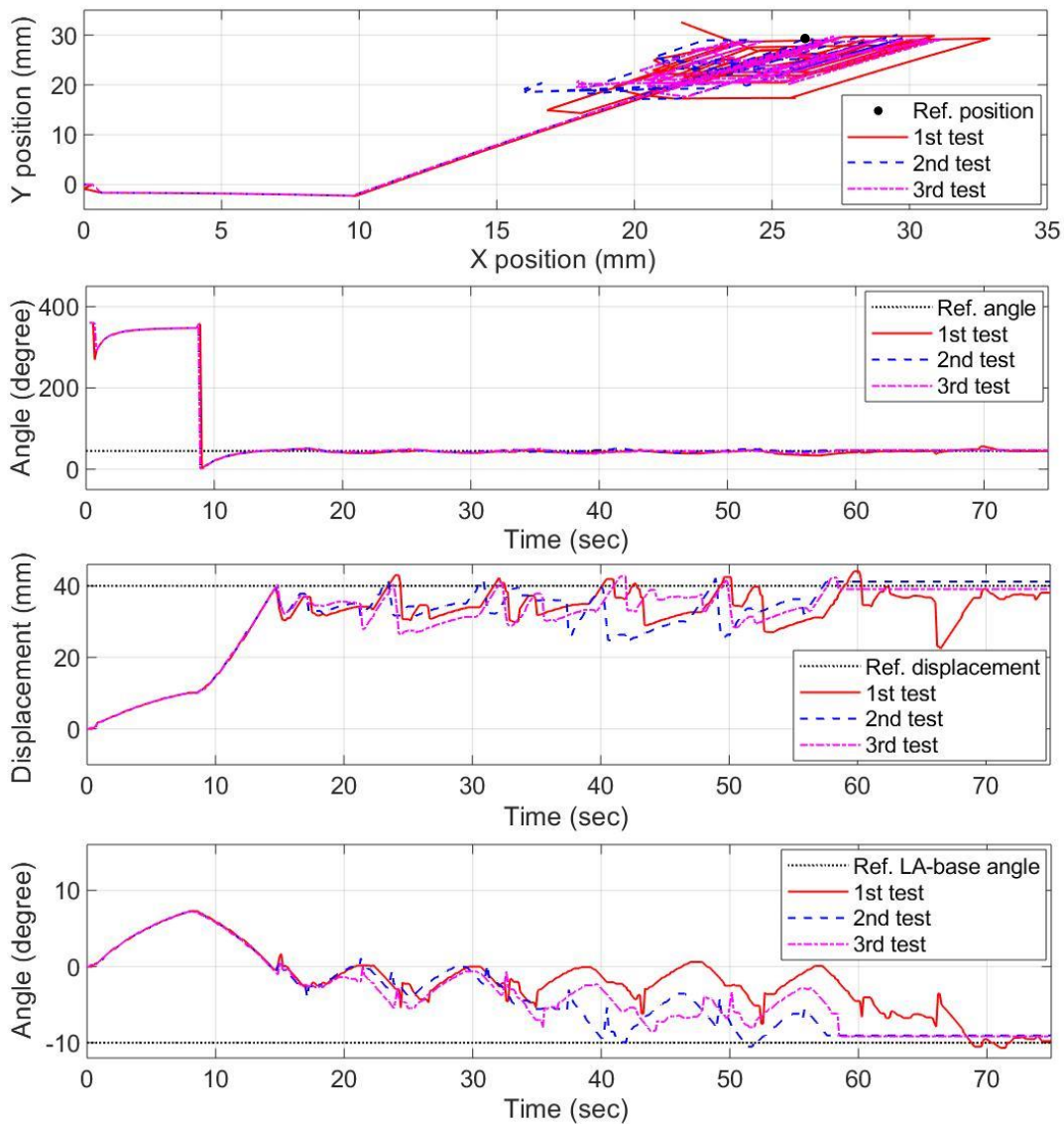


Figure 6.34 Experimental results of the end-effector position ($45^\circ, 40\text{mm}$) and end-effector-base angle control (-10°): (top) the end-effector movements in the X-Y plane, (second graph) the end-effector moving to the target angle, (third graph) the end-effector moving to the target position, and (bottom) the end-effector-base rotating to the target angle

Aside from the end-effector-base angle control of 10° and -10° , the end-effector-base angle controls of 0° , 5° and -5° are demonstrated. Each experiment is repetitively tested three times, and the experimental result data are summarised in Table 6.13.

The results suggest that the proposed control rules could generate control signals to control the LA-slider length and four PRMs effectively with small steady-state error within $\pm 2^\circ$ and $\pm 2\text{mm}$ (see green numbers in Table 6.13). The travelling time to the target point relates to the amount of the end-effector-base target angle. For example, at the end-effector-base target angle of 0° , the rise time of both end-

effector angle and displacement in reaching the target points is approximately 14 seconds, whereas the increase in time in end-effector target angle and displacement increases to 28.5 s at the end-effector-base target angle of 5° and -5° . Furthermore, to investigate the end-effector-base angle limitation, the end-effector-base angles of $\pm 15^\circ$ are tested. The end-effector-base angle could be controlled if the end-effector target positions are close to the original position (0,0) because the LA module has sufficient space to rotate itself without unexpected-cable-tension caused by the locking stage of the PRMs described earlier.

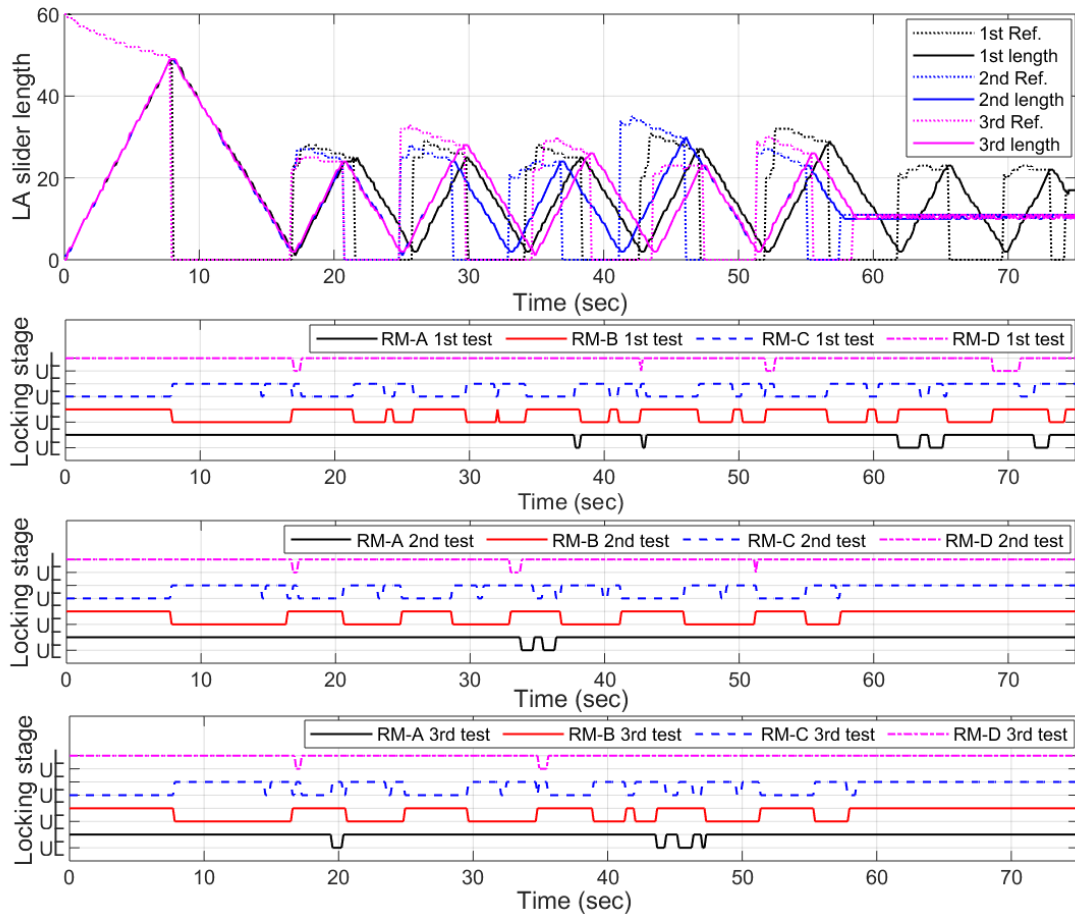


Figure 6.35 Control signal comparison of the three repetitive experiments generated by the proposed control rule for moving the end-effector to the target position ($LA_{ref}(45^\circ, 40mm, -10^\circ)$): (top) the LA-slider targets and movement, (three-bottom) the first, second, and third locking and unlocking control procedures of PRMs or RMs (A to D).

Table 6.13 Experimental results of the end-effector position control and end-effector-base angle control by using the proposed control rules; the end-effector target position is fixed as 45° and 40 mm while adjusting the end-effector-base target angles as 0°, 5°, -5°, 10°, and -10°.

$\theta_{l_{ref}}$ (°)	Test order	$\theta_{f_{s.s}}$ (°)	$t_s(\theta_{ref})$ (sec)	$e.e_{\theta_{ref}}$ (°)	$d_{f_{s.s}}$ (mm)	$t_s(d_f)$ (sec)	$e.e_{d_f}$ (mm)	$\theta_{l_{s.s}}$ (°)	$t_s(\theta_l)$ (sec)	$e.e_{\theta_l}$ (°)
0	first	46.53	13.74	0.76	38.27	14.68	1.73	-0.11	14.68	0.11
	second	46.58	13.61	-1.58	38.23	14.55	1.77	-0.15	14.55	0.15
	third	46.53	12.94	-1.53	38.27	14.69	1.73	-0.11	14.55	0.11
5	first	43.64	28.05	1.36	38.19	26.97	1.81	4.93	30.47	0.07
	second	44.35	30.07	0.65	39.71	29.8	0.29	5.43	28.31	-0.43
	third	43.41	27.37	1.59	38.37	25.89	1.63	4.1	27.91	0.9
-5	first	43.55	34.52	1.45	38.52	33.57	1.48	-5.97	34.65	0.97
	second	45.94	22.65	-0.94	38.68	23.46	1.32	-4.25	23.46	-0.75
	third	46.78	22.92	-1.78	38.05	24	1.95	-4.87	24	-0.13
10	first	46.71	45.98	-1.71	41.3	45.57	-1.3	10.37	45.71	-0.37
	second	44.56	44.36	0.44	38.04	43.41	1.96	9.05	43.41	0.95
	third	43.37	46.55	1.63	41.69	46.55	-1.69	9.84	46.42	0.16
-10	first	44.82	73.88	0.18	38.09	74.29	1.91	-9.8	74.29	-0.2
	second	46.52	56.22	-1.52	41.18	57.16	-1.18	-9.05	57.57	-0.95
	third	47	58.51	-2	39.08	58.51	0.92	-9.16	58.51	-0.84

Additionally, different end-effector target positions, which are in other quotas of the custom circular scale, and end-effector-base angles are repetitively demonstrated, as summarised in Table 6.14. The results demonstrate that the steady-state errors of all target values are in the range of the error allowances (see green number).

Table 6.14 Experimental results of different target positions and the end-effector-base angles controlled by the proposed control rule; the first target is (150°, 50 mm, 10°). The second target is (210°, 35 mm, -8°) and the third target is (305°, 60 mm, 5°).

Target	Test order	$\theta_{f_{s.s}}$ (°)	$t_s(\theta_{ref})$ (sec)	$e.e_{\theta_{ref}}$ (°)	$d_{f_{s.s}}$ (mm)	$t_s(d_f)$ (sec)	$e.e_{d_f}$ (mm)	$\theta_{l_{s.s}}$ (°)	$t_s(\theta_l)$ (sec)	$e.e_{\theta_l}$ (°)
first	first	150.8	53.43	-0.75	49.8	57.06	0.21	9.05	57.2	0.95
	second	150.4	53.43	-0.26	51.2	56.74	-1.23	9.48	57.1	0.52
	third	150.9	64.46	-0.96	48.9	68.25	1.1	10.6	68.1	-0.58
second	first	210.9	20.17	-0.97	34.1	21.91	0.91	-7.83	21.9	-0.17
	second	211.7	27.4	-1.74	33.3	25.3	1.69	-8.05	27.6	0.05
	third	211.4	25.18	-1.4	33.5	24.07	1.49	-7.36	24.6	-0.64
third	first	303.1	11.19	1.89	59.9	37.09	0.1	4.28	37.8	0.72
	second	303.1	11.19	1.88	58.5	29.67	1.46	4.93	29.7	0.07
	third	303.3	11.33	1.73	60.1	35.87	-0.04	4.44	36.6	0.56

It may be concluded that the proposed control rules can be used to control the end-effector position to move to target points effectively. Cooperation between the extending/retracting procedures of the LA and the locking/unlocking procedures of the PRM may be employed to move the end-effector to the desired positions.

6.2.3 Configuration Time and Power Usage Analysis

This section analyses the structural configuration time and power usage between the new and existing actuation methods. To compare the actuation method performance, all parameters of each actuator are defined identically. For the actuated cable mechanism, the diameter of the rotating wheel (r) is defined as 12.25 mm, which is the same diameter of the cable storage of the PRM. The DC-gear motor speed (v) is defined as 31.4 rpm, which is the same as the motor speed for the braking element of the PRM. Therefore, the cable-spooling speed of each motor can be calculated with the following formula:

$$v_{(m/s)} = \frac{2\pi \times r}{60} \cdot N_{(rpm)}, \quad (6.14)$$

where v is the linear velocity expressed in m/s , N is the angular velocity or motor speed expressed in rpm , and r is the rotating wheel radius expressed in m . Therefore, the DC-gear motor provides a maximum speed (v_{max}) of 40.26 mm/s to actuate cables for structure configurations. For the actuated strut mechanism, LA parameters are defined as the same as the proposed SE in this project. The maximum speed (v_{smax}) of the LA-slider movement is 12.9 m/s , and the stroke length is 100 mm.

In this analysis, a cross-shaped structure is chosen to analyse structural configurations using different actuation methods, including cable actuation, strut actuation, cable-strut actuation, and proposed actuation methods. The initial stage of the four cross-shaped tensegrity robots is presented in Figure 6.36

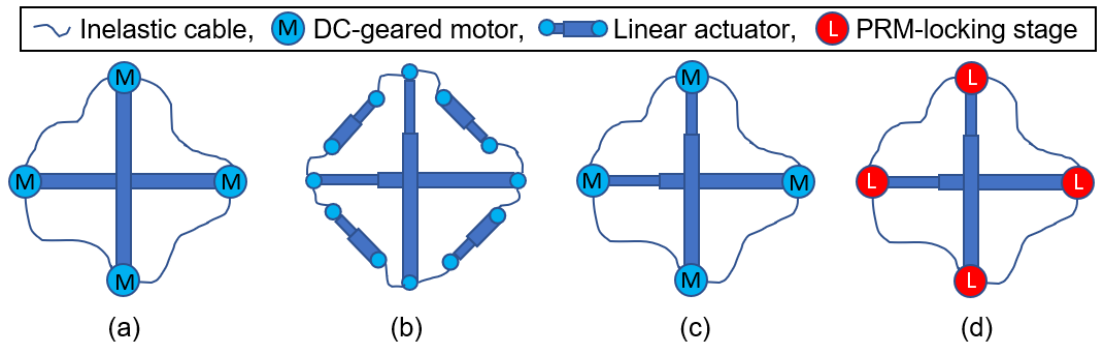


Figure 6.36 Cross-shaped tensegrity robots: (a) cable actuation method, (b) strut actuation method, (c) cable-strut actuation method and (d) proposed actuation method.

For the cable actuation method (see Figure 6.36(a)), a DC-gear motor is attached to each end of two struts of fixed length. The initial length of the four cables is 100 mm; they are loose, providing a soft structure. To create a hard structure, all

motors must spool cables individually until each cable has high tension, resulting in a hard structure, as presented in Figure 6.37.

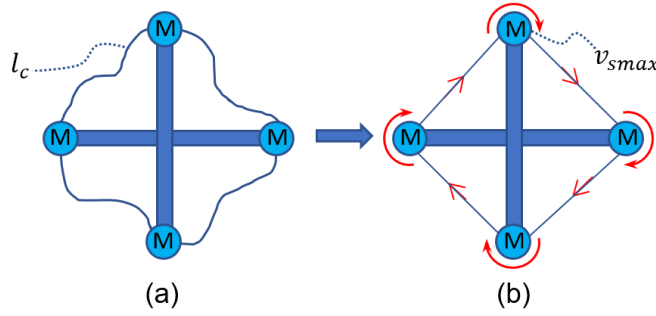


Figure 6.37 The structural configuration for swapping the structure from soft to hard, using the cable actuation method: (a) soft structure and (b) hard structure.

The configuration time (t_c) can be calculated using the speed of the cable length. In this analysis, the cable length (l_c) that makes the cable tension is assumed to be 50 mm. Therefore, the configuration time (t_c) to create the cable tension can be estimated with the following formula:

$$t_c = \frac{l_c}{v_{max}} = \frac{50mm}{40.26mm/s} = 1.24s \quad (6.15)$$

For the strut actuation method (see Figure 6.36 (b)), two LAs are used as the strut of the cross-shaped tensegrity robot. In addition, a small LA is placed between strut ends, and both ends of each small LA connect to the end of each strut via inelastic cables. In order to harden the structure, two LAs must extend their lengths to create high tension. Furthermore, four small LAs must reduce their length to spool cables to the opposite side of the strut-slider direction (see red arrow in Figure 6.38 (b)). This configuration leads to the creation of a hard structure.

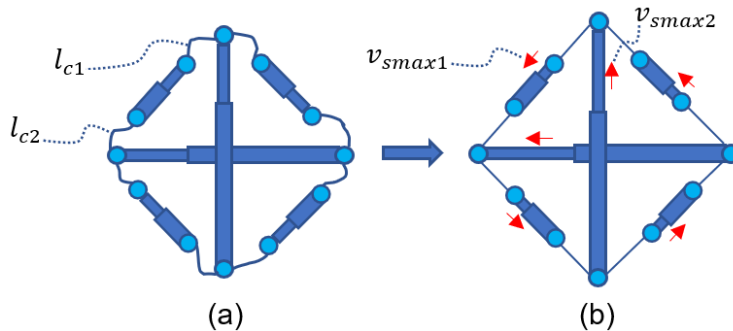


Figure 6.38 Structural configuration to create a hard structure, using the strut actuation method: (a) soft structure and (b) hard structure.

The configuration time (t_c) to swap from the soft to the hard structure can be estimated using the maximum speed of the LA slider (v_{smax}) and the rest length (l_c) of the cables (25 mm of each cable) that produce high tension, as shown in

the following equation. In this analysis, all angles between cables and LAs are neglected.

$$t_c = \frac{l_{c1} + l_{c2}}{v_{smax1} + v_{smax2}} = \frac{25mm + 25mm}{12.9mm/s + 12.9mm/s} = 1.93s \quad (6.16)$$

For the cable-strut actuation method (see Figure 6.36 (c)), two LAs are used for SEs able to adjust their length to spool cables for configurations, and four DC-gear motors are used to exert forces for actively spooling cables. Therefore, to create a hard structure, all DC-gear motors must spool cables while LAs extend their lengths to produce high-tension cables. This structural configuration is shown in Figure 6.39.

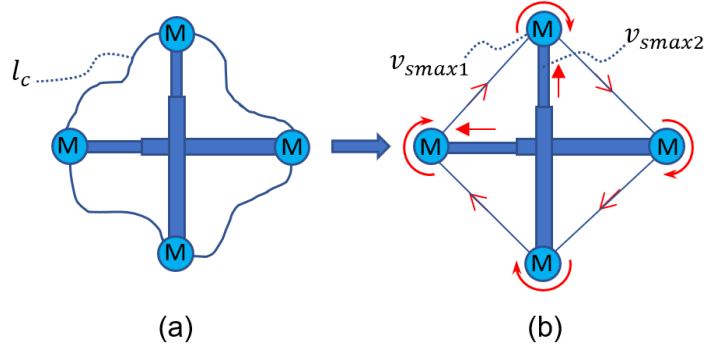


Figure 6.39 Structural configuration to make a hard structure using the cable-strut actuation method: (a) soft structure and (b) hard structure.

The spending time to change robot structure from soft to hard can be estimated using the following formula:

$$t_c = \frac{l_c}{v_{smax1} + v_{smax2}} = \frac{50mm}{12.9mm/s + 40.26mm/s} = 0.94s \quad (6.17)$$

For the proposed actuation method (see Figure 6.36 (d)), the cooperation between PRM and LA is performed on robot configurations. Two LAs are the SEs of the robots and are placed along the X and Y axes. Both ends of each LA contain PRM, providing locking and unlocking stages to restrict and release cable length during changing the LA-slider lengths. The robot configurations that can swap their structure from soft to hard can be achieved over two steps. Firstly, the unlocking stage is applied to all PRMs to tighten all cables, as shown in Figure 6.40 (b). The cable length (l_c) spooled by the PRM to be tight is defined as 50 mm, exerting the rotational speed (v_{PRM}) of 710 mm/s, which is determined by the physical experiment shown in Table 5.12.

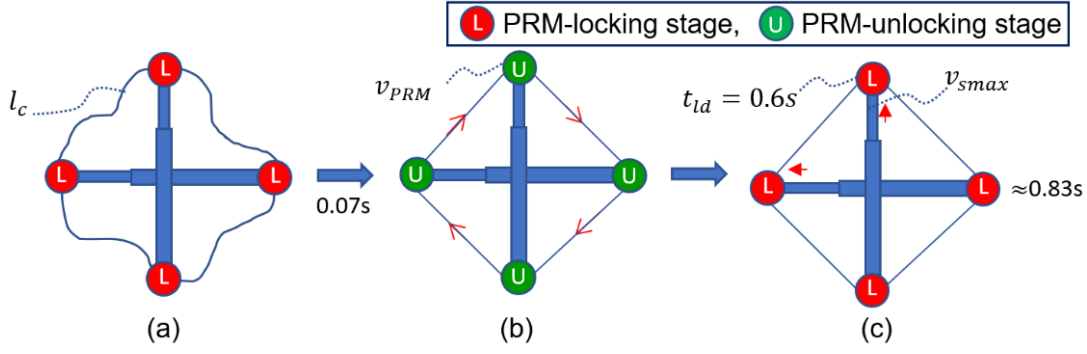


Figure 6.40 The structural configuration to make a hard structure using the proposed actuation method: (a) soft structure and (b) first step configuration and (c) second step configuration.

Thus, this configuration time in this step (t_{c1}) can be estimated as follows:

$$t_{c1} = \frac{l_c}{v_{PRM}} = \frac{50mm}{710mm/s} = 0.07s \quad (6.18)$$

The second step involves applying the locking stage to all PRMs to restrict all cables and extend both LA-slider lengths to create high tension cables to create a rigid structure. The configuration time in the second step (t_{c2}) may be estimated using the delay time of the locking stage (t_{ld}) of 0.6s while extending the LA slider (2mm) against the restricted cables (see Figure 6.40 (c)), as described in the following equation:

$$t_{c2} = t_{ld} + \frac{l_c}{v_{smax}} = 0.6 + \frac{2mm}{12.9mm/s} = 0.76s \quad (6.19)$$

The summation time of the structural configurations in step1 (t_{c1}) and step2 (t_{c2}) can then be estimated as 0.83s.

Based on the structural configuration analysis, the proposed actuation method provides the shortest time to swap the robot from soft to hard structures. In addition, it can be expected that the power usage for the configuration is also less than the cable actuation, strut actuation, and cable-strut actuation methods due to the rapid configuration and the short time operation of the PRM braking part that requires the power of only 0.6 s. The summary of the structural configuration using different actuation methods is presented in Table 6.15.

Table 6.15 Configuration time comparison between different actuation methods.

Actuation methods	Configuration time (s)		Powering time for one-step configuration
	Soft to hard structure	Hard to soft structure	
Cable	1.24	<0.2	Constantly for four motors
Strut	1.93	<0.2	Constantly for six LA
Cable-Strut	0.94	<0.2	Constantly for two LA and four motors
PRM-LA	0.83	<0.2	Constantly for two LA and 0.6s for four PRMs

For the swap from a hard to soft structure, the configuration times of all actuation methods are not different because the robot structure can suddenly become soft when releasing a cable length that can be achieved within 0.2 seconds after applying a motor command. However, the proposed actuation method could be more advantageous than other methods in terms of structural flexibility. The cross-shaped tensegrity robots driven by both cable actuation and strut actuation methods cannot deform their shape following external impact forces suddenly due to the slow speed of the actuators, as shown in Figure 6.41 (a) and (b). In contrast, the cross-shaped tensegrity robot actuated by PRM and LA elements can be deformed following external impact forces immediately, and all cables also remain in tension and change freely during unlocking due to the passive retractable joint capability, as shown in Figure 6.41 (c).

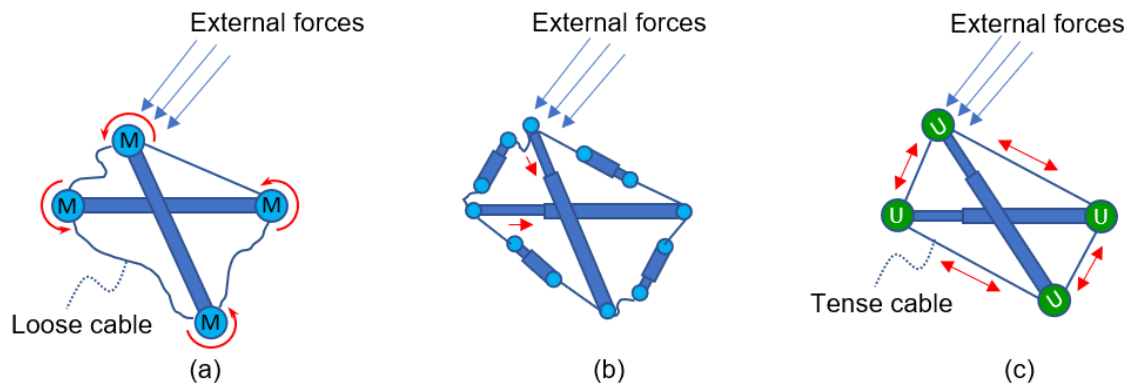


Figure 6.41 Motion analysis of different cross-shaped tensegrity robots interacting with external impact forces while performing in the soft body configuration: (a) cable actuation method, (b) strut actuation method, and (c) proposed actuation method.

6.3 Summary

This chapter investigated the control and structural configurations of several physical robot structures composed of the proposed LA and PRM. Experimental validation of the proposed LA and PRM was demonstrated individually to ensure that they perform effectively. LA-slider length and the PRM-cable length were scaled providing a closed-loop position control that had a position error of within

± 1 mm and without target overshooting. A P-controller was used for the local controller to control LA-slider lengths and could perform with the maximum payload of 4.8 kg when applying a control signal of 100% duty cycle. Furthermore, the P-controller could control the LA-slider moving to target length while carrying inconstant payloads generated by tension springs. The force sensor (FSR) was calibrated and measured the pressing forces between end caps of the LA and the wall. The maximum payload allowance related to the LA angle while holding on to the walls were investigated. For example, the LA could manage its position on the wall (parallel on the ground) while carrying the payloads up to 4 kg. However, if the LA angle changed over 20 degrees, the LA could not hold on to the wall. For PRM experiments, the PRM provided a rotational force of 1.25N to 5N to spool a cable during unlocking stage and provided the braking force of 8N to 11N to restrict cable length in the locking stage, depending on the cable length in which the locking stage occurred.

The 3-DOF and 5-DOF structures introduced in Chapter 3 were also constructed and demonstrated. The kinematic equations of the end-effector position of 3-DOF and 5-DOF could generate current end-effector positions, sending to a control module within the distance and angle error of ± 2 mm and ± 2 degrees, respectively. Then, to control the end-effector positions, the control rules for the structural configurations were designed based on a robot configuration analysis. The results showed that the control rules could generate patterns for the locking and unlocking stage of all PRMs before properly adjusting LA-slider length to move the end-effector position to target points with small steady-state errors. Although the end-effector movement behaviour was not smooth (zig-zag style), this proposed structural deformation method could achieve structural deformation by using PRM to control the cable length, which requires less power to perform the locking and unlocking.

In addition, the configuration time and power usage analysis showed that the proposed actuation method could be potentially used to design a tensegrity robot that can swap its structure between soft and hard quickly. Moreover, the unique functions of the PRM for restricting and releasing cable lengths by applying the power of within 0.6 s could be potentially used to design a tensegrity robot that requires less power for structural configuration.

Chapter 7 Case Study: Structural Configurations for Locomotion tasks

This chapter introduces a case study of the proposed structural deformation method for designing reconfigurable two-dimensional (2D) and three-dimensional (3D) robots based on class 1 tensegrity structures. Initially, environmental and robot requirements are defined, and a conventional crawling robot is then developed and demonstrated for inchworm behaviour. A locomotion of the 2D crawling robot based on the tensegrity structure is then demonstrated. Multiple modules of cross-shape tensegrity robots are presented to show the possibility to create a robot that moves like a snake by applying locking/unlocking stages for multiple modules of retractable joints with a cable locking mechanism (PRM) and linear actuator (LA) modules. Then, a 3D tensegrity robot is built to demonstrate useful abilities for the robot configurations to ensure that the proposed actuation method may be used to develop a climbing robot based on the tensegrity structure.

7.1 Environmental Requirements

In this case study, the wall-pressing method with inch-worm motion behaviour is selected to design a robot able to move inside a narrow environment. Therefore, the environmental requirements suitable for the robot must meet the following criteria:

1. The environment has at least two sides where the robot end caps or feet can apply opposing force. Example environments include a pipe, duct, and air vent, which are a circle or rectangular shape;
2. The width of an environment is between 250 to 300 mm; and
3. The environmental surfaces are clean and dry.

7.2 Robot Requirements

In order to realise functional 2D and 3D robots based on tensegrity structure actuated by cooperation between LA modules and PRMs, the design must meet the following requirements:

1. Both SE and PRM are self-contained with computation, communication, actuation, and sensing capabilities. They can communicate with a master

module to receive control commands and send their status individually. A low-cost solution for most parts is preferable;

2. To make a compliant structure, all LAs are connected only using tensile elements that are PRMs. The cable length of the PRM can be restricted and released while adjusting LA length to produce cable tensions, utilised for robot configurations;
3. The LA must produce sufficient pressing force to hold the robot structure in both vertical and horizontal motions and be able to push the robot part upward, overcoming the weight of the movable parts and gravity in a vertical movement;
4. The cable of each PRM must withstand the pulling force of the LA while performing the cable locking stage; and
5. Robot configurations must provide different shapes, including body extension, body retraction, twisting left, and twisting right to access different shapes of environments.

7.3 Basic Wall-Pressing Robot Locomotion

To investigate the fundamental movements of a basic crawling robot, a conventional crawling robot based on the wall-pressing mechanism is rapidly constructed and presented in Figure 7.1.

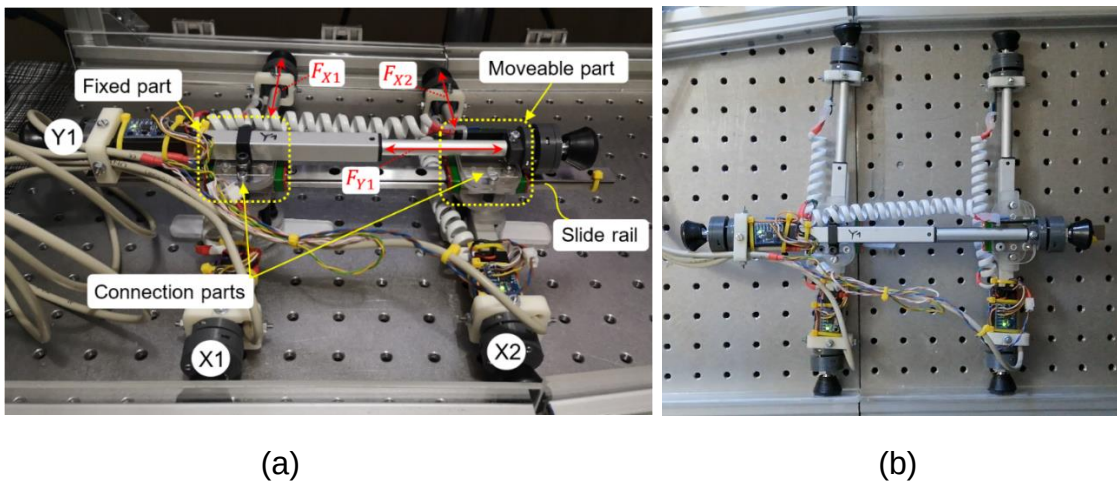


Figure 7.1 The basic crawling robot with wall-pressing mechanisms: (a) robot components and directional forces of three LAs and (b) a top view of the robot placed on the wall.

The robot consists of three LAs: X1; X2; and Y1. The X1 and X2 are robot legs to exert a pressing force (F_{X1} and F_{X2}) against the environment wall to hold one part while moving another part for locomotion. Each LA is connected using rigid joints. X1 is fixed on a sliding rail by a connection part. X2 is attached to the slide guide that can slide along the slide rail. The base of Y1 is connected to the X1

connection part, whereas the slider of Y1 is attached to the X2 connection part. Y1 is used to adjust the body length of the robot and also exert a pushing force and pulling force (F_{Y1}) to move forward and backwards in inchworm locomotion.

For the forward motion, the X1 is extended, pushing two end caps against the walls, and the X2 is retracted to eliminate friction between the two end caps and the walls. The Y1 is then extended to push X2 forward sliding along the slide rail. The X2 is then extended to push two end caps on the walls, and the X1 is retracted to allow its body to move. Finally, the Y1 is retracted to its initial length. At the same time, the X1 base is moved close to X2.

For the backwards motion, the step movements are the same patterns of the forward motion, but the X1 and X2 motion perform reversely. The extending and retracting procedures of the X1, X2, and Y1 to allow the robot to move forward and backward are summarised in Table 7.1.

Table 7.1 Extending and retracting procedures of all LA sliders to produce the inchworm motion.

Direction	Cycle	Stage	LA-Slider target length (mm)		
			X1	X2	Y1
Forward	Extending	1	100	90	0
		2	100	90	100
		3	100	100	100
	Retracting	4	90	100	100
		5	90	100	0
		6	100	100	0
Backwards	Extending	1	90	100	0
		2	90	100	100
		3	100	100	100
	Retracting	4	100	90	100
		5	100	90	0
		6	100	100	0

For the movement demonstration, an on-off control is used to control the LA-slider lengths by pressing microswitches on the key-interface board manually following the control procedures in Table 7.1. The robot moves along the constructed path, which includes two sections (30 mm height, 300 mm width and 300 mm length in each section). The first section is defined as a straight path, but the second section is narrowed by adjusting the bottom wall angle of 10° , reducing the width of the path to 265 mm at the end of the section. Therefore, in order to allow the robot to move through the different width paths, the adjustable length end caps of the X1 and X2 are placed on the bottom side, which makes the robot move backwards initially. The video frames of the robot movement implementations are presented in Figure 7.2.

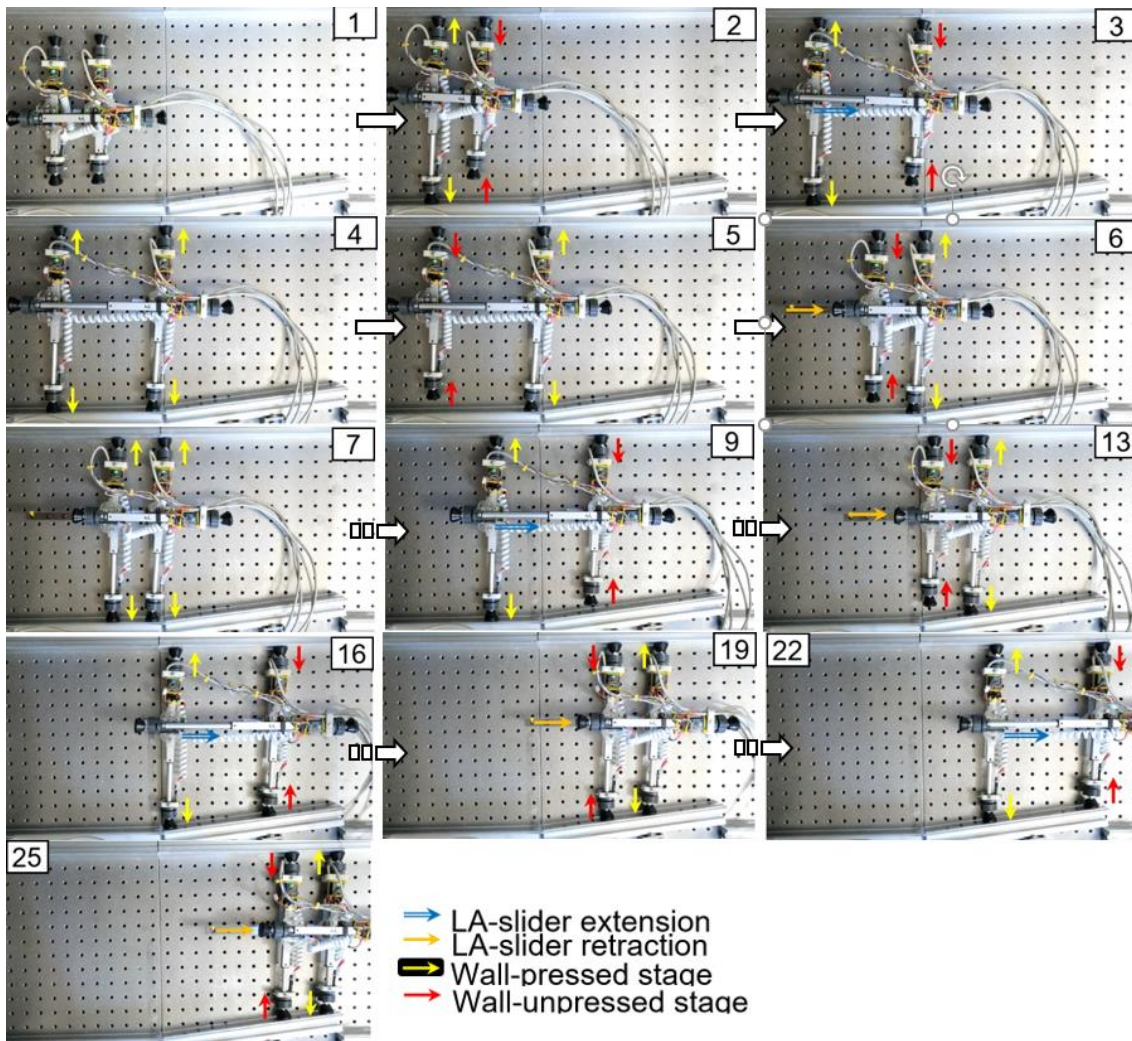


Figure 7.2 Video frames of the crawling robot locomotion on the X-Y testing backplane

The video frames show that the robot is able to move through the whole section by adjusting the lengths of two legs and body to produce inchworm locomotion. The demonstration shows that an important factor in the crawling robot movements is the sufficient pushing force to produce high friction at contact points between the robot legs and environmental surfaces. This pushing force should be generated continuously during holding. However, most crawling robots are generally designed using rigid joints to connect actuator and body parts. This rigid joint is one of the disadvantages of current crawling robots based on wall-pressing and inchworm locomotion type to access different shapes and sizes of environments due to the angular limitations of the rigid joints. Therefore, to avoid using rigid joints between the robot body and actuation to enhance locomotion performance, a new development of a crawling robot, including PRMs performing with LA modules, is proposed in Section 7.4.

7.4 Crawling Robot Based on New Actuation Method

7.4.1 Robot Configuration Analysis

Before building a crawling robot based on a tensegrity structure integrated with PRMs and LA modules, a 2D model design is designed and the structural configurations for locomotion are analysed. The design of the crawling robot is presented in Figure 7.3(a); this design consists of three LA modules (X1, X2, and Y1) and six PRMs (A to F). X1 and X2 are used to generate pressing forces between their legs and the wall, whereas Y1 is placed on the X1 and X2 modules. Y1 is used to generate push and drag forces to move X1 and X2 for locomotion. All LA modules are connected by inelastic cables without rigid joints to provide a compliant structure, which can change its shape based on environment size. For example, a robot can access a narrow area slightly smaller than the initial LA length, as illustrated in Figure 7.3 (b). In addition, a robot can enlarge itself by extending the strut-slider length in order to access different diameter sizes of the environments, as illustrated in Figure 7.3 (c).

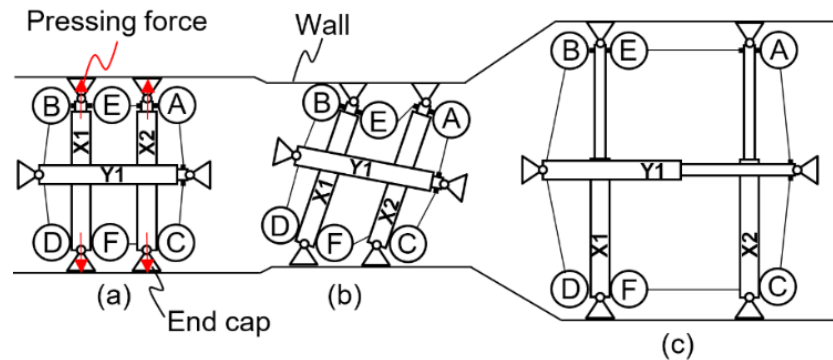


Figure 7.3 The design of a compliant crawling robot based on tensegrity structure (top view): (a) initial shape (minimise size), (b) compliant body to access inside the area, which is smaller than the initial shape, and (c) the full extension of the SE.

The locomotion analysis of the robot configurations is described as follows. The structural configurations consist of four stages: holding stage1; extending stage; holding stage2; and retracting stages, as shown in Figure 7.4. Holding stage1 is a crucial stage because the robot legs need to generate friction between end caps and the environmental surface to push or drag itself to move throughout the environment. The holding stages can be divided into two conditions, namely forward and backward conditions. For the forward condition, the holding stage can be achieved by applying an unlocking stage for all PRMs to allow the cable length to adjust. The X1 is then extended until the top and bottom end caps pressing the wall, while the X2 is slightly pulled back, as illustrated in Figure 7.4

(holding stage1). In contrast, the backward position can be achieved by extending the X2 to push the end caps attaching the wall while retracting the X1.

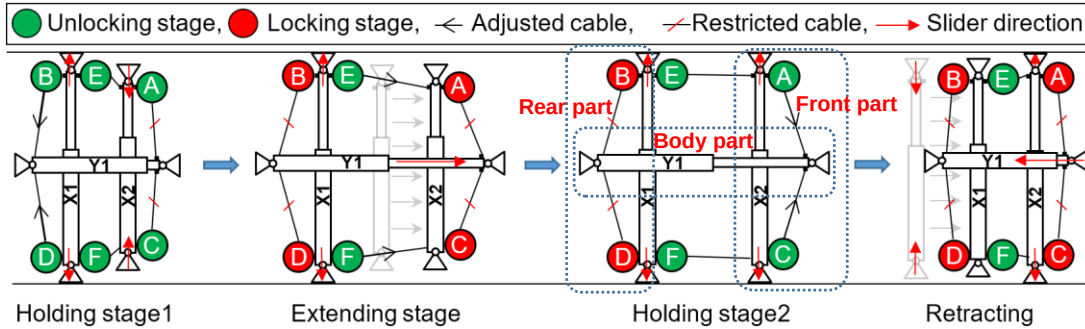


Figure 7.4 Robot configurations for inchworm locomotion.

The extending stage involves extending the robot body length to push the front part forward. In this stage, E and F must be part of the unlocking stage in order to roll out the cable following the directional extension of the Y1, as illustrated in Figure 7.4 (extending stage). However, before extending the Y1 length, A, B, C, and D cables must be restricted to hold the Y1-base position and maintain the distance between the X1 and the Y1-slider tips. Therefore, the front part of the robot is pushed forward when extending the Y1 length.

The holding stage must be performed again to hold the front part in place by applying the unlocking stage for A and C and then extending the X2 length until the end caps pressing the wall, as shown in Figure 7.4 (holding stage2).

Finally, the retracting stage involves retracting the body length to prepare for the next extending stage, which can be achieved by releasing the B and D cables before pulling back the X1 length. Then, the locking stage is applied for the B and D again before retracting the Y1 length. In this stage, the rear part is dragged close to the front part as same as holding stage1.

For the backward locomotion, the configurations of the robot structure are the same stage of the forward motion. However, the extending and retracting stages between the rear and front components perform conversely.

To turn the front or rear part of the robot, the locking stage is applied for E and F. Examples of the robot configurations for turning the front and rear parts are illustrated in Figure 7.5.

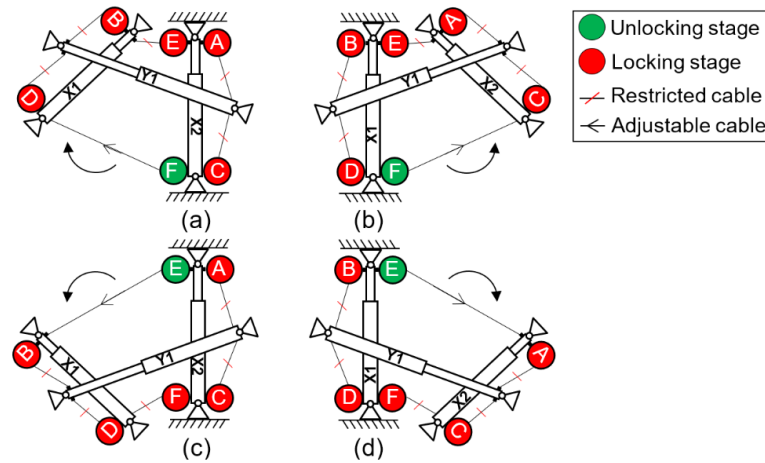


Figure 7.5 Robot configurations for turning its structure: (a) Turning right backwards, (b) turning left forward, (c) turning left backwards and (d) turning right forward.

Based on the robot configuration analysis, the proposed locking and unlocking stage procedures of the PRMs (A to F) before changing the LA length (X_1 , X_2 and Y_1) are able to develop a compliant crawling robot that potentially performs moving forward, backwards, and turning, and adjusting its structure size to access different sizes and complex junctions of an environment, as shown in Figure 7.6.

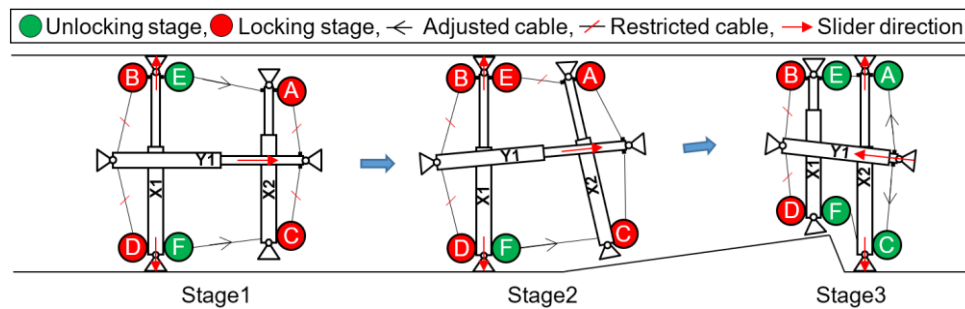


Figure 7.6 Example of robot configurations that move along different diameter sides of the environment: (Stage1) the extending stage for straight motion, (Stage2) the turning stage for adjusting the front part angle, and (Stage3) the retracting stage for overcoming step paths.

7.4.2 Physical Robot Demonstrations

The development and implementation of the crawling robot actuated by three LA modules cooperating with six PRMs to create structural robot configurations are shown in this section. The physical robot is presented in Figure 7.7.

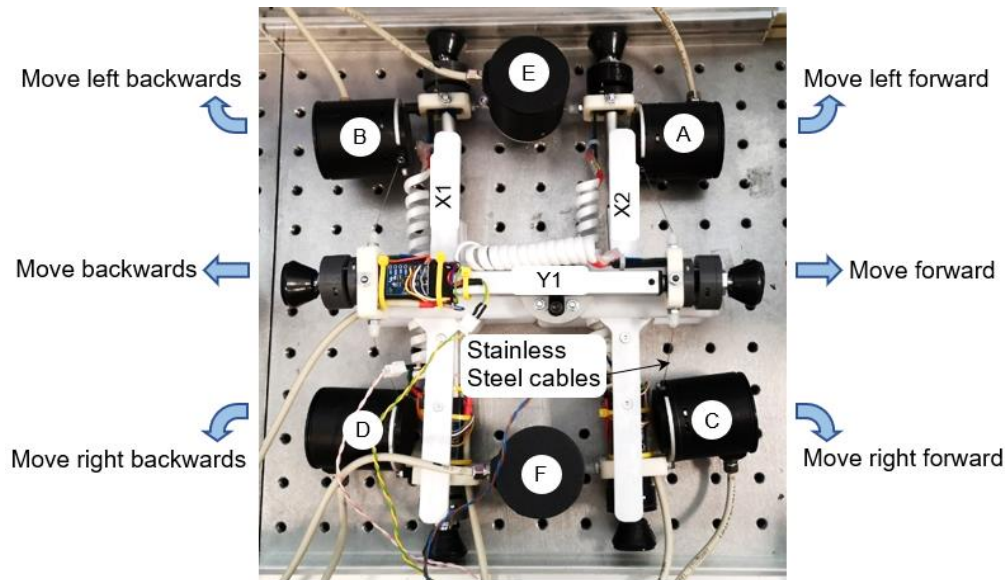


Figure 7.7 Rapid prototype of the crawling robot based on the tensegrity structure.

The robot components comprise three strut modules (X1, X2, and Y1) and six PRM modules (A, B, C, D, E, and F). All of the strut modules are connected by the cables of the PRMs without a rigid joint, providing a compliant structure. The robot structure can be divided into three parts: front; rear; and body. The front part includes X2, A, and C, whereas the rear includes X1, B, and D. The body part comprises Y1, E, and F. The X1 and X2 are placed on the plan, but Y1 is placed on X1 and X2 covers.

The details of the connection between the LAs and PRMs are described. For the front part, the A and C cases are attached to the top and bottom of the X2 end caps, respectively. The cable tip of A is screwed with the end cap of the Y1 slider to produce the cable-pulling force against the cable-pulling force of the C in the unlocking stage. For the body part, the E case is attached to the end cap of the X1 slider, and the cable tip is screwed to the end cap of the X2 slider, which is the front part. Similarly, the F case is attached to the end cap of the X1 base, and its cable tip is screwed with the end cap of the X2 base. For the rear part, the B case is connected to the end cap of the X1 slider, whereas the D case is connected to the end caps of the X1 base. B and D cable tips are connected to the end cap of the Y1 base.

For the forward and backward movements, the three LA motions are similar to the basic crawling robot. However, to make the robot move forward, backwards, and turn, the locking and unlocking procedures of all RMs to restrict and release their cable lengths while changing the LA length of the X1, X2 and Y1 need to be designed and are summarised in Table 7.2.

Table 7.2 The LA and PRM control procedures for the forward motion.

Direction	Cycle	stage	LA Slider Length (mm)			PRM stage (Locking (L)/Unlocking (U))					
			Rear	Front	Body	Rear		Front		Body	
			X1	X2	Y1	B	D	A	C	E	F
Forward	NC	1	0	0	0	U	U	U	U	U	U
		2	100	90	0	U	U	U	U	U	U
	Extending	1	100	90	0	L	L	L	L	U	U
		2	100	90	100	L	L	L	L	U	U
		3	100	90	100	L	L	U	U	U	U
		4	100	100	100	L	L	U	U	U	U
		5	100	100	100	L	L	L	L	U	U
		6	100	100	100	U	U	L	L	U	U
		7	90	100	100	U	U	L	L	U	U
	Retracting	1	90	100	100	L	L	L	L	U	U
		2	90	100	0	L	L	L	L	U	U
		3	90	100	0	U	U	L	L	U	U
		4	100	100	0	U	U	L	L	U	U
		5	100	100	0	L	L	L	L	U	U
		6	100	100	0	L	L	U	U	U	U
		7	100	90	0	L	L	U	U	U	U

Regarding the forward motion, it consists of two main cycles: extending and retracting cycle. The first and second stages of each cycle are important because A, B, C and D are defined as the locking stage to restrict the cable length making the front and rear parts being hard structure. E and F are defined as the unlocking stage that allows the robot body to extend and retract its length for locomotion with inchworm movement behaviour. However, before extending the body length, the rear part end caps must press onto the walls to maintain their current location, and the front part end caps must pull back their length from the wall separately to allow the front part to move forward. Examples of the forward motion stages are presented in Figure 7.8.

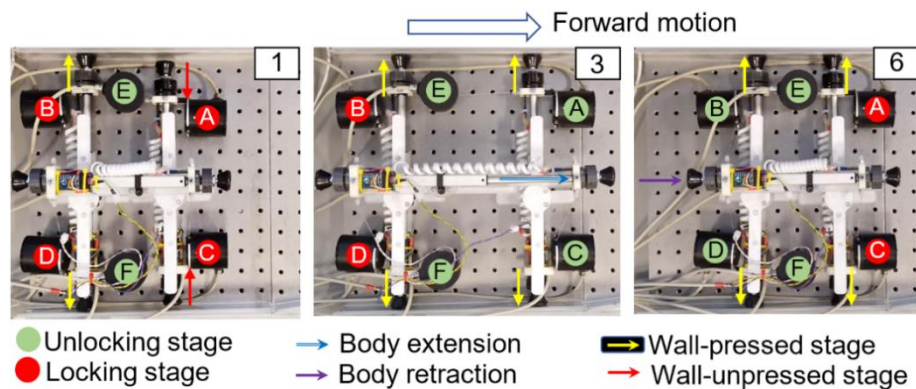


Figure 7.8 The forward movement cycle of the robot, referencing Table 7.2; the first stage is the initial stage where the rear part end caps are attached to the walls. In contrast, the front part end caps are pulled back, and the third stage is the body extension to push the front part moving forward and then pushing the front part end caps to the walls. The sixth stage is the body retraction preparing for the next forward motion cycle.

For the backward motion, the LA-slider extension and retraction procedures are similar to those of the forward motion. However, the locking and unlocking stages of A, B, C, and D are inverted from the forward motion. The control procedures of all LAs and PRMs for the backward motion are summarised in Table 7.3, and examples backward motions of the robot are presented in Figure 7.9.

Table 7.3 The LAs and PRMs control procedures for the backward motion.

Direction	Cycle	stage	LA Slider Length (mm)			PRM stage (Locking (L)/Unlocking (U))					
			Rear	Front	Body	Rear		Front		Body	
			X1	X2	Y1	B	D	A	C	E	F
Backward	Extending	1	90	100	0	L	L	L	L	U	U
		2	90	100	100	L	L	L	L	U	U
		3	90	100	100	U	U	L	L	U	U
		4	100	100	100	U	U	L	L	U	U
		5	100	100	100	L	L	L	L	U	U
		6	100	100	100	L	L	U	U	U	U
		7	100	90	100	L	L	U	U	U	U
	Retracting	1	100	90	100	L	L	L	L	U	U
		2	100	90	0	L	L	L	L	U	U
		3	100	90	0	L	L	U	U	U	U
		4	100	100	0	L	L	U	U	U	U
		5	100	100	0	L	L	L	L	U	U
		6	100	100	0	U	U	L	L	U	U
		7	90	100	0	L	L	L	L	U	U

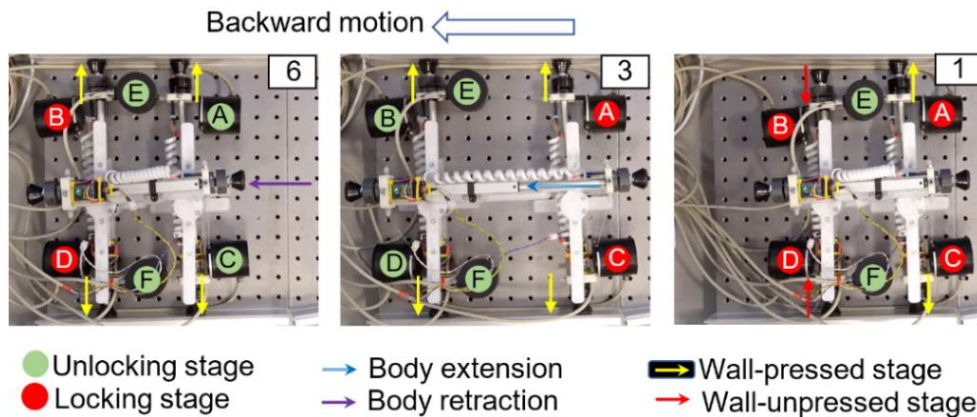


Figure 7.9 The backward movement cycle of the robot, referenced from Table 7.3; the first stage is the initial stage where the front part end caps are attached to the walls. In contrast, the rear part end caps are pulled back, the third stage is the body extension to push the rear part moving backwards and push the rear part end caps to the walls, and the sixth stage is the body retraction preparing for the next backward motion cycle.

For the turning motions, the locking stage is applied to E and F, which are the body part of the robot structure. The turning motion of the robot can be divided into four actions: forward left; forward right; backward left; and backward right. The turning motion of each action is achieved if the front and rear PRMs are performed in the locking stage to make the structures of the front and rear parts rigid.

For the forward-right turning, the X1 is extended to hold the rear part, and the X2 is fully retracted. After that, E is only assigned in the unlocking stage. In this stage, the cable of the front and rear parts are restricted. Y1 (body part) is fully extended to push X2 (front part) forward. During the Y1 extending, the F cable restricts to produce high tension, while the E cable is freely spooled, resulting in the X2 turning to the right and providing a turning angle of 25° , as presented in Figure 7.10 (bottom-right picture).

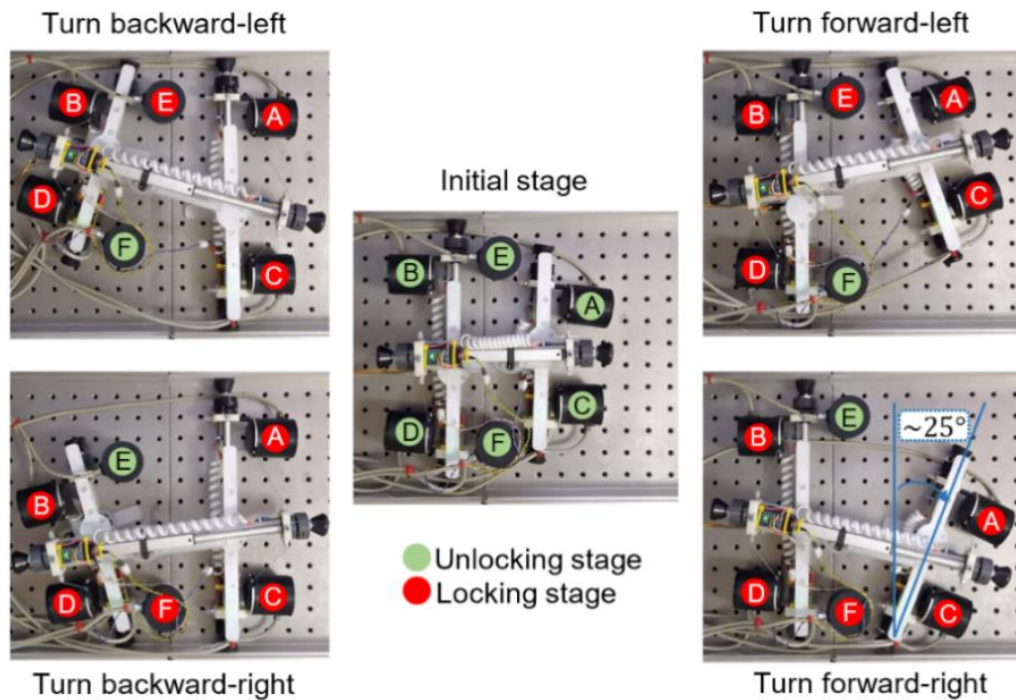


Figure 7.10 Turning motions for the forward and backward movements.

Forward-left turning can be achieved by defining the unlocking stage for F, whereas other PRMs are performed in the locking stage. Then, Y1 (body part) length is extended to force the front part to move forward and turn left (see Figure 7.10 (top-right image)).

The turning backwards left/right can be achieved by holding the front part on the walls and applying the unlocking stage for E and F in the same way as the forward left/right motions. The extension stage is then applied for Y1 to push the rear part backwards and turn to the left/right directions, as presented in Figure 7.10 (top-left and bottom-left images).

A summary of the extending/retracting stage of the LA rear, front, and body parts of the robot cooperating with the locking/unlocking stage of the PRMs for the turning motions is presented in Table 7.4.

Table 7.4 Control procedures of three LAs and six-PRM for turning motions, namely forward left, forward right, backward left and backward right.

Direction	LA-slider length status			PRM stage (Locking (L)/Unlocking (U))					
	Rear	Front	Body	Rear		Front		Body	
	X1	X2	Y1 (mm)	B	D	A	C	E	F
Forward left	Extended	Retracted	10-100	L	L	L	L	L	U
Forward right	Extended	Retracted	10-100	L	L	L	L	U	L
Backward left	Retracted	Extended	10-100	L	L	L	L	L	U
Backward right	Retracted	Extended	10-100	L	L	L	L	U	L

The next experiment involves demonstrating the robot moving on the 2D backplane in the same way as the environmental conditions of the basic crawling robot movements. The control procedure of the LAs and PRMs proposed in Table 7.2, Table 7.3, and Table 7.4 are used to control the robot movements manually using the microswitch interface board. The video frames of the robot motions are presented in Figure 7.11.

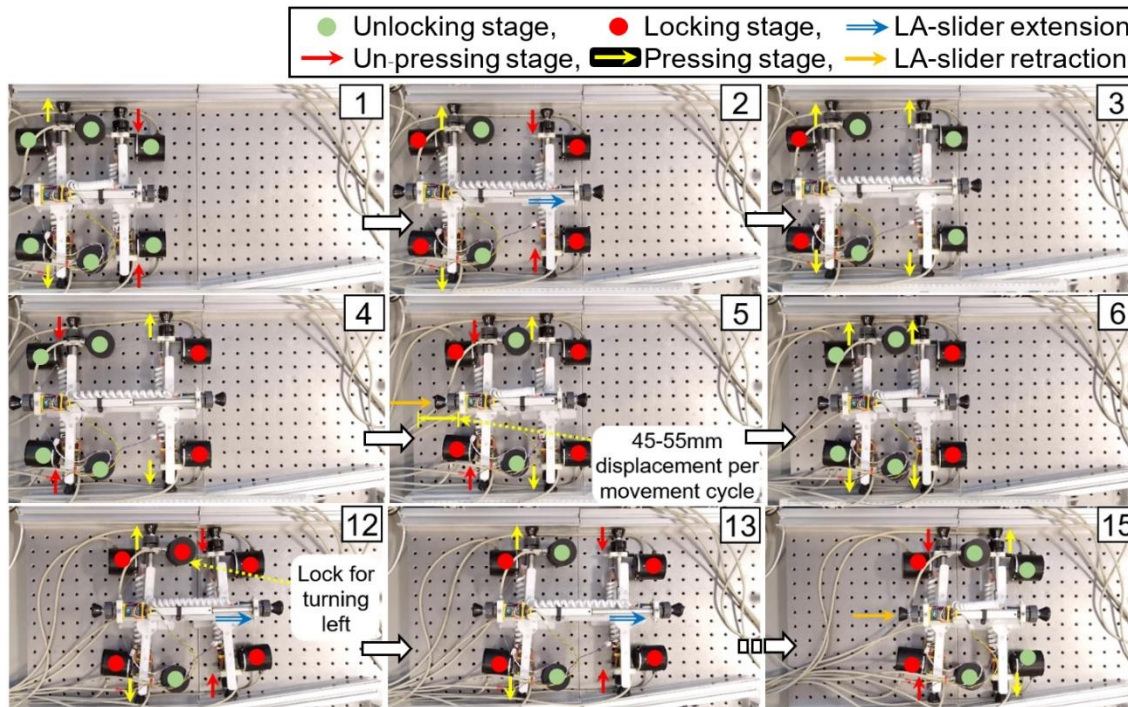


Figure 7.11 Example images of the manual control motions using the forward movement cycles.

The results show that the proposed deformation method could be employed to deform the robot structure for locomotion. The robot could move through the straight and slope paths by bending its front part. Although the robot has not been tested on curve and junction paths, the straight, turning motions, and adjustable size properties can be used to enhance a crawling robot ability to access different sizes and areas for inspection or exploration.

7.5 Other Advantages of the PRM for Robot Configurations

To demonstrate further advantageous features of tensegrity robot integrated PRMs and adjustable-length LA modules, simple tensegrity structures with and without PRMs are physically constructed and evaluated.

Figure 7.12 presents structural configurations of a cross-shape tensegrity structure with fixed and equal length cables. This figure consists of two LAs (X and Y) connected by inelastic cables of 106mm. Y is freely placed on the ground, and X is placed and slid on Y. The structural configurations can be achieved by changing LA-slider lengths. Figure (a) shows the initial structure. All cables are slack, and X can be moved following external impact forces. The shape of the cross-shape tensegrity structure can be changed by extending LA lengths to create different tensions among cables connected between X and Y, leading to movements between X and Y positions. The structure can be hard when X and Y are extended against the fixed-length cables, as shown in Figure (b). The cross-shape can be changed to a slim trapezoid by extending the slider length of the Y and retracting the X length, as shown in Figure (c) and a wide trapezoid shape by extending X length and retracting Y length, as shown in Figure (d).

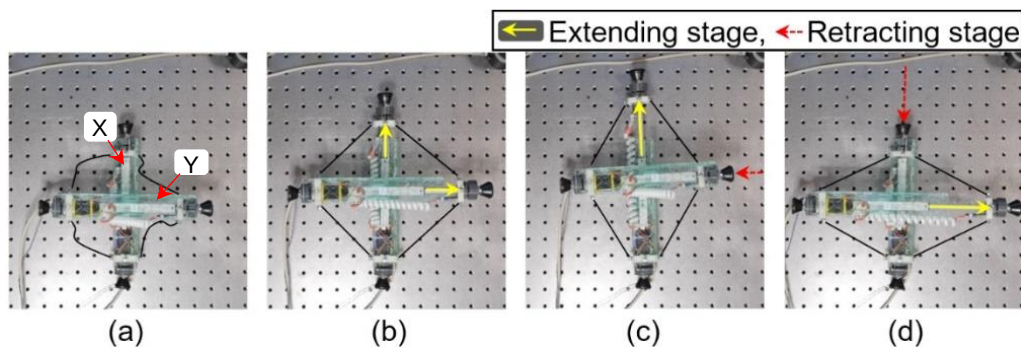


Figure 7.12 Cross-shape tensegrity structure with fixed-equal-length cable: (a) initial shape, (b) trapezoid shape, (c) slim-trapezoid shape and (d) wide trapezoid shape.

However, the deformable shapes of the structure are limited due to the equal-length cable constraint. If the lengths of the four cables are unequal, the configurations of the cross-shape structure may vary to provide another function used to twist the structure, as presented in Figure 7.13 (b), (c) and (d).

From the concepts of the fixed-equal and unequal lengths of the cables to change the configurations, multiple modules of cross-shape tensegrity robot can be constructed to demonstrate structural configurations beneficial to the design of a robot moving with various locomotion types. Examples of three modules of a tensegrity robot, including a front part (cross-shape structure), a body part

(parallel structure), and a rear part (cross-shape structure) are shown in Figure 7.14.

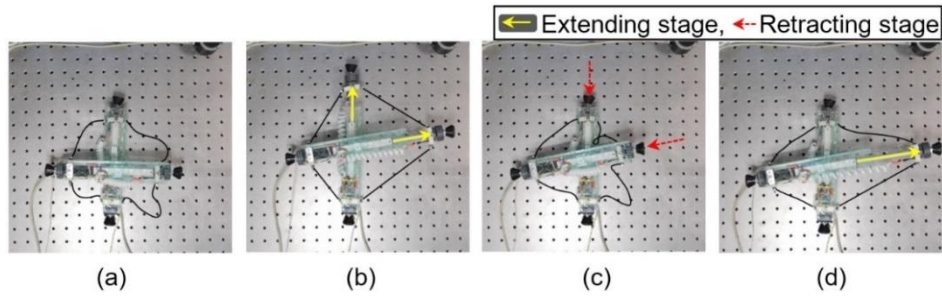


Figure 7.13 Cross-shape tensegrity structure with unequal-fixed cable length: (a) initial shape, (b) trapezium shape, (c) unstable trapezium with slack cables, and (d) unstable-widely trapezoid shape with slack and tight cables.

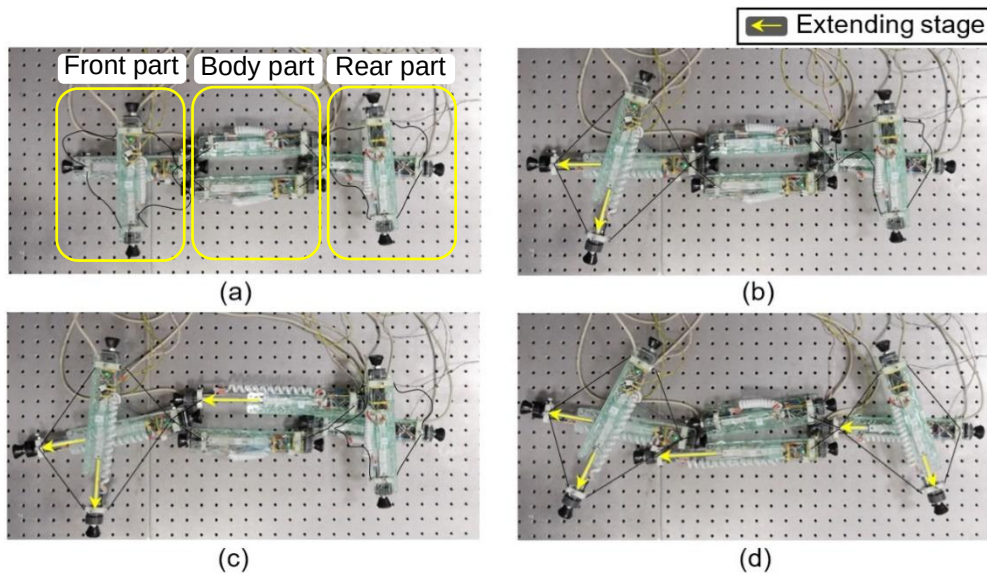


Figure 7.14 Multiple modules of a tensegrity structure with unequal-fixed cable length: (a) initial structure, (b) solid structure for the front module, (c) pushing above LA module for turning left, and (d) pushing below LA module for turning right and making solid structure for the rear module.

The demonstrations reveal that the multiple-module tensegrity structure could produce different configurations by extending and retracting LA length to drive the front, body, and rear parts to in different directions. However, the tensegrity structure with fixed cable length limits structural configurations.

To overcome this limitation, the retractable-passive joint with a cable locking mechanism (PRM) may be used to enhance the robot's structural configuration abilities by controlling the length of cables connected between the LA modules, which can be achieved by applying the locking and unlocking stages of the PRM to restrict and release cables while changing LA lengths to produce different cable tensions, as described in the following paragraphs.

Figure 7.15 presents the structural configurations of a cross-shape tensegrity structure consisting of two LA modules and four PRMs (A to D). A and B are

mounted on the left end cap of the LA (X), whereas C and D are mounted on the right end cap of X. The cable tips of A and C are attached to the top end cap of the Y, and the cable tips of B and D are attached to the bottom end cap of Y. All PRM cables remain in tension in the initial stage, where the unlocking stage is applied for all PRMs, as presented in Figure (a).

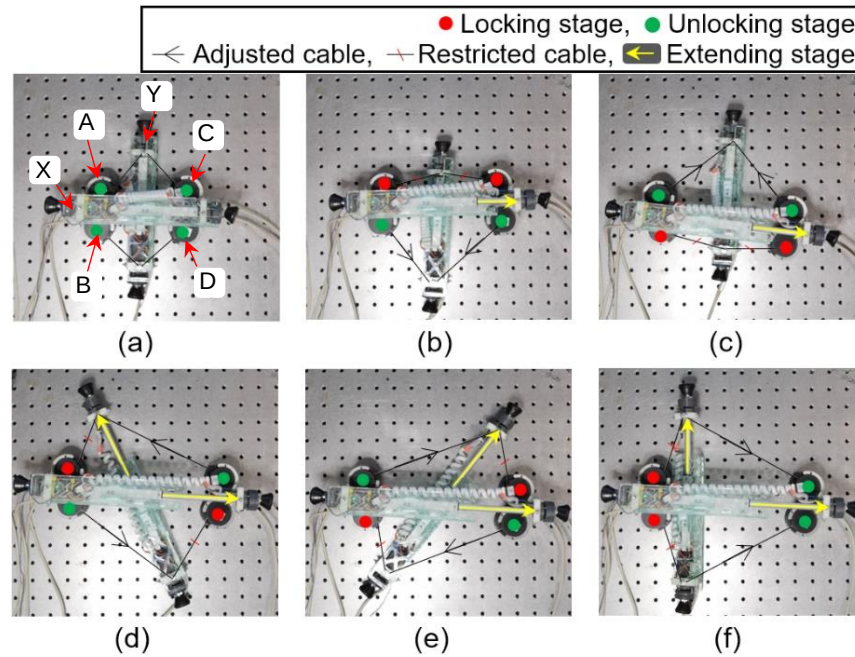


Figure 7.15 Cross-shape tensegrity structure using PRMs to adjust cable lengths for structural configurations: (a) initial shape, (b) diamond shape, (c) upside down diamond shape, (d) left-oblique trapezium shape, (e) right-oblique trapezium shape, and (f) left-side diamond shape.

Figure 7.15 (b) presents the structural configuration to move Y downward by applying the locking stage for A and C before extending the X length. PRMs can be used to change the robot shape by, for example, moving Y upward like an upside-down diamond shape, left and right oblique trapezium shapes and left-side diamond shape, as shown in Figure 7.15 (c, d, e, and f), respectively.

The multiple modules of cross-shape tensegrity structures consisting of PRMs can be constructed for crawling locomotion such as the snake motion, as shown in Figure 7.16. Figure (a) show the initial stage, in which PRMs use the unlocking stage to make all cables tight with the cable-pulling force generated by power springs. This structure is similar to the previous three modules of a tensegrity structure. However, the PRMs are connected between LA-slider modules instead of fixed-lengths. Therefore, the configurations of this structure are more changeable and controllable. Figure (b) shows the turning-left motion of the front module, which can be achieved by applying the locking stage (see red circle) and the unlocking stage (see green circle) of the PRMs. Figure (c) shows the turning-right motion. From these examples of configurations, it may be posited that, if

there are 100 tensegrity structure modules with multiple PRMs and LAs, it is possible to design a robot that can change its shapes to access different areas where human cannot. This actuation method could be used not only for a robot, but also for other applications that require lightweight, less power use, and reconfigurable structure.

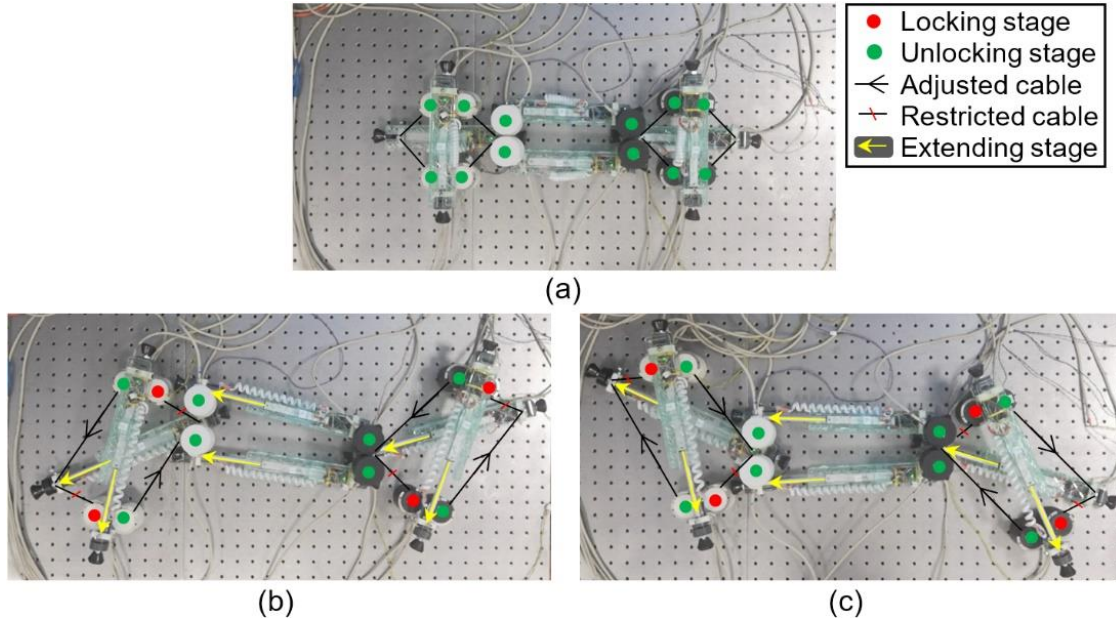


Figure 7.16 Three modules of a tensegrity structure with PRMs for adjusting cable length to change structural configurations: (a) initial structure, (b) structural configuration for turning left, and (c) structural configuration for turning right.

7.6 3D Robot Configurations

This section presents three-dimensional (3D) robot configurations to demonstrate different abilities that a climbing robot needs, such as shape-changing, soft/hard-structural adapting, angular correcting, and strut level adjusting using cooperation between the LA and PRM modules.

The proposed 3D robot is designed, as shown in Figure 7.17; it consists of five LAs (X1, X2, Y1, Z1, and Z2) and 12 PRMs (A to L). All PRM cables (1 to 12) connect to both end sides of all LAs. Two fixed-length cable (13 and 14) are used to connect LA-Z2 and LA-Y1 instead of two PRMs due to the lack of PRM modules. However, 12 PRMs are sufficient to demonstrate that the proposed actuation method could be used to possibly develop a robot with climbing ability.

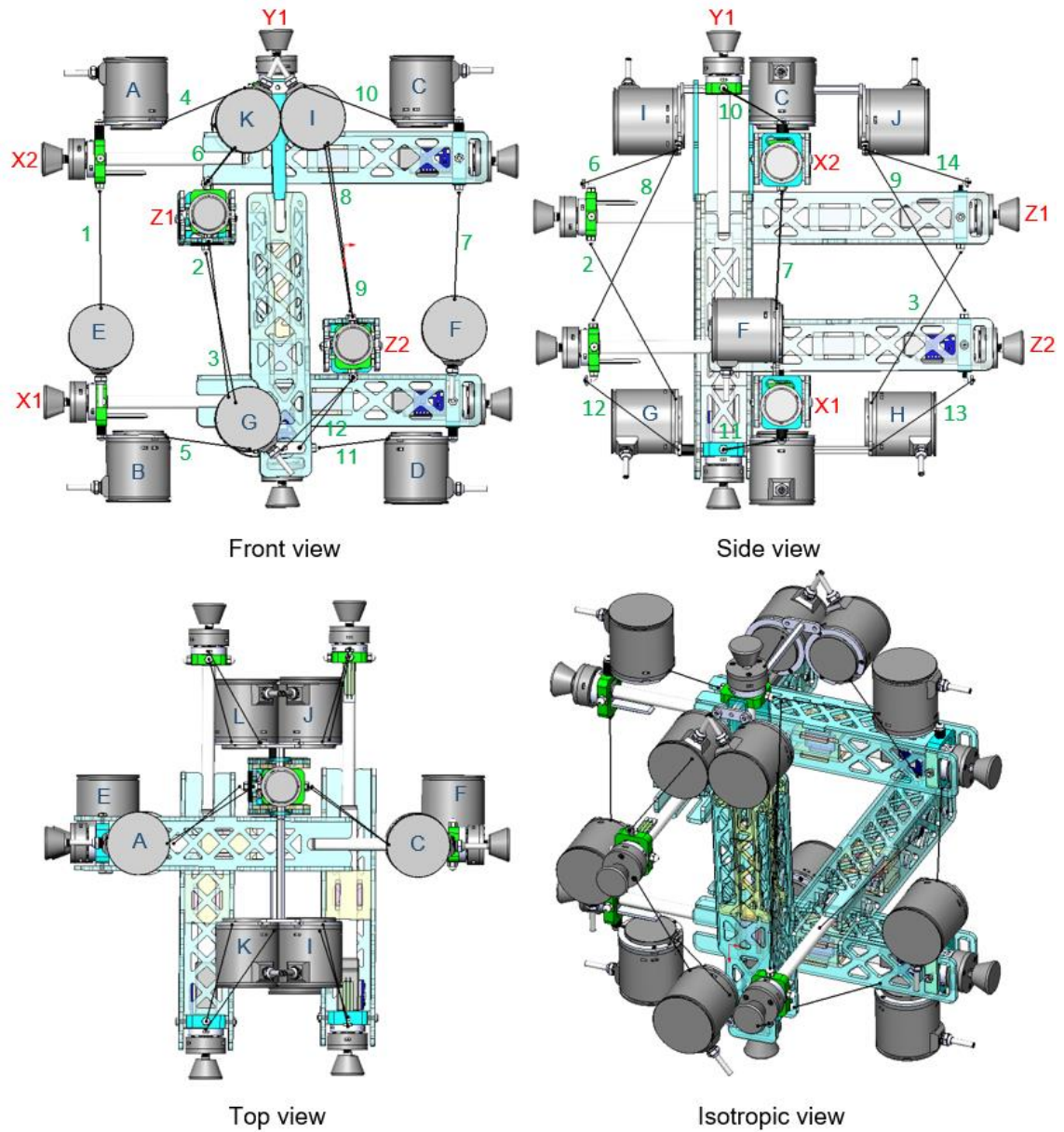


Figure 7.17 3D model of the proposed 3D robot based on tensegrity structure: (top left) front view, (top right) side view, (bottom left) top view, and (bottom right) Isometric view; the robot consists of five SEs (X1, X2, Y1, Z1 and Z2) and 12-PRM elements (A to L). 12PRM cables (1 to 12) and two fixed-length cables (13 and 14) are used to connect all SEs.

7.6.1 3D Shape-Changing Ability

This experiment aims to demonstrate 3D-robot configurations to change the structural sizes beneficial for accessing different environment dimensions. The physical tensegrity robot in its initial and enlarged size is presented in Figure 7.18.

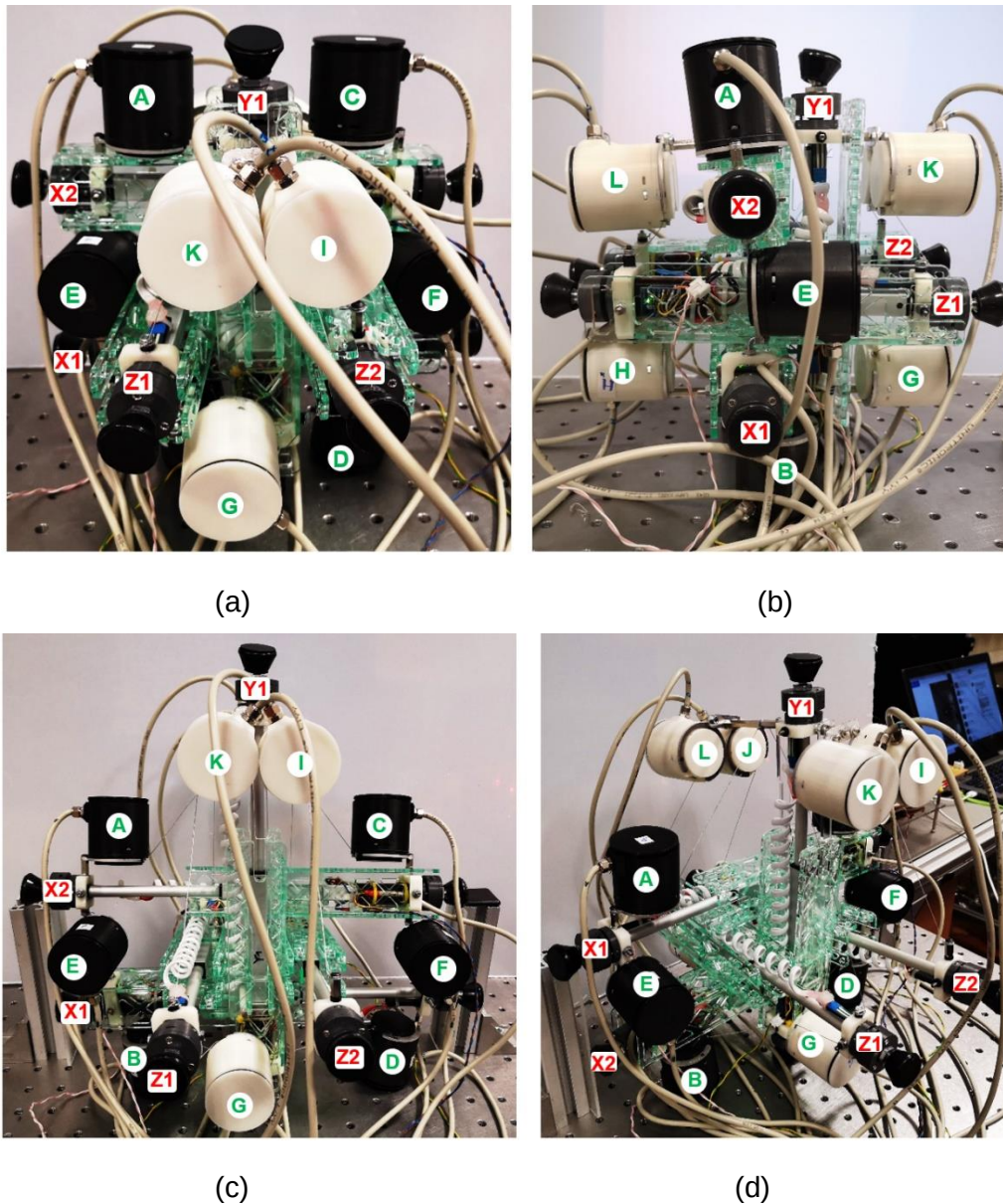


Figure 7.18 A physical tensegrity robot structure: (a) initial robot configuration (front view), (b) initial robot configuration (side view), (c) full extension of the robot (front view) and (d) full extension of the robot (isometric view).

Due to the robot being constructed in a cube shape by placing LA modules along the X, Y, and Z axes, the size of the robot can be estimated by measuring the length of the LA module. In this demonstration, the initial size of the robot is 250 mm and the maximum size, fully extending all LA length, is 325 mm. Therefore, the robot can access environments that have a diameter range of 260 mm to 325 mm. However, this range can be changed depending on individual element design and application requirements.

7.6.2 Soft/Hard Structure Adaptation Ability

Another useful ability of the proposed 3D robot integrated with PRM is changing the structure soft and hard quickly, providing different structural properties. The soft structure is beneficial for moving in narrow environments, such as pipelines

and caves for inspection tasks. In addition, the soft structure can be adapted following environments to withstand any impact forces, interacting with the robot. On the other hand, the hard structure is useful in generating different tensions of the cables to exert forces for locomotion or carry tools for maintenance tasks. The video frames of the soft structure demonstrations are presented in Figure 7.19.

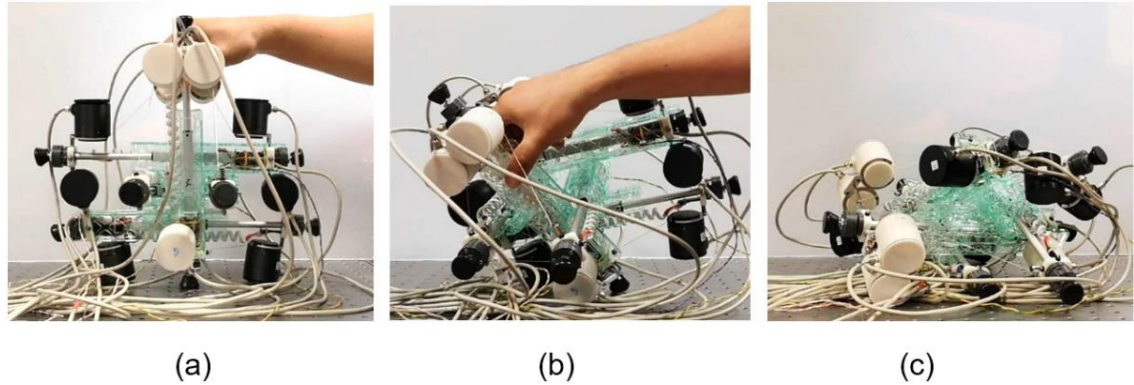


Figure 7.19 Demonstration of the soft structure: (a) initial stage (all PRMs are applied unlocking stage), (b) the structure becomes soft, in which the robot shape can be changed following external force, and (c) the structure collapse on the ground.

The experiments suggest that, after applying the unlocking stage of all PRMs, all cables freely roll to allow the movement of the LA modules in different directions. Therefore, the robot shape may be changed following an external impact or pressing force (see image (b)). Additionally, the robot could collapse on the ground with a height of 190 mm reduced from the initial height to 140 mm. However, the height of the collapsed structure can be decreased by minimising the size of the LA case.

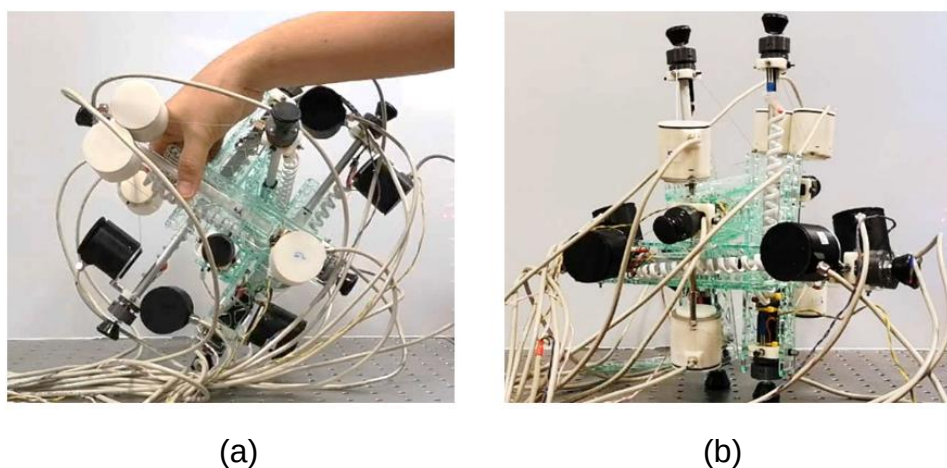


Figure 7.20 Demonstration of hard structure: (a) each LA can maintain its position by restricted cables (all PRMs are applied as the locking stage) and (b) the robot standing on the ground by rotating its structure.

Figure 7.20 presents a hard structure demonstration. The locking stage is applied for all PRMs to restrict the length of all cables before extending LA lengths. These

configurations make the robot structure harder, and the LA modules could maintain their position or slightly change because of the flexible joint allowed by the cable connections without rigid joints. The hard structure may also withstand external impact. Therefore, the robot has a compliant structure even though the structure is hard.

The swapping between soft and hard structures is also demonstrated. After applying the locking stage for all PRMs while LA-slider length extending, the robot structure can swap its structure from soft to hard, and each cable has high tension, within 0.5 s after applying control signals. The robot can also swap its structure from hard and soft within 0.2 s by applying the unlocking stage for all PRMs.

7.6.3 Angular Correcting Ability for Climbing Locomotion

Another function that a climbing robot requires is the ability to maintain the angle of robot elements while moving in vertical directions. Therefore, this experiment demonstrates angular stabilisation for the linear actuator (X2) module by using the PRMs (E and F) to restrict and release cables while changing slider length of the linear actuator Y1.

Before experimenting, X1 end caps push against two poles to fix the robot structure standing on the ground, as presented in Figure 7.21 (a) in the initial stage. Figure 7.21 (b) presents the reference angle of the X2 (θ_{x2ref}) as 0° .

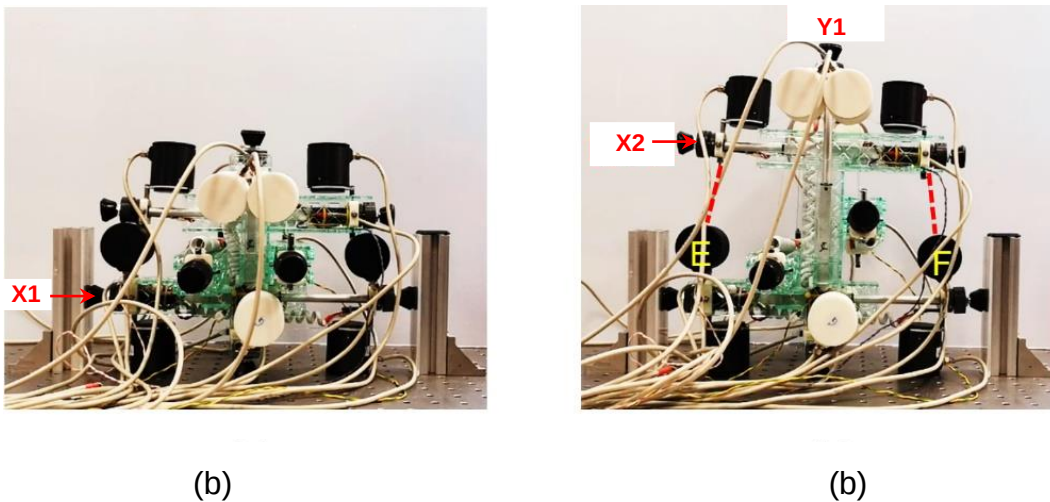


Figure 7.21 Experimental setup for the structural stabilisation control demonstration: (a) the initial stage and (b) the final stage (red-dash lines indicate the controlled cables)

The on-off controller is chosen to generate the locking and unlocking stages of E and F automatically using the feedback X2 angle (θ_{x2}) generated by an inertial measurement unit (IMU), which is mounted on the X2 module. The directions of the X2 angle are specified in Figure 7.22

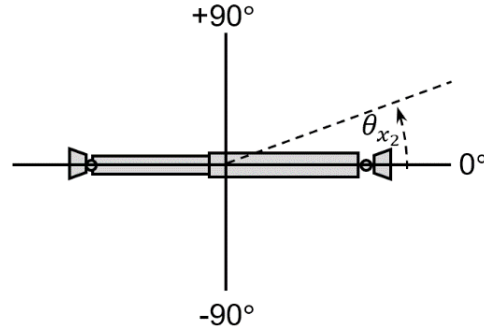


Figure 7.22 X2 angular diagram.

The control signals for the PRMs (E and F) can be generated with the following conditions.

$$\text{PRM (E)} = \begin{cases} \text{Lock,} & \theta_{x_2} < 0^\circ \\ \text{unlock,} & \theta_{x_2} \geq 0^\circ \end{cases} \quad (7.1)$$

$$\text{PRM (F)} = \begin{cases} \text{Lock,} & \theta_{x_2} > 0^\circ \\ \text{unlock,} & \theta_{x_2} \leq 0^\circ \end{cases} \quad (7.2)$$

Several parameters are initially defined before demonstrating. The chosen maximum speed of the Y1 slider to exert forces pushing the X2 is defined as 11.21 mm per second, and the duty cycle of Y1 is constantly defined as 220. The slider length of Y1 is defined as travelling from 0 mm to 90 mm.

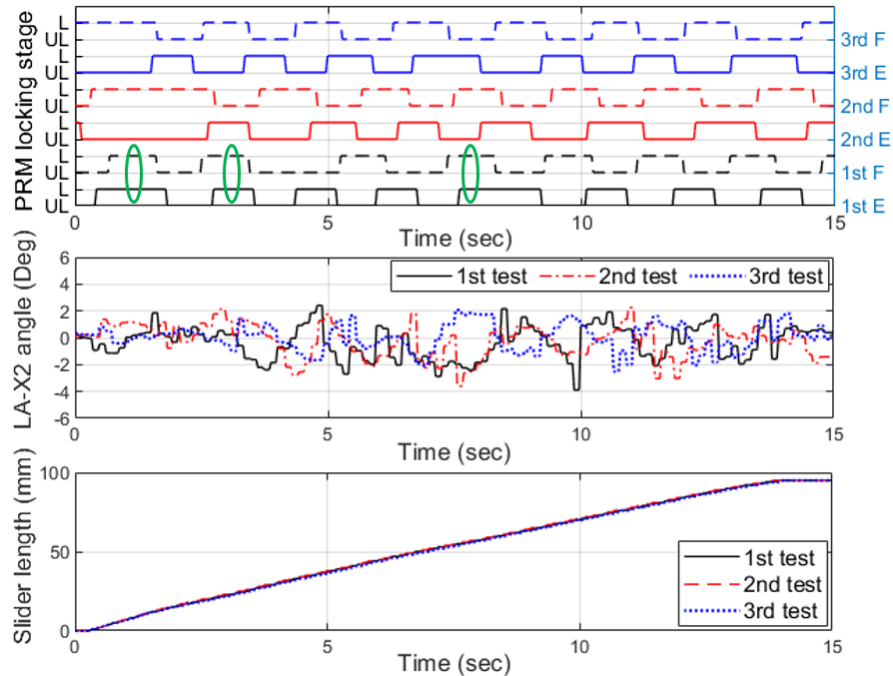


Figure 7.23 Experimental results of X2 angle stabilisation (0°): (top) locking/unlocking stages of E and F, (middle) X2 slider angle, and (bottom) Y1 slider length

Figure 7.23 presents the results of three-repetitive experiments of the X2 angular control. Although E and F could be restricted and release cables to correct the

X2 angle oscillating between -4° and 2° , the unexpected locking stage occurs while changing Y1 slider length. E and F perform the locking stage at the same time, resulting in the restriction of X2 moving upward, as indicated by the green ellipses in Figure 7.23 (top). The unexpected locking stage occurs because E and F could not restrict and release cables suddenly after receiving the locking command from a controller. The braking mechanism requires 0.4 to 0.6 s to restrict cable length due to the speed limitation of the DC-geared motor for driving the braking mechanism.

To reduce this problem, a motor that provides high speed and torque to drive the braking mechanism is replaced. Another solution to prevent the overlapping-locking stage involves modifying the unlocking stage rule by defining an angle error boundary for the reference angle. After analysing the angle oscillating around the X2 target angle (0°), the angle error boundary is defined as $\pm 1^\circ$ from the target angle for generating the unlocking stage of E and F. The modified control rule is shown in the following formula:

$$\text{PRM (E)} = \begin{cases} \text{Lock,} & \theta_{x_2} \leq (\theta_{x_2\text{ref}} - 1^\circ) \\ \text{unlock,} & \theta_{x_2} \geq (\theta_{x_2\text{ref}} + 1^\circ) \end{cases} \quad (7.3)$$

$$\text{PRM (F)} = \begin{cases} \text{Lock,} & \theta_{x_2} \geq (\theta_{x_2\text{ref}} + 1^\circ) \\ \text{unlock,} & \theta_{x_2} \leq (\theta_{x_2\text{ref}} - 1^\circ) \end{cases} \quad (7.4)$$

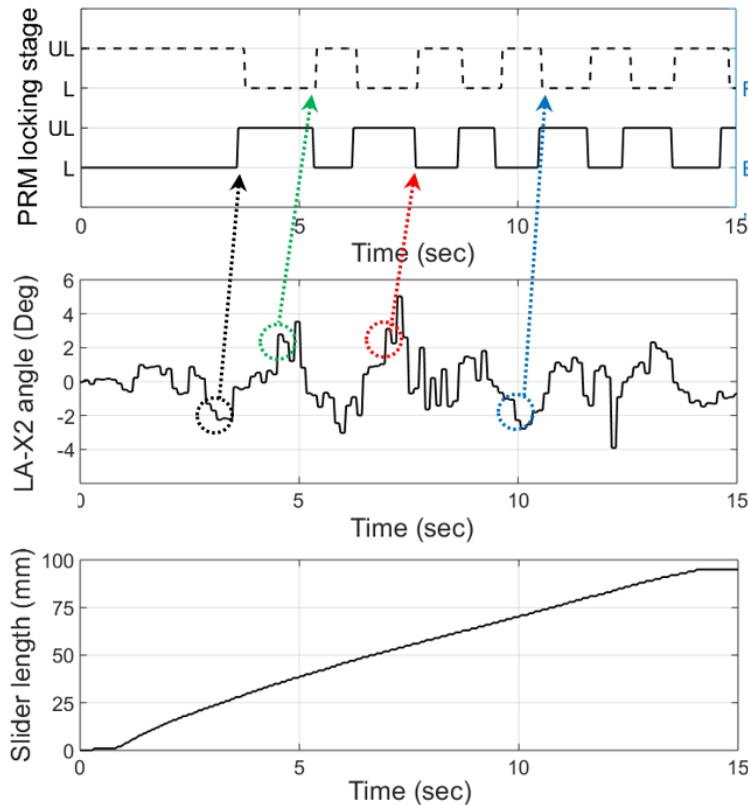


Figure 7.24 Experimental results of X2 angle stabilisation: (top) Y1 slider length and the locking/unlocking stages of E and F and (bottom) X2 slider angle stabilised by controlling E and F cables.

Figure 7.24 presents the experimental results of the X2 angular control using the modified control rule. The result show that the modified locking stage rule can generate the locking stage, where E and F did not perform simultaneously. E could restrict the cable when the X2 angle is less than -1° (see black dash arrow) and release the cable when the angle is more than $+1^\circ$ (see the red dash arrow). Similarly, F could restrict the cable when X2 angle is more than $+1^\circ$ (see green dash arrow) and release the cable when the X2 angle was less than -1° (see blue dash arrow). For consistent results, three-repeatable demonstrations are performed, as presented in Figure 7.25.

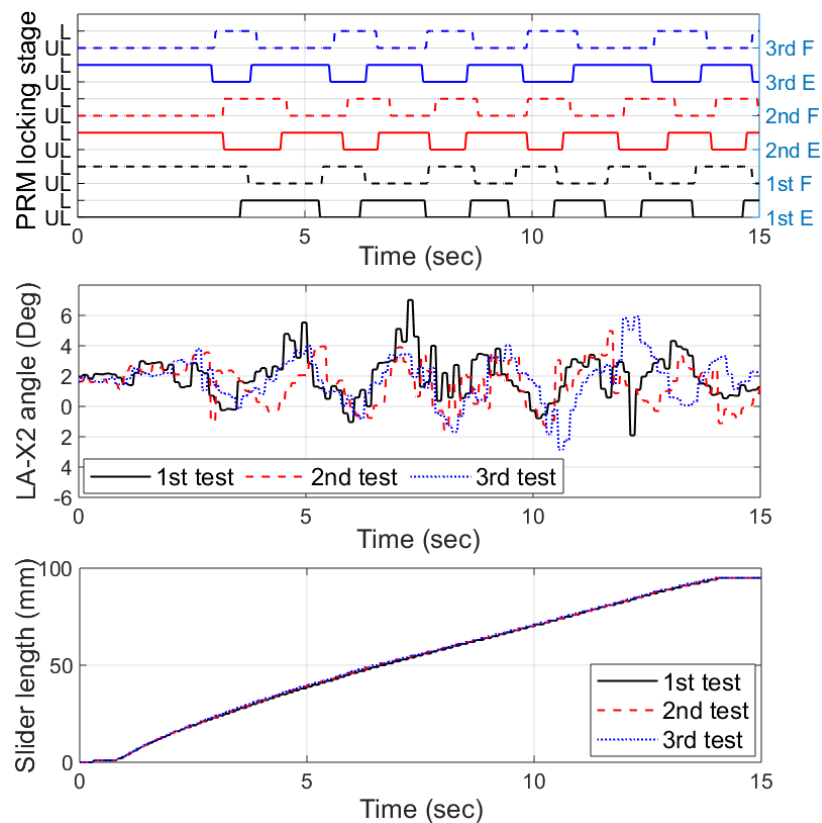


Figure 7.25 X2 angle stabilisation control demonstrations.

The repeatable experimental results show that the modified control rule could properly generate locking and unlocking commands sending to E and F without locking stage overlapping. Although the X2 angle oscillated between -3° and 7° , X2 could be controlled around the reference angle of 0° , which meant that the X2 motion could be moved straight on average. Therefore, the proposed PRM can sufficiently control the LA module angle vertically by restricting and releasing cables during changing LA-slider lengths.

To investigate further factors that affect angle stabilisation performance, the target angle of the X2 is changed to 10° , 20° , -10° , and -20° , while the Y2 slider

length travels from 0 to 95 mm. The three experiments are tested repeatably for reliable results, as shown in Figure 7.26 to Figure 7.29.

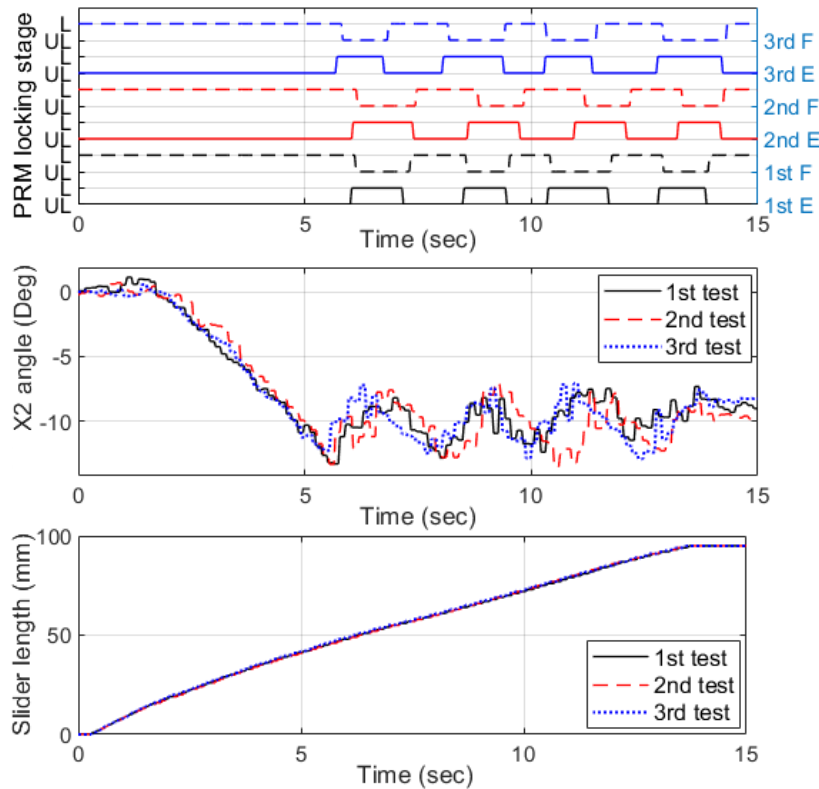


Figure 7.26 Experimental results of the X2 angular control of -10° : (top) PRM locking stage, (middle) X2 angle and (bottom) the Y1 slider displacement.

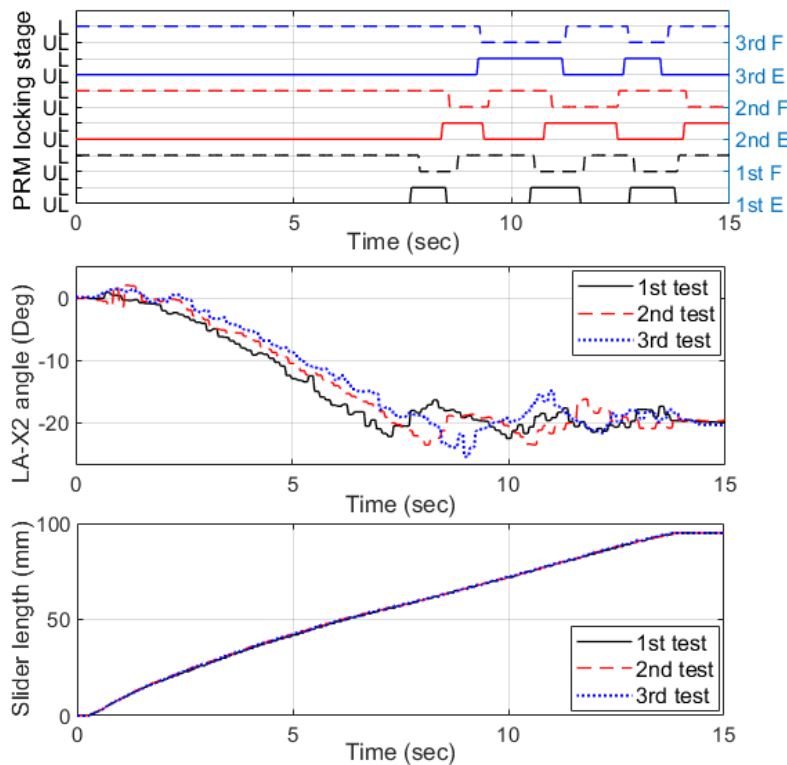


Figure 7.27 Experimental results of the X2 angular control of -20° : (top) PRM locking stage, (middle) X2 angle and (bottom) Y1 slider displacement.

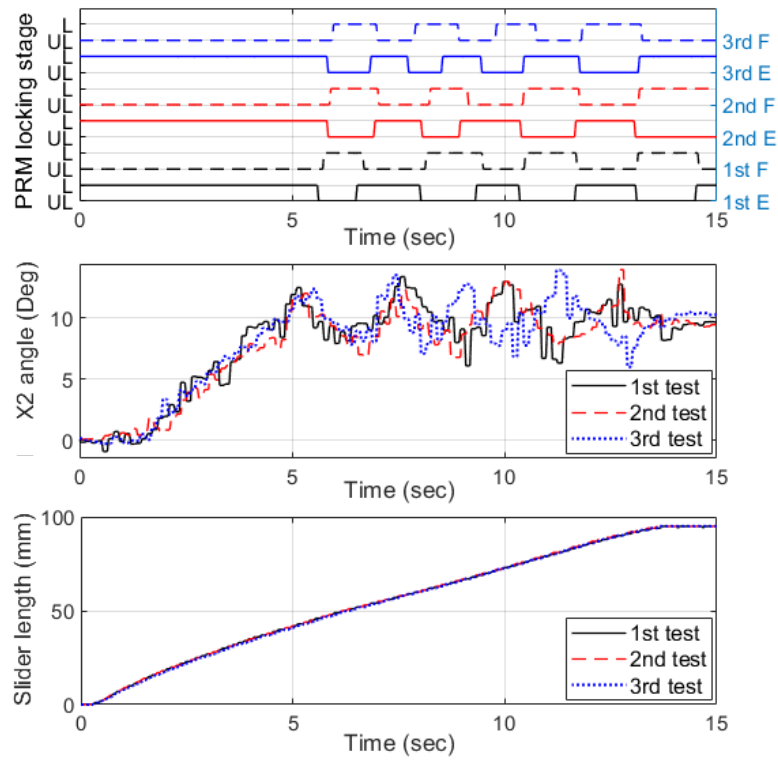


Figure 7.28 Experimental results of the X2 angular control of $+10^\circ$: (top) PRM locking stage, (middle) X2 angle, and (bottom) Y1 slider displacement.

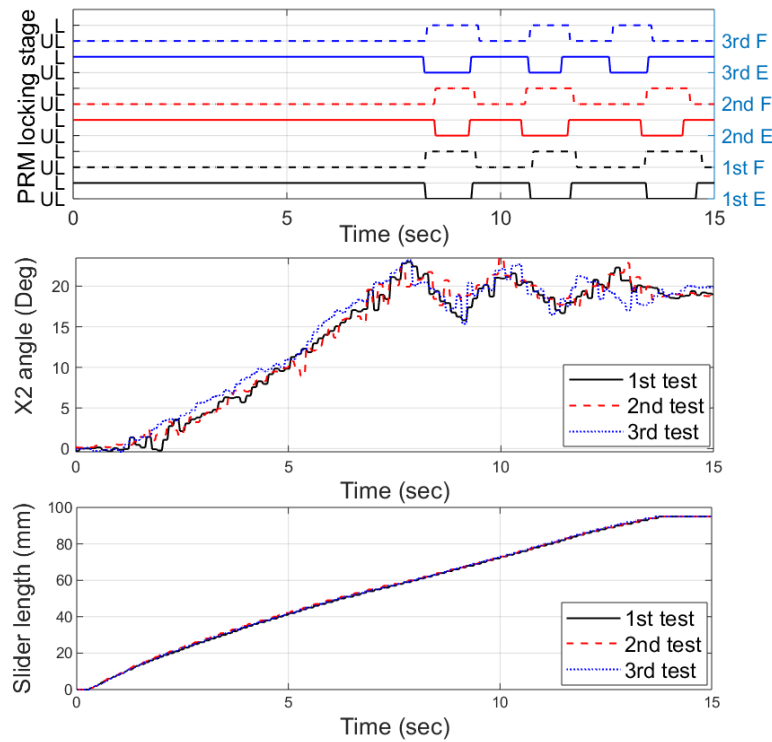


Figure 7.29 Experimental results of the X2 angular control of $+20^\circ$: (top) PRM locking stage, (middle) X2 angle, and (bottom) Y1 slider displacement.

The experimental results show that the X2 angle could be controlled oscillating around the target angles. E and F provide the braking force suitably to correct the reference angles of X2, which is pushed by the Y1 slider.

Another factor that affects the peak-to-peak amplitude of X2 swing angles oscillating around reference angles is the speed of the Y1 slider. Therefore, different Y1 slider speeds of 7.14, 8.24, 11.21, and 12.5 mm/sec are defined to move X2 upwards by applying four-constant duty cycles of 140, 160, 220, and 250 for the Y1 slider, respectively. Y1 displacement is defined as 90mm. The experimental results are presented in Figure 7.30.

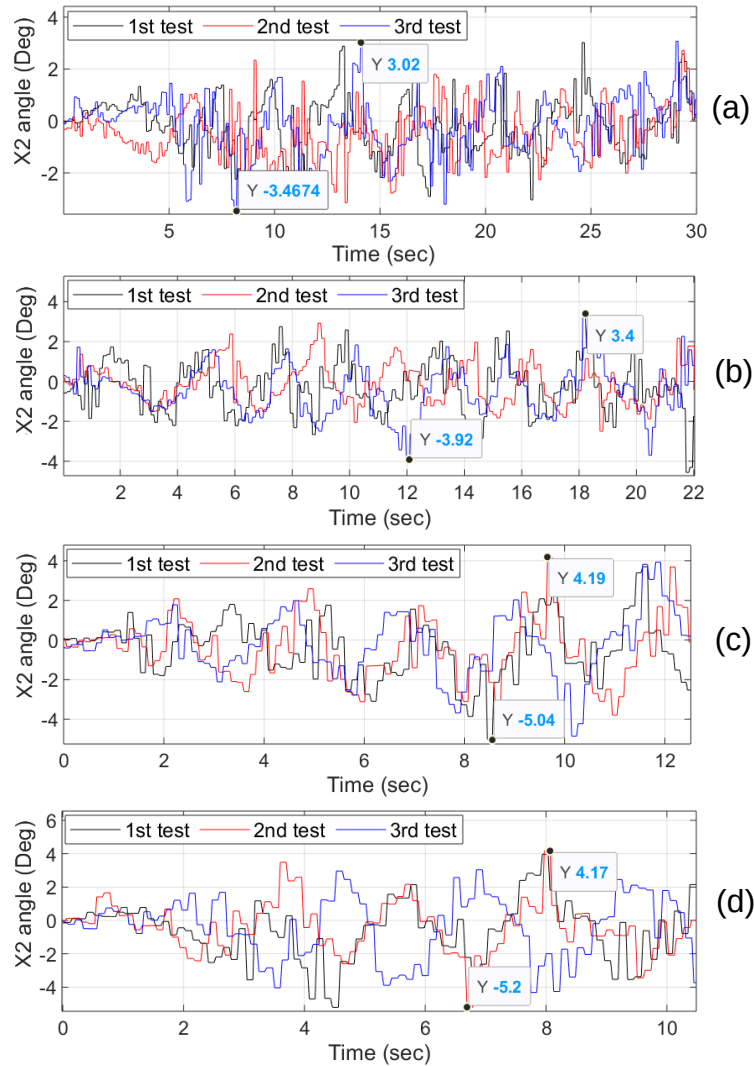


Figure 7.30 Experimental results of the X2 angular control of 0° , using four different speeds of the Y1 slider- (a) 7.14 mm/s, (b) 8.24 mm/s, (c) 11.21 mm/s and (d) 12.5 mm/s

The results show that the higher the speed of the Y1 slider is applied, the more swing angle amplitudes occur. For example, when applying the speed of the Y1 as 7.14mm/s, the swing angle is smallest as 6.49° , while the highest swing angle occurred as 9.37° when applying the speed of the Y1 slider as 12.5 mm/s.

From the experimental results of the angular control ability, it may be concluded that the PRMs can restrict and release the cables inside the robot structure while changing LA-slider lengths to make the robot moving upwards. Furthermore, this

configuration method may also be used to develop a steering mechanism for a climbing robot that requires lightweight, compliant features.

7.6.4 Strut Level Adjustment Ability

This experiment demonstrates the height adjustment of Z1 and Z2, which are placed in the middle of the robot structure. This adjustment is used to control the Z1 and Z2 in different heights that perform robot locomotion in case of X1 and X2 end caps not being able to produce friction on environmental surfaces, such as accessing a tee junction in a pipeline. For the experimental setup, Z1 cooperates with I, J, G and H, while Z2 cooperates with K, L, G, and H. However, G and H are rearranged for Z1 and Z2 motions due to the lack of two more PRM modules. From this constraint, the experiments are divided into two parts, namely Z1 and Z2 motions.

The first experiment involves moving Z1 upward, which can be achieved by applying the locking stage for A, C, I, and J. I and J are used to restrict the cable to fix the Z1 with the end cap of the Y1 slider. Therefore, if the Y1 slider length is extended, Z1 will also be moved upward. However, E, F, and G must be defined as the unlocking stage to allow their cables to roll freely. The video frames of the demonstrations are presented in Figure 7.31.

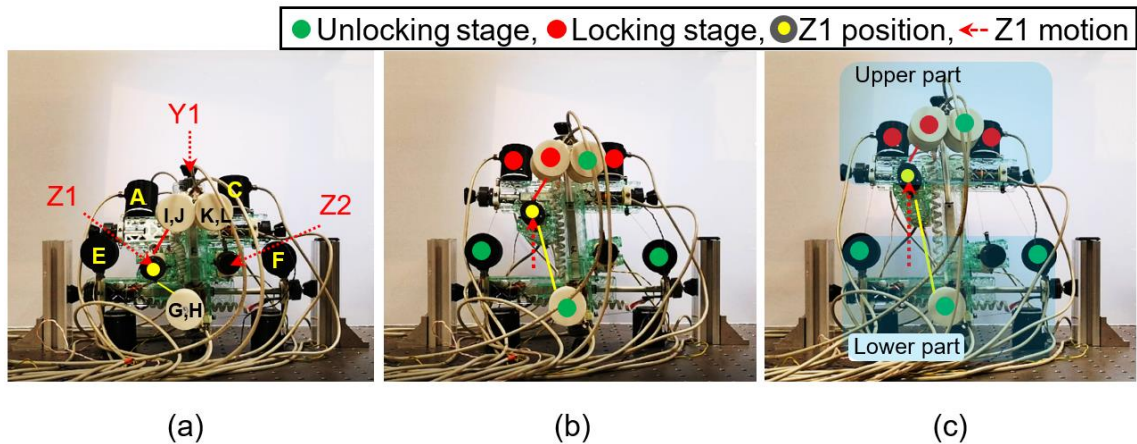


Figure 7.31 Demonstration for moving the Z1 upward: (a) the initial position, (b) Z1 is moved upward following the Y1 slider extension, and (c) the final position of the Z1; the yellow line indicates adjustable-length cable, and the red line indicates restricted-length cable.

The experimental results show that I and J produce braking force to restrict the cables sufficiently, resulting in Z1 moving up following the Y1 slider extension. Therefore, the braking force of the PRMs sufficiently withstands the total weight and the cable-pulling forces caused by the PRMs of the bottom of the robot.

In contrast, Z1's position can be maintained in the initial position during extending the Y1 slider length. G and H are defined as the locking stage to fix Z1 with the end cap of the Y1 base, and I and J are defined as the unlocking stage that allows cables to change. The results show that G and H could restrict the cables to hold the Z1 position effectively. The video frames of the demonstrations are presented in Figure 7.32.

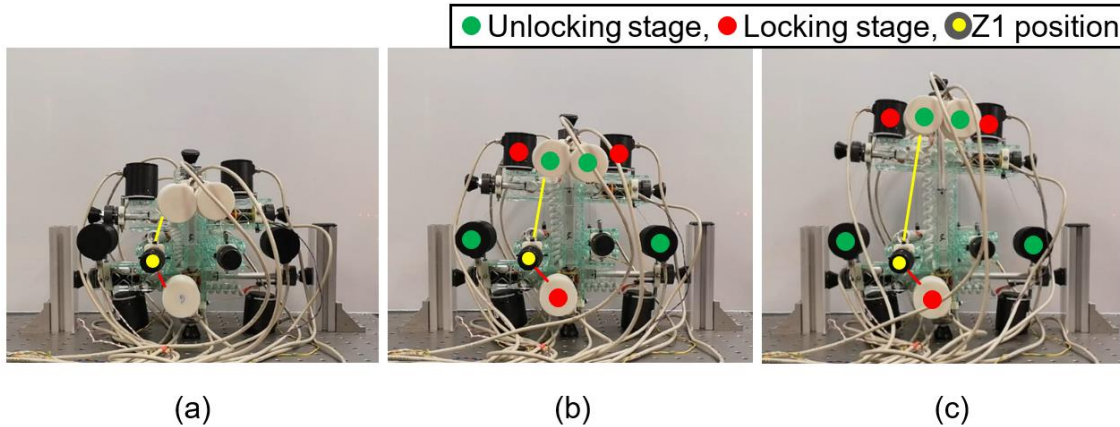


Figure 7.32 Demonstration of holding the Z1 in place: (a) the initial position, (b) the medium stage of the experiment, and (c) the final stage of the experiment; the Y1 slider length fully extends while the Z1 is still in place. The yellow circle indicates Z1's position, the red line indicates the restricted-length cable, and the yellow line indicates adjustable-length cable.

These experimental steps can be used for the second experiment to control Z2's positions. G and H are changed on the right side of the Y1 base to restrict and release cables that connect to the Z2 module. A, C, K, and L are defined as the locking stage, whereas E and F are defined as the unlocking stage. Then, the Y1 slider is fully extended. The results showed that K and L could produce braking force to restrict their cable, resulting in the LA-Z2 moving upward following the LA-Y1 slider extension.

Z2 could be held in place during extending the Y1 slider length. G and H are defined as the locking stage to fix Z2's position, while I and J are defined as the unlocking stage to allow cables to change. The results show that G and H could restrict the cables to hold Z2's position properly in the same way as the first experiment.

The results suggest that the PRM could produce braking force to hold and move the LA module in different positions. The locking and unlocking stages of the PRMs while changing the slider lengths of LA modules could be used to change the robot configurations in different shapes to provide vertical motion ability to develop a compliant climbing robot able to negotiate complex environments.

7.7 Summary

This chapter presented case study of the employment of the proposed structural deformation method by developing reconfigurable 2D and 3D robots based on class 1 tensegrity structure, including proposed PRMs and LA modules. Various useful abilities, such as adjustable sizes, hard and soft structure configurations, and structural stabilisation, were presented to ensure that the proposed deformation method could be employed to develop a tensegrity robot that can change its configurations for locomotion tasks, such as crawling and climbing motions with fast configurations, particularly swapping between soft and hard structures.

The new actuation method is able to deform robot's structure swapping between soft and hard quickly. The robot is able to change its shape from soft to hard, which all cables have high tension, within 0.5 s after applying control signals. The robot can also swap its structure from hard to soft within 0.2 s after applying unlocking stage to all PRMs. This structural configuration method may possibly be faster than conventional tensegrity robots due to fast change of the cable tensions.

For the energy consumption, due to the short time operation for PRM locking and unlocking stages of 0.5 s, it is able to anticipate that the robot may require less power than conventional tensegrity robots constructed using the same number of strut and actuated cable elements, as analysed in the Chapter6 (section 6.23).

Although this case study was not used to demonstrate climbing robot moving in vertical directions, the presented useful abilities show that, if a robot constructed with multiple PRMs and LA modules providing various structural configurations, it could potentially move in different environments and dangerous areas inaccessible by humans

In addition, the cooperation between the PRMs and the LA modules to deform a robot structure is the new actuation method of the reconfigurable tensegrity robot for locomotion tasks.

Chapter 8 Conclusions and Future Work

This chapter concludes this paper's research findings and discusses further research directions.

8.1 Assessment of Research Objectives

This section evaluates the extent to which the research objectives, outlined in Chapter 1, have been achieved.

- 1) Review the advantages of the tensegrity structure properties used in different research areas and critically assess existing literature on existing tensegrity robot types and locomotion classified by structure geometry. Investigate the mechanical design for compressive element and actuated tensile element utilised for solving any mechanical problems.

The advantages of the tensegrity robots and locomotion types, mechanical problems and solutions were investigated to gain knowledge into tensegrity robot designs. Force distribution, lightweight structure, and robust to failure properties were reviewed. Mechatronics designs and hardware implementations of existing tensegrity robots were analysed and compared to enhance prototyping techniques from state-of-the-art actuation methods and individual element designs.

- 2) Investigate locomotion types of existing tensegrity robots and current limitations of their configurations to design and develop a new approach to overcome these limitations.

Tensegrity robot locomotion and the mechanical designs of the compressive and tensile elements are summarised and selected. The crawling motion behaviours based on a wall-pressing method was chosen for developing a reconfigurable tensegrity robot due to its ability to move in both horizontal and vertical directions. However, existing tensegrity robots still have limitations due to slow speed for configurations, heavyweight mechanisms, and high power use caused by the limitations of the actuation method. Therefore, to overcome these limitations and reduce this problem, a new actuation method should be explored.

- 3) Design a new structural deformation concept and analyse the kinematics of the design.

The fundamental motions of the proposed structural deformation method were introduced. The examples of class1, 2 and 3 tensegrity robots are first presented

to understand how a passive-retractable joint with a cable locking mechanism (PRM) performs with an adjustable-length SE. 3-DOF systems were then used to describe how the end effector move to the desired positions along the x-axis by applying the locking and unlocking stage procedures of the PRMs before adjusting SE-slider lengths. The angular control of the 3-DOF system was also described and analysed. In addition, the end-effector motions of the 5-DOF system, consisting of four PRMs and one SE, were analysed. The kinematic equations of the proposed structure were derived to identify end-effector positions used for the closed-loop control system.

- 4) Design and develop SE and PRM based on the structural deformation concept.

The mechanical designs of the SE and PRM were performed. The required force for the SE was first analysed mathematically, and the theory and design of a spiral power spring, selected for producing passive-rotational forces, were investigated. The required rotational force of the PRM relating to the power spring design was then analysed. For a locking mechanism, a friction-based locking method was selected to design a braking component for the PRM due to the controllable-positioning brake. The required actuator torque to control the braking component was derived.

The required force for the SE and PRM were calculated. Before designing the SE and PRM mechanism, the miniature linear actuator (LA) and sensors for the SE and PRM were firstly selected in order to determine their dimensions. The LA and force sensors for the SE were selected based on the required force calculated by giving the robot weight estimation, and the power spring for the PRM was selected considering the minimum requirement of the rotational force. The actuator for the braking component was selected giving the required actuator torque. The 3D model of the SE and PRM were designed based on the SE and PRM requirements, as summarised in Table 4.1 and Table 4.2, respectively.

The SE and PRM were manufactured and implemented. The frictional components were manufactured using CNC technology and made of aluminium, brass, and stainless steel to withstand high friction while performing locking and unlocking. The non-frictional, complex, and tiny parts were created using 3D printing technology due to the low cost and lightweight material. All of the mechanical parts of the SE and PRM were implemented. Finally, the design of electronics control boards and selected communication for sending control signals and gathering sensor data from the SE and PRM were described.

- 5) Validate that SE and PRM prototypes conform to the structural deformation concept. Then, construct, demonstrate, and evaluate the new structural deformation method and control.

SE and PRM could exert the required rotational force to spool the cable and withstand the spooling force in the locking stage to meet the necessary requirements. Before constructing the different shapes of tensegrity robots, the accuracy and durability of the physical SE and PRM prototypes were demonstrated and evaluated. The LA-slider length and PRM-cable length were scaled providing the closed-loop position control that had a position error within $\pm 1\text{mm}$ and without target overshooting. The P-controller was designed and controlled the LA-slider lengths with a small steady-state error of $\pm 0.3\text{ mm}$ and without signal overshooting. The force sensor (FSR) was calibrated to measure the pressing forces between the SE end caps and a wall. This sensor was beneficial in sensing the end cap state for locomotion.

3-DOF and 5-DOF structures introduced in Chapter 3 were constructed and demonstrated to evaluate the proposed structural deformation method using cooperation between the SE and PRMs. The kinematic equations of the end-effector position of 3-DOF and 5-DOF structures were physically tested to identify end-effector positions. The derived forward kinematic equations provided end-effector position accuracy for closed-loop position control. The new control rules produced control signals to generate locking and unlocking stage procedures of the PRMs before or while changing SE-slider lengths. It was found that the proposed control rules could be used to calculate the control signals for PRMs and the SE effectively to achieve closed-loop control of the end-effector position and angle with small steady-state error of $\pm 2\text{ mm}$ and $\pm 2\text{ degrees}$, respectively. Although the end-effector motion of the proposed 5-DOF structure did not move to all positions in the workspace in the same way as conventional cable-direct-driven-robot by exerting high-torque to roll cables actively providing smooth motion reaching to target points, the proposed PRM is able to roll the cable passively with low torques to make a similar function but use less power in operations because the braking element can perform locking and unlocking when applying power for only 0.5 s. In contrast, the existing actuation methods require constant power to actuate cable or SEs for their configurations and locomotion. The PRM provides a light weight of 135g and the maximum braking force of 11N to restrict cable resulting in the possibility to design a lightweight tensegrity robot doing different tasks.

- 6) Extend the proposed structural deformation method by developing the physical class1 tensegrity robots based on the wall-pressing method for locomotion.

The case study on the employment of the proposed structural deformation method to design reconfigurable crawling and climbing robots based on class 1 tensegrity structures was achieved. Before constructing the robots, environmental and robot requirements were first defined considering inch-worm motion behaviour and the proposed structural deformation method constraint. Experimental work was then conducted to demonstrate the robot's ability to achieve crawling and climbing motions with promising results.

The first experiment involved constructing a simple-conventional crawling robot to demonstrate the minimum number of actuators required for the robot and inch-worm motion behaviour to observe the pushing force of the SE end caps to interact with the wall surface during locomotion. The robot was manually controlled and successful in crawling along horizontal-straight and slope paths.

A climbing robot based on a class 1 tensegrity structure was also constructed and tested. Useful climbing abilities, which are soft/hard body, retraction/extension robot sizes, and struts angle stabilisation, were demonstrated. Although the robot has not yet been tested in a vertical environment, the experimental results of the 3D-shape changing, fast swapping between soft and hard structure, angular correcting, and strut level adjustment abilities reveal that the proposed structural deformation concept could be used to develop a reconfigurable-tensegrity robot that moves both horizontally and vertically. Another advantage of the proposed tensegrity robot was the compliant structure. Without rigid joints between each SE, all connections of PRM cables allowed each SE to move in 6-DOF directions, providing more ability for the robot configurations to access rough terrains.

8.2 Conclusions

The following conclusions are relevant to the specific tasks performed.

8.2.1 Design

- 1) The proposed structural deformation concept was successfully employed to construct robots to achieve a crawling locomotion task in horizontal directions, using inch-worm motion behaviour. The proposed actuation method allowed the 3D robot to swap between soft and hard structures within 0.5 s. The adjustable length of the SE exerting force to drive the robot structure cooperating with PRMs to restrict and release cables can produce robot configurations with less power use because the locking and unlocking stages of the PRM require a short time of 0.5 s to apply power. Without rigid joints connecting the SE, robot structures are adaptable naturally following different environmental diameters.

2) The overall design of both SE and PRM satisfied the design specifications presented in Chapter 4 and 5. The selected actuators and fabricated mechanical parts allowed the PRMs to achieve cable restriction/release or locking/unlocking stages before or while adjusting SE-slider length to effectively perform structural configurations. Therefore, the structural deformation concept or actuation method was physically proved. In addition, the friction-based method for braking parts performed effectively and durably. The braking element could withstand the pulling force up to 11 N in the PRM locking stage. If a pulling force was higher than 11 N, the braking element also performed the locking stage without damage. Moreover, due to the weight of 135 g of the PRM, it is possible to design a lightweight robot for maintenance tasks that require a lightweight structure.

3) The employed miniature magnetic encoder was able to measure the cable length of the PRM and could generate 512 CPR connecting with the gear module, providing a resolution of 0.26mm per count to measure the cable length of the PRM.

4) The adopted Teensy 3.2 and Arduino Nano microcontroller are appropriate for implementing a centralised or distributed communication network and accomplishing research tasks. The Teensy 3.2 controller, utilised for the master board generating control procedures for LA and PRM, provides a clock speed of 72Mhz, which is suitable for sending the control procedure signals to 18-Slave control boards, including six-LA boards and 12-PRM boards.

5) The LA and PRM have modularity; the PRM cable tip can connect to SE easily using a plastic ball nut. Therefore, it is simple to construct and reconstruct a robot structure to build different robot shapes following application requirements.

There are several restrictions to PRM. Firstly, due to the small rotational force of the power spring, it could not spool the cable if the payload weight was higher than the rotational torque of the power spring. Therefore, the power spring torque should be selected depending on application requirements.

Secondly, in the locking stage, the cable could not be restricted suddenly after receiving the locking command caused by the mechanical delay time of approximately 0.4 and 0.6 s, which can be improved by minimising the gear ratio to provide a faster speed and sufficient force to drive the braking part.

8.2.2 Modelling

Although simulation software was not used to simulate the proposed structural deformation technique due to unavailable-suitable cable with a locking and unlocking stage toolbox, the simple physical hardware was roughly demonstrated

instead to test the proposed concept, as described in Chapter 5. However, the forward kinematic equations of the end-effector position were derived to identify the end-effector position of the 5-DOF structure, including one SE and four PRMs. The derived kinematic equations may be physically used to calculate the current end-effector positions sending to a microcontroller in the closed-loop control system.

8.2.3 Control

1) The developed control rules for the locking and unlocking stage procedures of PRMs before or while changing the LA-slider length are capable of the end-effector position and angle controls for the 3- and 5-DOF structures. The maximum speed of the LA-slider, target-position-error allowance, and an additional target of the LA-slider length are important parameters of the proposed control rules; they need to be tuned following the required speed of the movement. For example, if the maximum speed is set to high, the target-position-error allowances should be set to high; otherwise, the rise time of the end-effector travelling to a target point will take more time or oscillate due to the braking delay time caused by the low-speed rotation of the DC-geared motor, as detailed in Appendix A1.

2) The developed P controller for the SE performs well in terms of its step response and positioning accuracy. A slight steady-state error occurred while carrying heavyweight payloads; however, this error is acceptable for the structural configuration experiments for robot locomotion. The sampling time for closed-loop control affects the control performance. For instance, a sampling time of 0.01 s can control the SE-slider length without per cent overshoot and a small steady-state error. Using the same P-controller gain, there is a small per cent overshoot when the sampling time is defined as 0.1s because the SE-slider mechanism cannot respond immediately after receiving a control signal caused by the gear ratio of 100:1 of the LA. The result is a delay in responding to the control signal. Therefore, the shorter the sampling time used, the higher the control performance achieved.

8.3 Summary of Key Accomplishments and Limitations

The project's accomplishments are summarised as follows:

1) The development of a novel actuation method for a tensegrity robot was developed in the form of cooperation between a passive-retractable joint with a cable locking mechanism (PRM) and an adjustable-length strut element (SE).

Both PRM and SE can exert forces and make different cable tensions to deform robot structures. Robot configurations can be achieved by restricting and releasing cables while changing SE-slider lengths. This proposed actuation method may potentially increase the speed of robot configurations, requiring less energy than the existing tensegrity robot, as analysed in Chapter 6 (Section 6.2.3).

In addition, this proposed actuation method is different from others; it was designed using the cooperation between cable and strut actuation methods. Existing cable actuation methods are designed using only an active actuator with a gearbox to exert high torques to spool a cable, generating different cable tensions to change robot shapes. However, this structure has slow speed for structural configurations due to the gearbox effects. In contrast, the cable-spooling mechanism of the PRM proposed in this project was designed using a power spring to produce passive cable-spooling force to roll cables, providing higher cable-spooling speed than the existing method. Moreover, the PRM can restrict cable length while changing SE length to create varied cable tensions for robot configurations.

2) The new design of a passive-retractable joint with a cable locking mechanism called PRM is able to restrict and release cable length while changing strut length. The unique properties of the PRM could potentially enhance the existing tensegrity robot configurations in terms of configuration speed and energy consumption as also analysed in Chapter 6 (Section 6.2.3).

The new concept of control rules for the proposed actuation method can be used to generate locking and unlocking for PRMs and calculate SE-slider lengths in order to move the end-effectors of 3- and 5-DOF structures to target points effectively, which was also described in Chapter 6.

However, the proposed actuation method has a number of limitations:

- 1) The proposed actuation method may not be suitable for an application that requires smooth and high-speed motions such as a cable-direct-driven robot (CDDR) because the proposed actuation method cannot control the length of the cables that connect to an end effector directly; and
- 2) Although the PRM can rapidly spool a cable that connects to a lightweight SE using the rotational force generated by the power spring, it cannot be used to spool a cable that connects to a heavyweight element.

8.4 Future Directions

This section describes future research directions.

8.4.1 Design

1) Using a high strain ratio and high thrust force could enhance the SE performance by enabling the SE length to extend further, in turn allowing access to a larger environment. The end cap material could be made of memory foam. An end cap of this material, in a circular shape, could increase contact point surfaces. Such an end cap could enable attachment to differently shaped environmental surfaces without a ball joint; a ball joint could cause an angular motion constraint. For the PRM mechanical design, a flat bearing inserted between the power spring case and the motor mounting plate could reduce frictional surface area, providing smooth rotations during rolling and releasing of a cable. These changes would make the rotational torque generated by the power spring smooth and potentially enhance robot configurations.

2) Minimising the number of electronic control and sensor wires could reduce traction forces that would otherwise occur. This could be accomplished by custom design and development of the electronic control boards of each element to be integrated into SE and PRM modules. Based on this concept, the master-electronic-control board could communicate with SEs and PRMs using only four wires, including power, ground, clock, and data. Aside from wire communications, a wireless method may be adopted for this application.

3) The enclosure of the SE and PRM should be designed to withstand extreme environmental elements such as high-pressure water and gas that could overwhelm mechanical engineering technologies.

8.4.2 Modelling

1) To explore further the possibility to move on rough and soft terrain or active water in a pipeline, the robot dynamics model should be derived and simulated by software simulations that provide a tensegrity toolbox that supports the tensegrity structure elements.

2) The dynamic model of the proposed 5-DOF structure, as well as crawling and climbing robots, would be derived for software simulations that could demonstrate other advanced control algorithms such as CPG to generate locking/unlocking stage procedures of the PRMs before or while changing SE-slider lengths. Furthermore, this dynamic model would be compared to physical robots to calibrate or tune simulated parameters providing an accurate simulated robot model that would facilitate and speed up the controller development.

8.4.3 Control

The P gain can be evolved using a genetic algorithm and a self-adaptive controller implemented to adjust the P gain in real-time. Parameters associated with the proposed control rules may be optimised using other control algorithms to enhance the locking/unlocking pattern generator to control the PRM cable in robotic systems.

An advanced control algorithm and communication system may be adopted to control the proposed climbing robot configurations for locomotion and allow the robot to determine its location inside of the square pipe. Similarly, a communication method for long distances would need to be developed to allow commands to be sent to the robot and information sent back to be able to autonomously detect obstacles and handle complex terrains during locomotion.

Appendix A

A.1 Strut Element Manufacture and Assembly

The example pictures of the 3D printed elements of the end cap are shown in Figure A-1.



Figure A-1 Image of end cap parts (five sets) created from 3D printing technology: (a) ball joint holder of the linear actuator (LA) base tip, (b) ball joint holder of the Slider tip, (c) pressing plate of the LA-base tip, (d) pressing plate of the slider tip, (e) the connecting base of the slider tip and (f) the connecting base of the LA base tip.

Figure A-2 shows the end cap assembly procedures as described from the following steps: (a) Insert the FSR through the slot of the connecting base. (b) Glue the FSR attaching the connecting base surface. (c) Insert three 2mm-screws into the top side of the pressing plate. (d) Flip the pressing plate and put three compressing springs into three screws and glue the FSR surface protector to the pressing tip. (e) Attach the pressing plate to the connecting base screwing three screws with a 0.5mm gap between the pressing tip and FSR surface. (f) insert the ball joint foot through the ball joint holder screwing with a 6mm nut. (g) Put together the ball joint foot holder with the pressing plate from step (e) using three 2mm screws and (h) mount the connecting base on the both LA-slider and LA-base tips.

For wiring, a 28-AWG spring cable is adopted to connect between the FSR poles on the LA-slider side and LA-base to allow the FSR cable extension and retraction following the LA-slider movements. Although the spring cable exerts a force of 0.63N while extending the LA-slider length of 100mm. However, that force is small and does not affect the LA-slider extension because the LA can drive a maximum payload of 42N. The tension force demonstration of the spring cable is shown in Figure A-3.

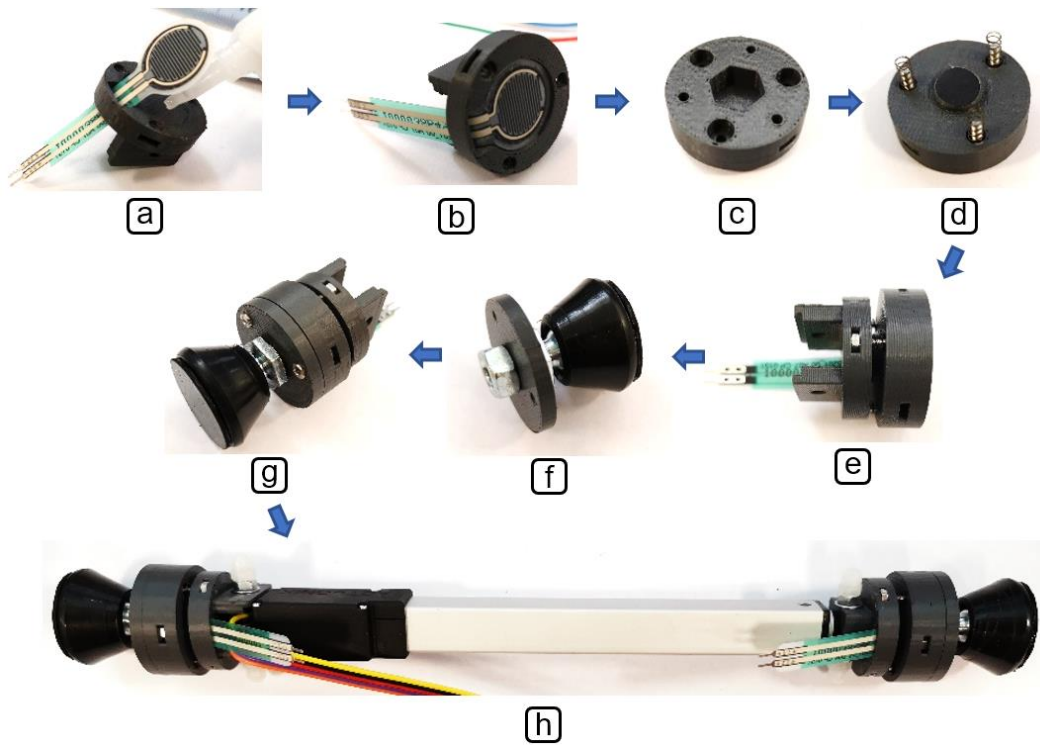


Figure A-2 Assembly procedure of the strut element prototype.

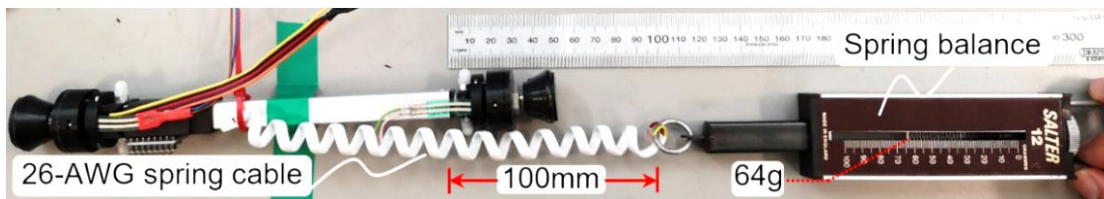


Figure A-3 Image of the tension force of the spring cable experiment.

After connecting between the spring cable and FSR on the LA-slider side, the IMU is mounted on the LA-base alongside the end cap. Finally, all electronics and sensors are wired and connected to a connector. The physical prototype and weight testing of six-strut elements are shown in Chapter 4, Figure 4.33.

A.2 Passive-Retractable Joint with a Cable Locking Mechanism (PRM) Manufacture and Assembly

The example of 3D printed parts for the PRM is shown in Figure A-4.

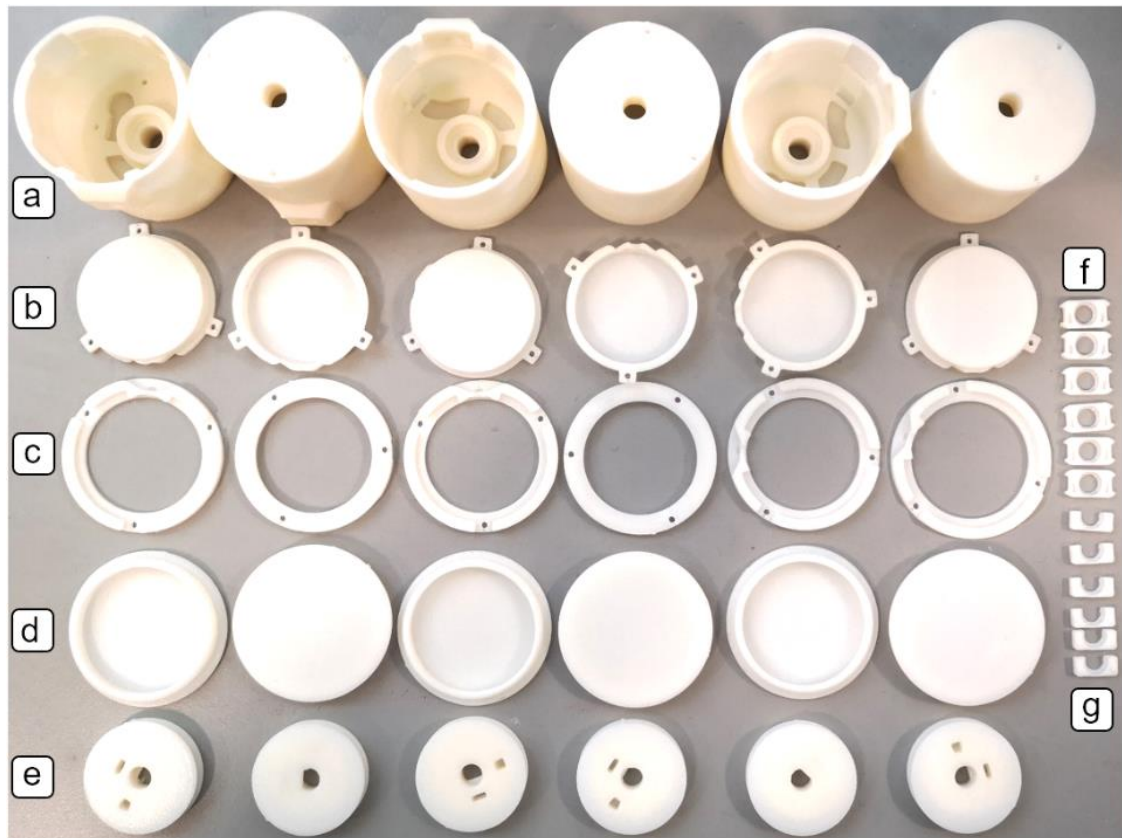


Figure A-4 Example of 3D printed parts for the PRM-G to PRM-L made from ABS-M30 filament: (a) PRM case, (b) upper cover, (c) lower cover, (d) PRM lid and (e) cable storage.

The CNC machine is utilised to make the frictional parts, small thickness parts and connecting parts. Different material is used to machine PRM components providing durable use and overall weight reduction. Aluminium is mainly used for rotational parts (see Figure A-5 (a and b) and fixed parts (see Figure A-5 (e) due to the lightweight material. Also, small thickness parts (see Figure A-5 (c, f, g and h) and connecting parts (see Figure A-5 (d)) are made of aluminium because they need to withstand external forces generated from other components during the robot configurations. The frictional parts (see Figure A-5 (i, j and k)) is constructed from brass to provide durability when requiring friction with other parts of the mechanism. For example, the unlocking guide is frequently pressed and grazed by a ball plunger, which is made of stainless steel. Therefore, the use of material with different characteristics for friction parts will reduce the abrasion at the frictional surface areas providing the durable operation. A gear shaft (see Figure A-5 (l)) is only one part that is made of stainless steel because it is very tiny and needs to be a strong part.

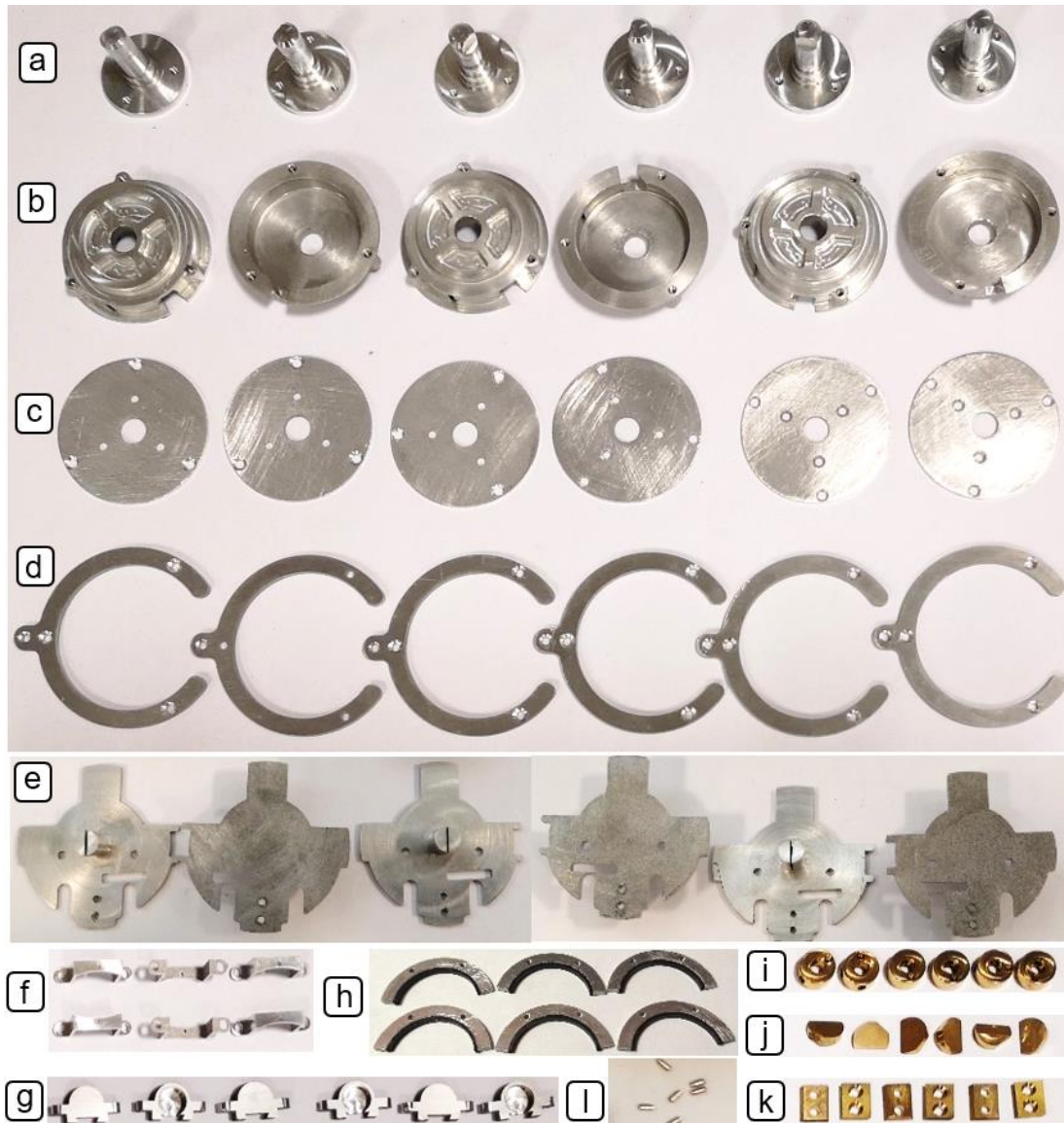


Figure A-5 Images of CNC machined parts for PRM modules: (a) rotational shaft, (b) power spring case, (c) power spring case covering plate, (d) connecting plate, (e) motor mounting plate, (f) driven gear holder, (g) unlocking guide case, (h) breaking part, (i) hard coupling, (j) unlocking guide, (k) slide guide, and (l) gear shaft.

Figure A-6 shows the assembly procedures of the second version of the physical PRM prototype: (a) insert the gear shaft through the driven gear and then glue the driven gear with the 4mm magnet, (b and c) were the bearing in the bearing holder, (d) place the magnet in the bearing, (e) were the gear shaft, and the bearing holder in the driven gear holder, (f) insert the rotary shaft bearing in the PRM case, (g) mount the miniature magnetic encoder to the circular slot and slip the encoder wires along the PRM case slot to keep it entangling with the rotational part while spinning, (h) put the driven gear set from step (e) inside the PRM case and check the installation by wearing the rotational shaft with driving gear through the rotary shaft bearing. Then, if both driving gear and driven gear rotate smoothly, the installing is suitable, (i and j) assemble the hard coupling with a ball

plunger and 2mm magnet for reed switch, (k) ware the hard coupling on the motor shaft, (l to n) mount the DC-g geared motor on the motor mounting plate by using motor bracket, (o) glue the 1mm rubber sheet which is the breaking material with the breaking part circular surface and screw the spacers on the breaking part, (p and q) assemble the breaking part with unlocking guide case and tension springs and then slice the unlocking guide along the slide guide by hooking the tension springs on the screws using for mounting the motor, (r) put the spiral power spring into the power spring case, (s) attach the driving gear with rotational shaft to the power spring case covering plate, (t) put the power spring case on the motor mounting plate and enclose with power spring case covering plate, (u and v) insert assembled rotational part into the PRM base and wire the motor and encoder signal, (w) enclose the PRM base with PRM case lid, (x) attach the plastic ball nut to the tip of 0.45mm stainless steel wire and roll the stainless steel wire, 30cm length, on the cable storage, and then ware the cable storage on the rotational shaft, and finally (v) enclose the cable storage with the lower/upper cover and connecting plate.

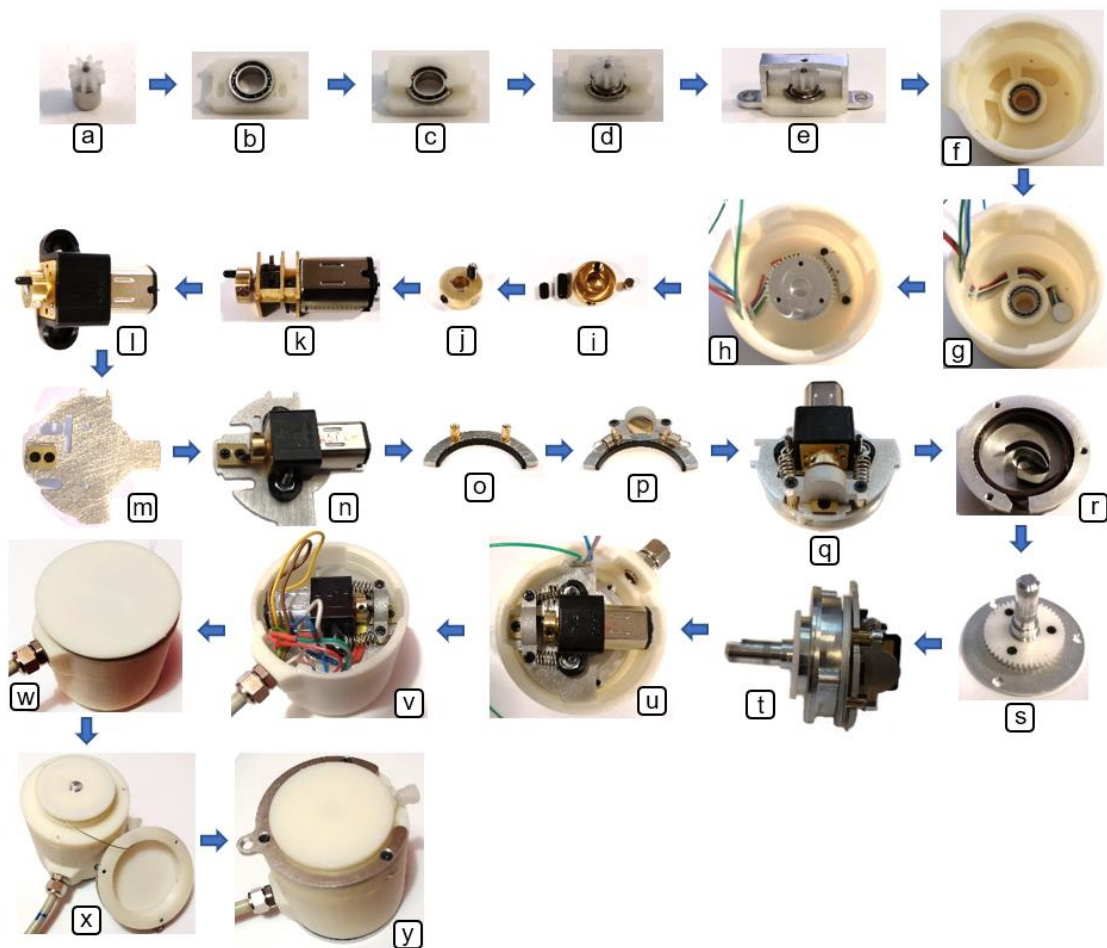


Figure A-6 Assembly procedure of the 2nd version PRM prototype.

Appendix B

B.1 Electronic Board Design and Development

B.1.1 Microcontroller Module Selection

A microcontroller module is the most important unit. It is used to control the electronics components and mechanical parts of the individual elements in order to control the robot locomotion. After searching the microcontroller boards in robotics, there are many electronics development boards with multiple features used in the robotics community such as Arduino[106], Raspberry Pi [107], BeagleBone[108] and Teensy [109]. However, Arduino and Teensy provide small size, SPI/I²C serial communications and low cost.

Table B-1 compares selected miniature electronics development boards which are Arduino Nano V3/V4/Every, Arduino Micro, Arduino Pro Mini 328-5V and Teensy 3.1/3.2. These boards are potentially and sufficiently used in this project. Arduino Pro Mini 328-5V is the cheapest and smallest; however, a USB port for programming does not be included on-board. While the Arduino micro and Arduino Nano have almost the same functionalities, but the Arduino Nano provides more current for output pin of 40mA, the smaller board size, lighter weight and lower cost. Teensy 3.1/3.2 is the best functionalities. It gives a high-speed running clock of 75 MHz which is more than four times of the rest candidate board. Also, flash memory and SRAM are large, which is beneficial for a large source code such as complex equations and control algorithms. However, the cost of the Teensy development board is more expensive than the Arduino Nano.

Based on the above analysis, Arduino Nano V4 is selected for eighteen slave control boards due to its functional and cost-effective solution. Teensy 3.2 is also chosen for a master control board because of the fast processing and large memory. The pictures of Arduino Nano V4 and Teensy 3.2 are shown in Figure B-1.

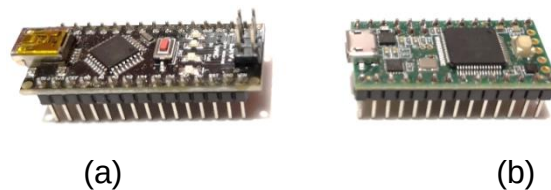


Figure B-1 Image of the selected microcontroller boards: (a) Arduino Nano V4 and (b) Teensy 3.2.

Table B-1 The comparison of miniature electronic development boards.

Boards	Arduino Nano V3/V4/Every	Arduino Micro	Arduino Pro Mini 328 - 5V	Teensy 3.1/3.2
Microcontroller	8 bit / ATmega328	8 bit / ATmega32U4	8 bit / ATmega328	32 bit /ARM Cortex-M4
Clock speed	16 MHz	16 MHz	16 MHz	72 MHz
Flash memory	32 KB	32 KB	32 KB	256 KB
SRAM	2 KB	2.5 KB	2 KB	64 KB
EEPROM	1 KB	1 KB	1 KB	2 KB
Input voltage	7 - 12V	6 - 20V	5 - 12V	3.7 - 5.5 V
Operating voltage	5 V	5 V	5 V	3.3 V
Analogue I/O pins	8	12	6	16 (share with Digital I/O pin)
Digital I/O pins	16	13	14	34 (share with Analogue pin)
Input pull up mode	Available	Available	Available	Available
PWM	6	7	6	12
I/O pin current	40 mA	20 mA	40 mA	25mA
Communication	I2C, SPI, UART	I2C, SPI, UART	I2C, SPI, UART	I2C, SPI, CAN, UART
USB Programming	mini USB	micro USB	N/A	micro USB
PCB size	18 x 45mm	18 x 48mm	18 x 33mm	18 x 35mm
Weight	6 g (with pin)	13 g	less than 2g	5 g (with pin)
Dealer / Cost (Inc. VAT)				
https://www.hobbytronics.co.uk	£10.80	N/A	£8.94	£19.20
https://www.digikey.com	£18.32	N/A	N/A	£18.22
https://uk.farnell.com	£17.28	£19.20	N/A	N/A
https://uk.rs-online.com	£17.28	£18.36	N/A	N/A
https://coolcomponents.co.uk	£10.99	£19.19	£9.22	£17.99

B.1.2 Motor Drive Module Selection

Motor drives are selected based on the operating voltage and the stall current of the selected motors. Therefore, the range of the operating voltage and the maximum output current of a motor drive is the crucial factors that need to be evaluated first. If the maximum current of a motor drive is insufficient to meet the motor needs, the motor speed and torque will be reduced and may cause the motor drive damage due to overheating. The operating voltage of the linear actuator for the strut module is 12V and the stall current of 185mA while the operating voltage of the DC-geared motor for the PRM is 6V and the stall current of 90mA. Therefore, the operating voltage and current of the motor drive employed for driving both strut element (SE) or linear actuator (LA) and PRM should be higher than the actuator power specifications. In this project, a safety factor of 2.25 is chosen for the motor drive selection [110]. Thus, the output current of the motor drive specification should be more than 416.25 mA for the linear actuator and 202.5 mA for the DC-geared motor. After searching and comparing different miniature motor drives with H-bridge and free-wheeling diodes, the MAX14870 motor drive is selected for both linear motor and DC-geared motor, as shown in Figure B-2.

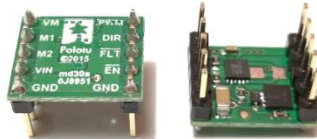


Figure B-2 Picture of the selected motor drive for both linear actuator and DC-geared motor.

B.1.3 Communication Method

In order to avoid expanding other communication devices on both master and slave control boards, the inter-integrated circuit (I²C) and the serial peripheral interface (SPI) protocols that are integrated onboard peripherals are firstly considered. Both I²C and SPI bring their advantages and limitations as communication protocols [111].

SPI bus consists of four signals for the communication: master out slave in (MOSI), master in slave out (MISO), serial clock (SCK), and active-low slave select (/SS). It provides a full-duplex bus, which allows transmitting and receiving data between master and slave devices simultaneously at rates of up to 10 Mbps. However, the disadvantage of the SPI is to require a /SS lines separately for each slave and the master control boards. It is not enough to use for eighteen slave control boards.

The I²C bus is a half-duplex, synchronous, multi-master bus requiring only two signal wires: serial data (SDA) and serial clock (SCL). It uses an addressable communication protocol that provides the master to communicate with individual slave devices by using a 7-bit or 10-bit address. The I²C ensures that the data sent is received by the slave devices. For example, in some cases, the slave device is not able to cooperate with the clock speed given by the master and needs to slow it down a little. This problem is solved automatically by the clock stretching mechanism [111]. For these communication analyses, the I²C protocol is selected for all electronics control boards because it requires only two pins (SDA and SCL) to communicate between master and slave control boards. Additionally, it gives automatic multi-master conflict handing and built-in addressing management to ensure that the data is already sent to slave devices.

B.1.4 Schematic Diagram of Electronic Control Boards

The schematic diagram of the master control board, voltage level translator, I²C multiplexer board, displacement measurement and voltage regulator modules are shown in Figure B-3.

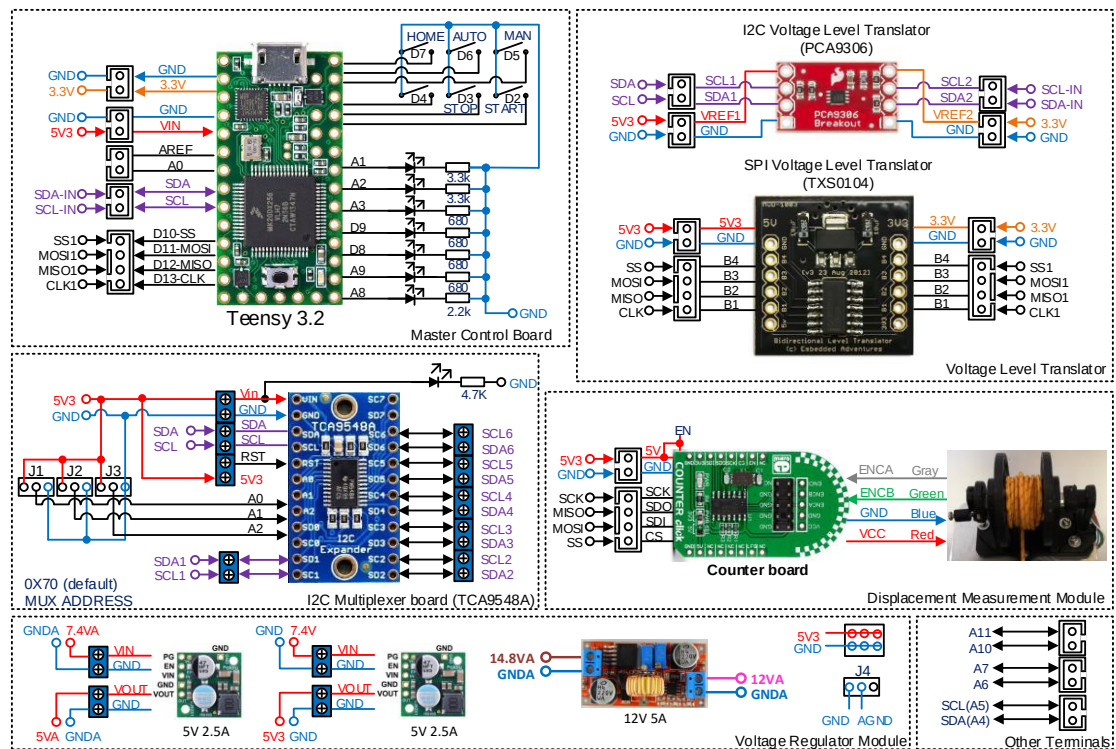


Figure B-3 Schematic diagram of the master control module, voltage level translator, I²C multiplexer board and displacement measurement and voltage regulator modules.

Figure B-4 shows the schematic diagram of the LA control board. It is designed for each LA control board, including LA-X1, LA-X2, LA-Y1, LA-Y2, LA-Z1 and LA-Z2. There are three interface modules connected to the LA control board, which

are an opto-isolator, motor drive and IMU (gyroscope and accelerometer) boards. The Arduino Nano v4 is the controller which can be coded using the Arduino IDE software to write and debug source code via USB cable.

To control the LA-slider length, the controller will generate a pulse width modulation (PWM) signal (Pin2) and a Direction signal (Pin3) to control the speed and directions of the LA slider. These signals are sent to the opto-isolator board (SparkFun opto-isolator breakout board) to separate between the control circuit (5V, GND) and the motor power circuit (5VA, GNDA). It prevents the back-electromotive force (back-EMF), which causes unstable voltage in the control circuit [112]. Although the motor drive MAX14870 integrates diodes to prevent the back-EMF effect while running the motor, the opto-isolator board will be beneficial for control circuit performance. However, the need for another power supply with a separate ground is required for the opto-isolator board.

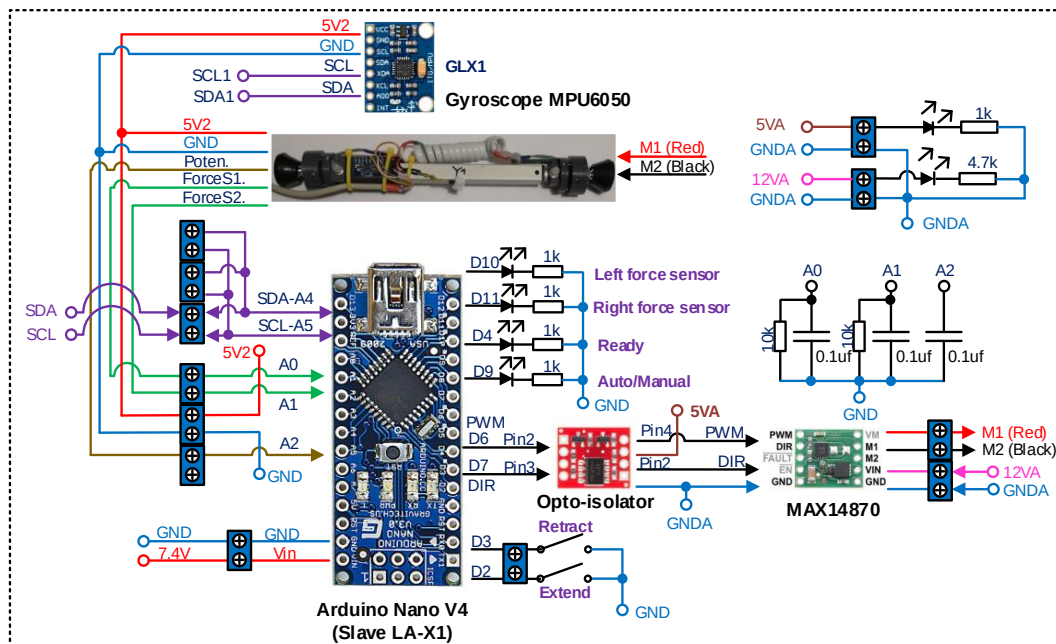


Figure B-4 Example of the schematic diagram of the LA control module.

The LA-slider length measurement can be achieved by getting the voltage generated by a potentiometer inside the linear motor. This voltage linearly changes following the slider length. The more the slider length increases, the more the potentiometer value increases. This value is sent to the analogue input pin A0 of the microcontroller to calculate the length of the LA-slider for the closed-loop control system.

The force-sensitive resistors (FSR) signal, generated from the left and right side of the LA end caps, are sensed via analogue input pin A1 and A2, respectively. However, there is analogue noise occurring in the FSR and potentiometer output

voltages, a simple low pass filter with three capacitors of 0.1uF are connected between three analogue pins (A0, A1 and A2) and ground individually.

The angle of each LA module is measured by a gyroscope board (MPU6050), which is mounted on each LA base. The I²C pins (SCL and SDA) of each MPU6050 are connected to the input ports of the I²C multiplexer board. While The I²C signals of the multiplexer board are connected to the analogue pin A4 (SDA) and A5 (SCL) of each control board parallelly.

Two microswitches are designed to control the LA-slider movement in the manual control mode. They are connected to a digital pin D2 for the extension stage and D3 for the retraction stage. The control mode, ready stage, left force sensor and right force sensor are indicated by four Light Emitting Diodes (LED), which are connected to digital output pins D9, D4, D11 and D10, respectively.

Figure B-5 details the schematic diagram of the PRM control module. This diagram is used for each PRM control board including PRM-A to PRM-L.

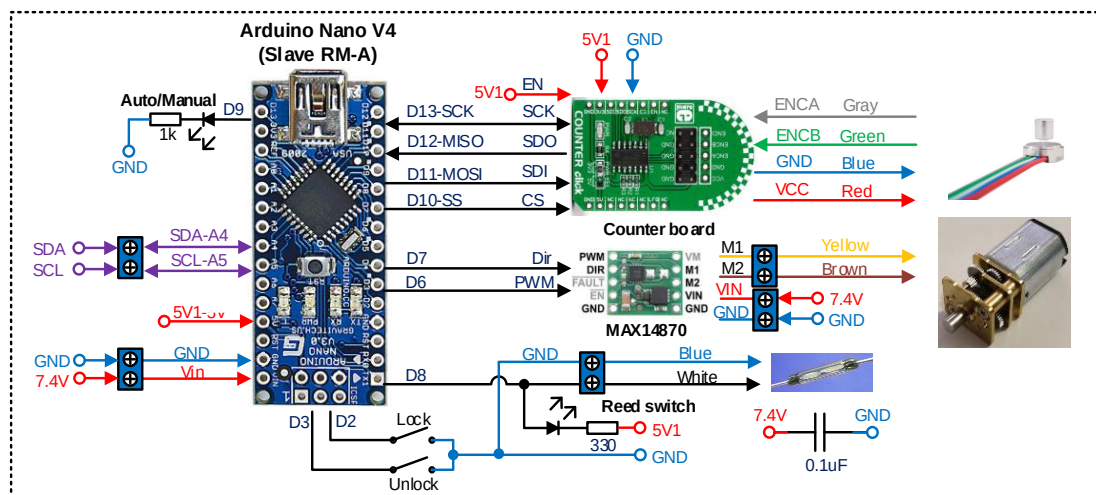


Figure B-5 Example of the schematic diagram of the PRM control module.

The Arduino Nano V4 board is used to send and receive digital signals to control the DC-gearred motor for locking and unlocking stages of the PRM mechanism. The digital pin D6 is defined to generate PWM signals to control the speed of the motor while the digital pin D7 is assigned to control the motor shaft rotations: clockwise (CW) and counterclockwise (CCW). These signals are sent to the motor drive board (MAX14870) to drive the motor for locking and unlocking stages. The digital Pin D8 is defined to sense the reed switch sensor utilised for checking the locking and home stage of the PRM as described in section 0.

The encoder counter board is used to count the encoder signal A and B generated by the miniature magnetic encoder. The digital pin D10, D11, D12 and D13 are set as the SPI communication which are CS, SDI, SDO and SCK signals,

respectively. The counter board counts the pulse A and B from the encoder automatically with the sampling time of 0.05 microseconds or 20 MHz, while the maximum frequency of the encoder is 4 MHz with a speed of 30,000 rpm, which is more than the maximum speed of the rotational part of the PRM during unlocking stage. Thus, it can ensure that every encoder pulse generated from the encoder will be counted and gathered by the encoder counter module precisely. The microcontroller will send a group of commands to communicate with the encoder counter board to get the data via the SPI bus. Two microswitches are used for controlling the locking and unlocking stage in the manual control mode for testing the locking mechanism. They are connected to the microcontroller pin D2 for the locking stage and D3 for the unlocking stage.

After designing the schematic and wiring diagram of all electronics boards, all electronics control and interface boards are developed and wired.

Figure B-6 shows the picture of six LA electronics control boards that are used to control the LA-slider lengths. The example of connection details is also identified in the pictures.

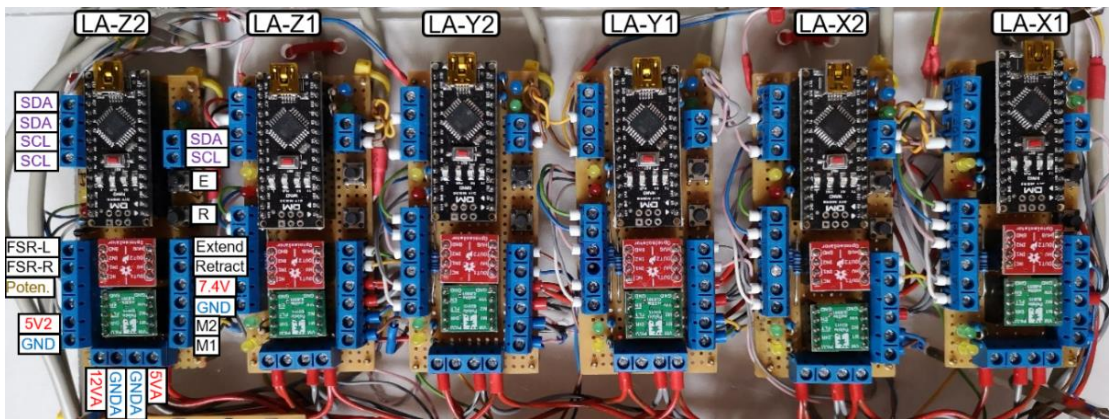


Figure B-6 Image of six LA electronics control boards used for a local closed-loop of the LA-slider length.

Figure B-7 shows the first version prototypes of six-PRM electronics control boards utilised to locally control the locking/unlocking stages of the PRM-A to PRM-F. Also, the example of the wiring label is indicated in the picture.

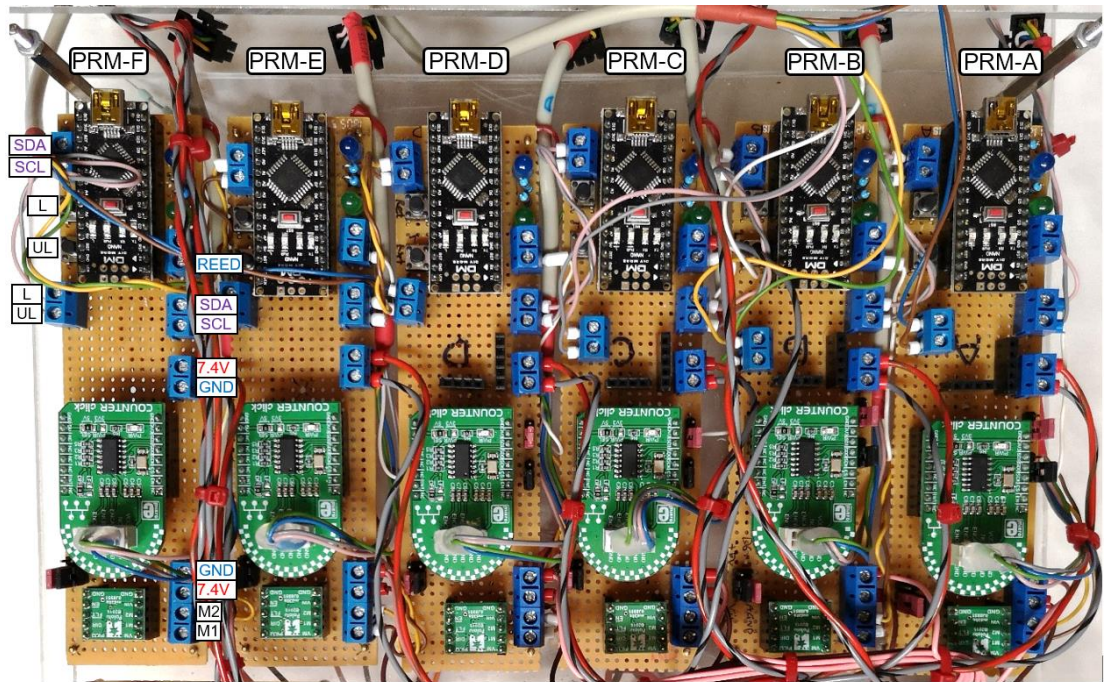


Figure B-7 Image of the first version prototypes of six-PRM electronics control boards used for local closed-loop control for PRM-A to PRM-F.

Figure B-8 shows the second version prototypes of the PRM electronics boards used to control the locking/unlocking stages of the PRM-G to PRM-L. They are developed for spare parts and the other designs of different robot structures and experimentations to prove and validate the fundamental movement. The schematic diagram of these boards is the same as the first version. However, some components are rearranged to reduce the board size.

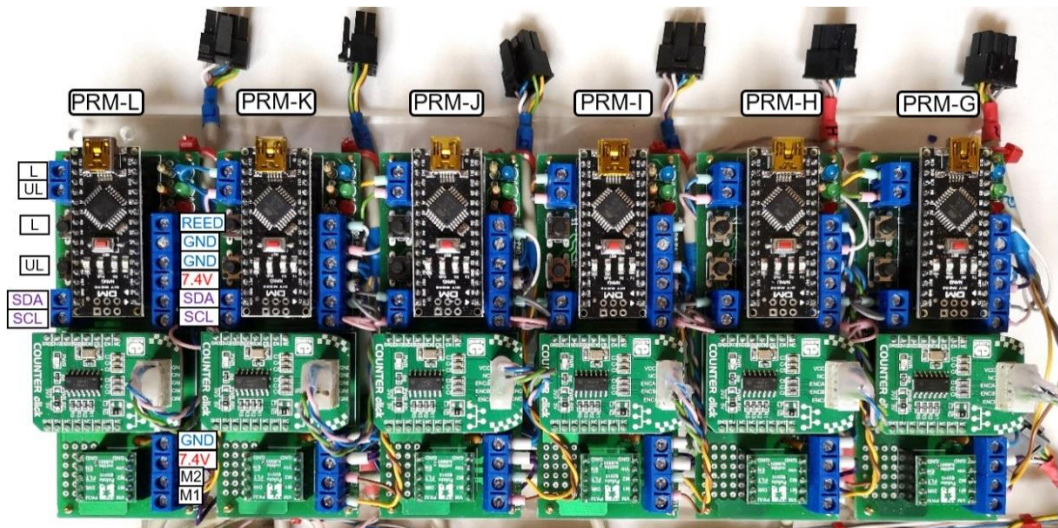


Figure B-8 Image of second prototypes of the PRM electronics control boards used for controlling the PRM-G to PRM-L.

Figure B-9 shows the master control board, displacement measurement board, I²C multiplexer board, voltage level translator boards and power supply boards.

Additionally, key interface boards are developed for controlling all individual elements in the manual control mode in order to initially test the movement behaviour concept of the proposed deformation technique using the locking/unlocking stage of the PRM while extending/retracting the LA-slider lengths. The schematic diagram of the key interface boards is not detailed because all switches are just paralleled with micro switches alongside the microcontroller in each control board.

In order to connect signals between the LA and PRM prototypes and the electronics control board easily, the Molex Micro-Fit 3.0 female and male connectors are used. The details of various connector pins for the LA modules and PRM modules are shown in Figure B-10 and Figure B-11, respectively.

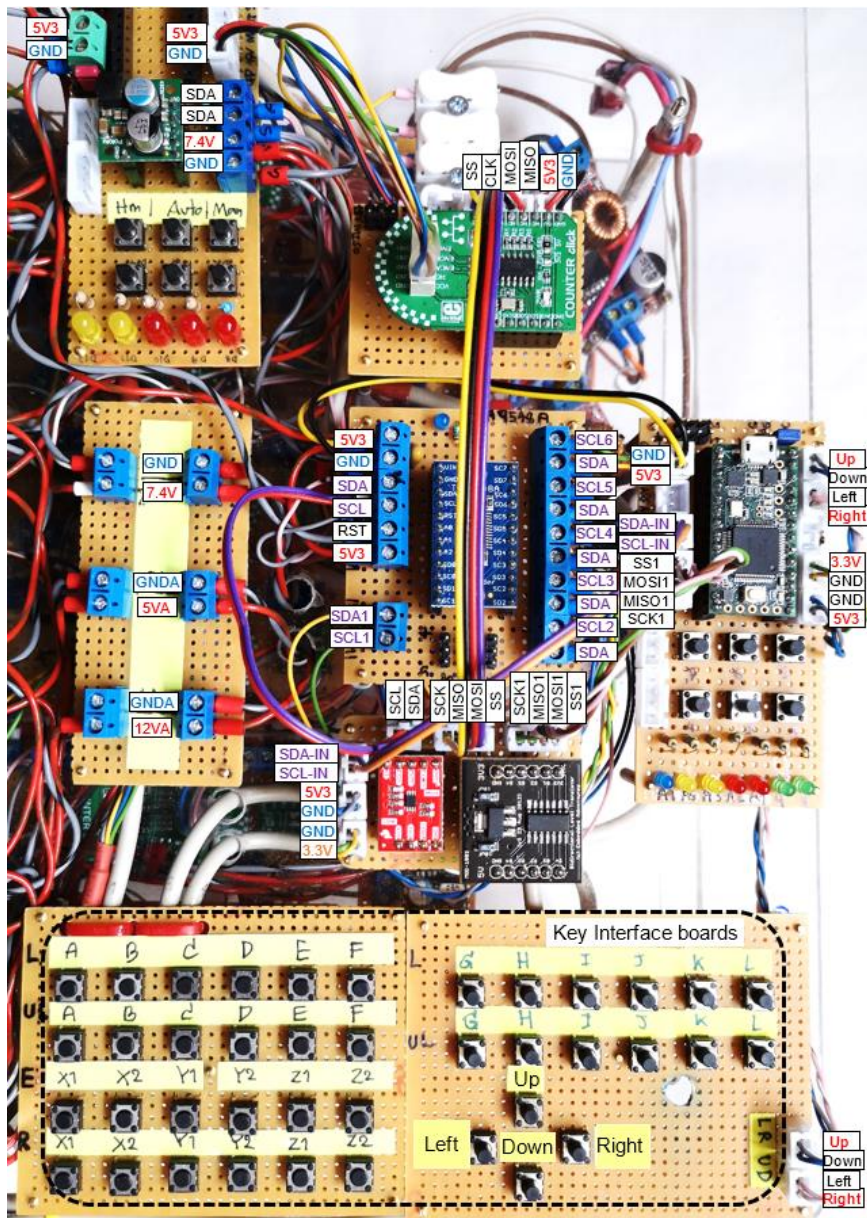


Figure B-9 Prototype of the master control board, voltage level translator, power regulator, I²C multiplexer and cable length measurement.

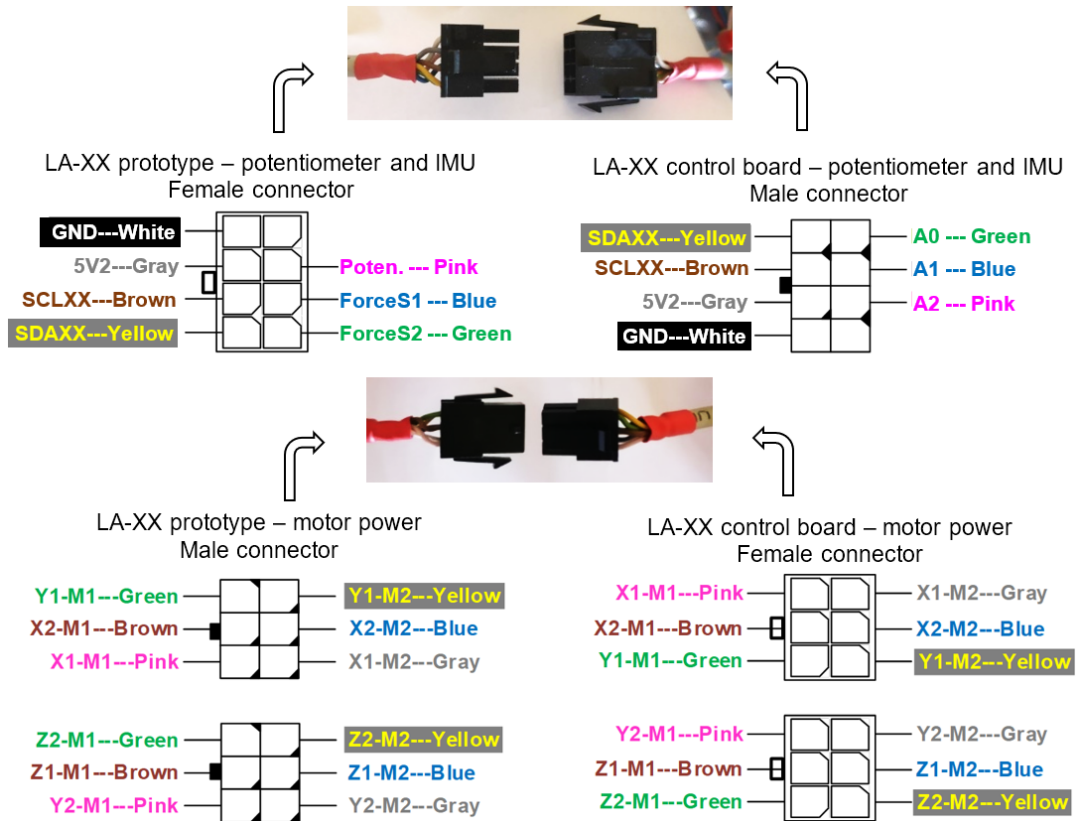


Figure B-10 Connector details between the LA module and control board.

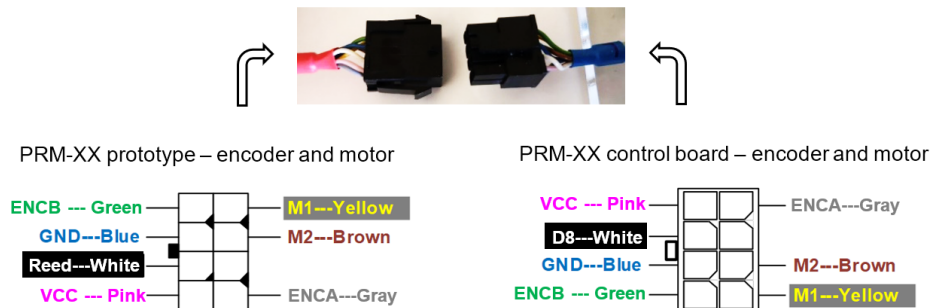


Figure B-11 Connector details between the PRM module and control board.

Appendix C

C.1 LA-slider Displacement Scaling

The slider displacement mapping consists of two steps. First, the initial and full extension lengths of the LA slider are measured by a commercial-linear-scale measurement with 0.01mm resolution and ± 0.1 mm accuracy. Concurrently, a microcontroller is used to gather the potentiometer output voltages and convert them to 10-bit data (0-1023) via the ADC module. Second, a mapping function of the microcontroller is used to convert the 10 bits data to the slider displacement (0 – 100mm). Finally, the slider displacements are calculated and sent to the controller module. The diagram of the slider displacement mapping is shown in Figure C-1.

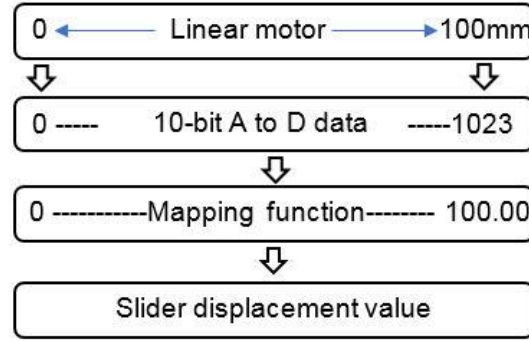


Figure C-1 Process diagram of the slider displacement mapping.

The following equation can calculate the mapping equation between input and output data:

$$D_{out} = \frac{(D_{in} - In_{min})(Out_{max} - Out_{min})}{(In_{max} - In_{min})} + Out_{min}, \quad (C-1)$$

where the D_{out} is the slider displacement output, D_{in} is the raw data input 10-bit gathered by ADC module, In_{min} is the minimum data input 10-bit, In_{max} is the maximum data input 10-bit, Out_{min} is the minimum slider displacement output and Out_{max} is the maximum slider displacement output. The unit of all slider displacement parameters is millimetres.

However, the minimum and maximum slider displacements of each LA are not equal to 0mm and 100mm, and the minimum and maximum data input 10-bit are not equal to 0 and 1023. It is because the voltages of the potentiometer of each LA are not equal to 0 volt (minimum) and 5 volts (maximum). Therefore, these essential parameters should be measured experimentally to substitute their value in Equation (C-1). The summary of the minimum and maximum values of the

potentiometer voltage, raw data 10-bit and physical slider displacement of six LA modules are shown in Table C-1.

Table C-1 Summary of six-LA experimental data.

LA	minimum length			Maximum length			Single-step distance (mm per step)	Single-step voltage (voltage per step)
	Slider length (mm)	10-bit raw data	P* output (voltage)	Slider length (mm)	10-bit raw data	P* output (voltage)		
X1	0	8	0.05	99.94	1013	4.98	0.09866	0.004916
X2	0	9	0.05	99.85	1014	4.92	0.09847	0.004852
Y1	0	12	0.07	100.12	1013	4.91	0.09884	0.004847
Y2	0	8	0.05	100.03	1013	4.82	0.09875	0.004758
Z1	0	8	0.05	100.12	1012	4.94	0.09893	0.004882
Z2	0	14	0.08	100.02	1014	4.88	0.09864	0.004813

P* is the potentiometer output voltage

The slider length errors occur inevitably in the scaling process because of the 10-bit data limitations. For example, in the LA-X1 module, the stroke of the LA is 99.94mm, and the maximum data read from the ADC is 1013; therefore, the single-step distance (STD) per one data change can be calculated by the following formula:

$$STD = \frac{(Sl_{max} - Sl_{min})}{Data_{max}} = \frac{(99.94 - 0)}{1013} = 0.09866, \quad (C-2)$$

where Sl_{max} is the maximum slider length (mm), Sl_{min} is the minimum length or initial slider length (mm) and $Data_{max}$ is the maximum 10-bit data. This STD data also identify the minimum-constant error of the slider length, where the microcontroller can read from the potentiometer. It means that if the slider moves shorter than 0.09866mm mechanically, the microcontroller would not be able to measure this length. Therefore, the error of the LA-X1 slider movement is ± 0.09866 mm or ± 0.1 mm approximately.

C.2 The summary data of the LA-Y1, LA-Y2, LA-Z1 and LA-Z2

Table C-2 Summary of the LA-Y1 and LA-Y2 slider accuracy experiments.

Linear scale length (mm)	Linear actuator module: Y1		Linear scale length (mm)	Linear actuator module: Y2	
	Slider length (mm)	Length error (mm)		slider length (mm)	Length error (mm)
0	0	0	0	0	0
5.02	4.9	-0.12	5.04	4.78	-0.26
10.01	9.8	-0.21	10	9.75	-0.25
15.01	14.8	-0.21	15	14.63	-0.37
20	19.7	-0.3	20	19.51	-0.49
25.03	24.9	-0.13	25.01	24.29	-0.72
30.02	30.31	0.29	30.02	29.06	-0.96
35	35.31	0.31	35	33.74	-1.26
40.04	40.71	0.67	40.01	38.72	-1.29
45.04	46.01	0.97	45.01	43.5	-1.51
50	50.81	0.81	50.01	48.27	-1.74
55.06	55.71	0.65	55.06	53.35	-1.71
60.02	60.51	0.49	60	58.43	-1.57
65	65.31	0.31	65	63.7	-1.3
70.02	70.21	0.19	70.04	68.68	-1.36
75	75.12	0.12	75.01	73.85	-1.16
80.02	80.22	0.2	80.08	79.23	-0.85
85.01	85.32	0.31	85.01	84.4	-0.61
90.05	90.42	0.37	90.03	89.68	-0.35
95.03	95.12	0.09	95	94.85	-0.15
100.01	100.02	0.01	100	99.93	-0.07

Table C-3 Summary of the LA-Z1 and LA-Z2 slider accuracy experiments.

Linear scale length (mm)	Linear actuator module: Z1		Linear scale length (mm)	Linear actuator module: Z2	
	Slider length (mm)	Length error (mm)		slider length (mm)	Length error (mm)
0	0	0	0	0	0
5	4.89	-0.11	5.01	5.04	0.03
10	9.47	-0.53	10.04	10.29	0.25
15	14.26	-0.74	15.03	14.96	-0.07
20	19.45	-0.55	20.01	20.42	0.41
25	24.53	-0.47	25.03	25.26	0.23
30	29.32	-0.68	30.01	29.93	-0.08
35.03	34.1	-0.93	35.02	35.38	0.36
40.05	39.09	-0.96	40.02	40.5	0.48
45.01	44.08	-0.93	45.01	45.15	0.14
50	49.06	-0.94	50.02	50.42	0.4
55.02	54.25	-0.77	55.03	55.75	0.72
60.04	59.53	-0.51	60.02	60.36	0.34
65.01	64.72	-0.29	65.02	65.58	0.56
70.02	69.8	-0.22	70	70.94	0.94
75.03	74.99	-0.04	75	75.29	0.29
80.03	80.38	0.35	80.03	80.45	0.42
85	85.36	0.36	85.01	85.61	0.6
90	90.35	0.35	90.01	89.95	-0.06
95.01	95.23	0.22	95.02	95.14	0.12
100.01	100.02	0.01	100.02	99.82	-0.2

C.3 Proportional Gain Finding for Close-Loop Control

According to the closed-loop control with the P-controller block diagram, the proportional gain of the P-controller can be calculated by the following formulas.

$$G_c(s) = K_p. \quad (\text{C-3})$$

$$U(s) = K_p E_c(s), \quad (\text{C-4})$$

where K_p is the proportional gain, E_c is the position error and U_p is the control signal. To determine the proportional gain (K_p), the second method of Ziegler-Nichols rules is employed [104]. The K_p is increased from 0 to a critical value $K_{p_{cr}}$ until the output first sustained oscillations, as seen in Figure C-2. Thus, the critical gain K_{cr} and the corresponding period P_{cr} are experimentally obtained as 2500 and 0.13 seconds, respectively. From the Ziegler-Nichols tuning rule in the second method, the values of the parameters K_p can be calculated using the formula in Table C-4.

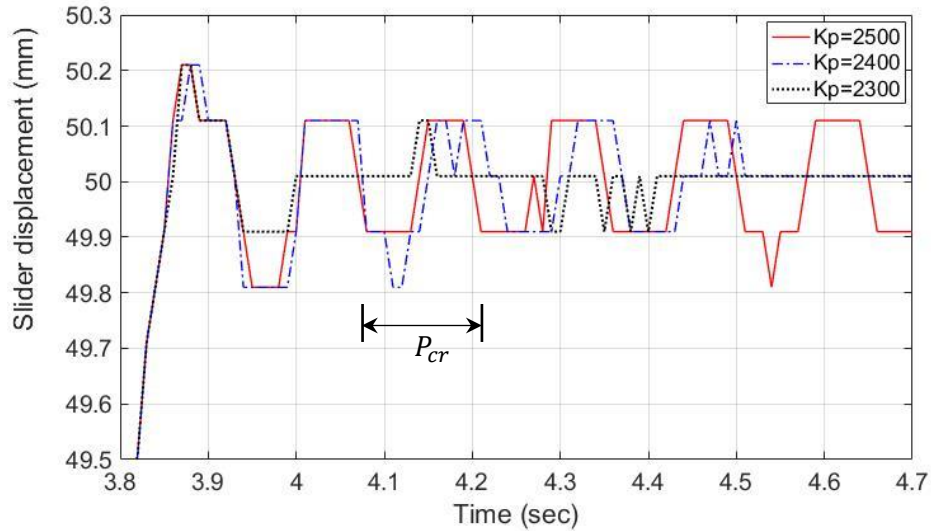


Figure C-2 Oscillation signal response.

Table C-4 Ziegler-Nichols tuning rule [104].

Controller type	K_p	T_i	T_d
P	$0.5K_{cr}$	∞	0
PI	$0.45K_{cr}$	$1/2P_{cr}$	0
PID	$0.6K_{cr}$	$0.5P_{cr}$	$0.125P_{cr}$

Therefore, the proportional gain of the P-controller can be calculated as

$$K_p = 0.5 * 2500 = 1250 \quad (\text{C-5})$$

The calculated proportional gain is then initially used for closed-loop control implementations. The P-controller with K_p of 1125 is used to control the LA slider travelling from 0mm to 50mm. There are small values of the maximum per cent

overshoot (MP) of 0.22%, steady-state error ($e_{s.s}$) of 0.01mm, and settling time (t_s) (2% of the target position) of 3.79 seconds.

To eliminate the MP, the K_p is tuned by the trial-and-error method experimentally. First, the LA slider displacement is controlled using P-controller with the K_p of 1000 and then decrease 100 values for the next experiments until the LA slider travelling to target positions without MP. Second, the K_p is adjusted around the K_p gain, where the MP does not occur increasing or decreasing the K_p of 50 values. Eventually, the proper K_p gain is obtained. The desired target distance for the LA slider is 50mm due to the middle length of the maximum LA slider stroke. It is controlled to move from 0 to 50mm downwards and 50mm to 10mm upwards. The experimental results are shown in Figure C-3.

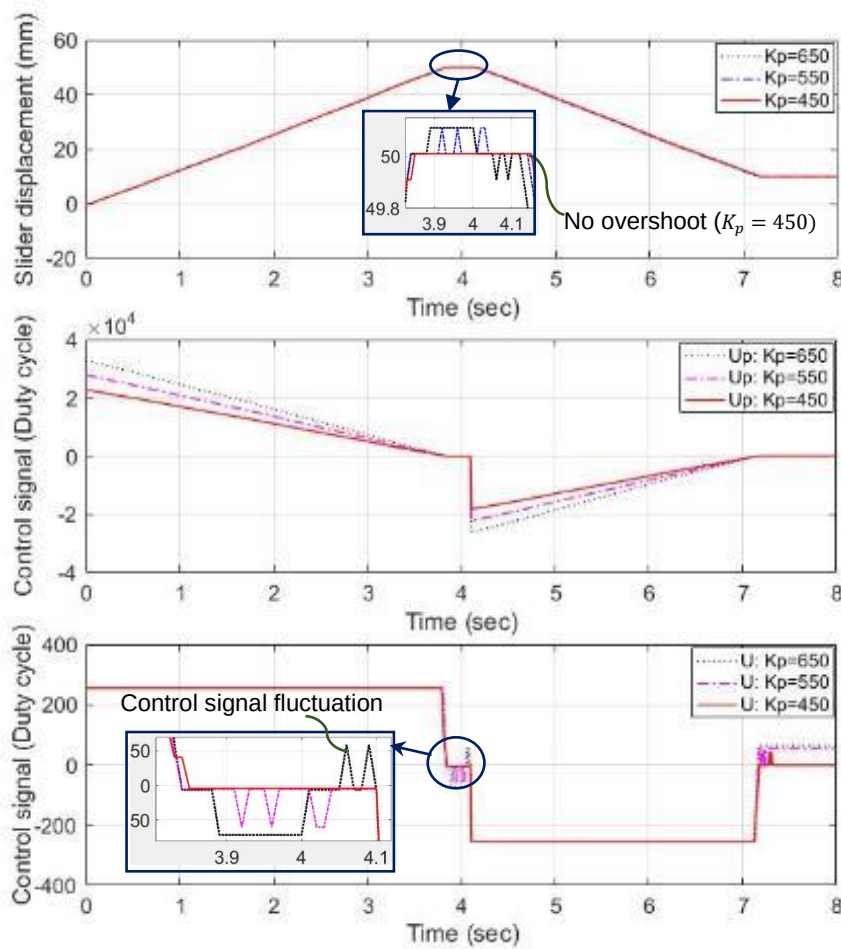


Figure C-3 Proportional gain (K_p) tuning experimentations: (top) LA slider position, (middle) the proportional control signal (u_p) and (bottom) the control signal (u) sending to the LA motor drive.

The experimental results suggest that the MP is eliminated when the K_p reduces to 450, as shown in Table C-5. The steady-state error does not occur in upwards movement, but it slightly occurs around 0.01mm in downwards movement. In this

result, it is acceptable that this error value does not significantly affect the structure configurations.

For the control signal, the P control signal (u_p) and the control signal (u) are the same signals, but the control signal (u) is restricted at ± 255 due to the maximum and minimum values of the PWM module which generated 0 – 100% of duty cycle to drive the LA motor (see Figure C-3(bottom)). However, the proportional control signal (u_p) does not restricted to allow the proportional controller to calculate the control signal (u_p) unboundedly, as shown in Figure C-3 (middle). Henceforth, the proportional control signal (u_p) is only shown as the control signal of the closed-loop control system to show how the P-controller generated the signal for controlling the LA slider movements. Additionally, it is observed that the control signal (u) is fluctuated around the target positions, as illustrated inside the blue ellipse (see Figure C-3 (bottom)). It is because that the potentiometer generates unexpected output voltage like electrical noise to change the LA slider position resulting in the target error occurring in the system. The P controller, therefore, produces control signals to compensate for the target error. However, the electrical noise happens very quickly around 10ms, which does not significantly affect the LA slider movements.

Table C-5 Experimental result example for the proportional gain (K_p) tuning implementations to control the LA slider travelling from 0 to 50mm downwards and 50mm to 10mm upwards.

K_p gain	p_{ref} (mm)	Steady-state position ($p_{s,s}$) (mm)	t_s (sec)	$e_{s,s}$ (mm)	M_P (mm)	M_P (%)
1125	0 to 50	50.01	3.79	0.01	0.11	0.22
	50 to 10	9.9	3.04	0.1	0	0
1000	0 to 50	50.01	3.79	0.01	0.11	0.22
	50 to 10	9.9	3.05	0.1	0	0
650	0 to 50	50.01	3.76	0.01	0.11	0.22
	50 to 10	9.9	3.03	0.1	0	0
550	0 to 50	50.01	3.76	0.01	0.01	0.22
	50 to 10	9.9	3.04	0.1	0	0
450	0 to 50	50.01	3.76	0.01	0	0
	50 to 10	10	3.05	0	0	0
300	0 to 50	50.01	3.78	0.01	0	0
	50 to 10	10	3.08	0	0	0

C.4 Inconstant-Force Payload Experiments

This section details displacement control of the slider of a linear actuator (LA) when carrying an inconstant-force payload of 0.17N/mm and 0.83 N/mm.

In this experiment, two target position groups are defined for the multiple-step implementations. First, the target distances are 0 to 10mm, 10mm to 30mm and 30mm to 60mm in downwards movements and 60mm to 45mm, 45mm to 15mm

and 15mm to 5mm in upwards movements. The 0.17N/mm extension spring is used to generate the compressive forces. The P-controller with the proportional gain K_p of 450 is used to control the LA slider displacement. The experimental results of the first multiple-step group are shown in Figure C-4 and summarised in Table C-6.

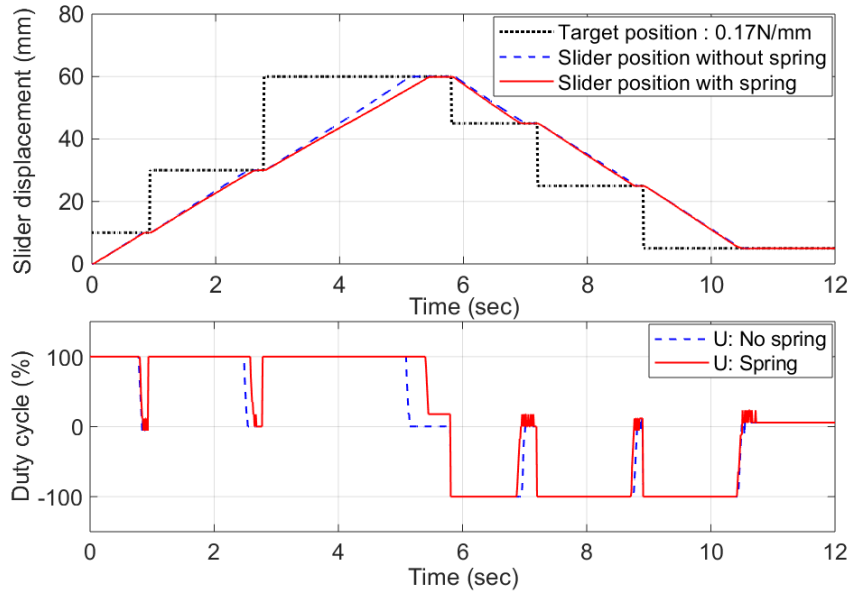


Figure C-4 Multiple-step response of the LA slider moving to the target positions with 0.17 N/mm extension spring payload: (top) the slider position and (bottom) the proportional control signal (u_p).

Table C-6 Experimental result summary of the multiple-step response of the LA slider movement with 0.17 N/mm extension spring payload.

Spring value (N/mm)	Direction	p_{ref} (mm)	$p_{s.s}$ (mm)	t_s (sec)	$e_{s.s}$ (mm)
0	Downwards	0 to 10	10.03	0.82	-0.03
0.17			10.03	0.83	-0.03
0		10 to 30	30	1.54	0
0.17			30	1.64	0
0		30 to 60	60	2.27	0
0.17			59.9	2.57	0.1
0	Upwards	60 to 45	45	1.12	0
0.17			45	1.04	0
0		45 to 25	25.03	2.95	-0.03
0.17			24.93	1.52	0.07
0		25 to 5	4.97	1.57	0.03
0.17			4.97	1.56	0.03

Second, the target distances are 0 to 5mm, 5mm to 15mm and 15mm to 25mm in downwards movements, and 25mm to 20mm, 20mm to 10mm and 10mm to 0 in upwards movements. The 0.83N/mm extension spring is utilised to produce the compressive forces which vary on the spring elongation. The experimental results of the third-multiple-step group are illustrated in Figure C-5 and summarised in Table C-7.

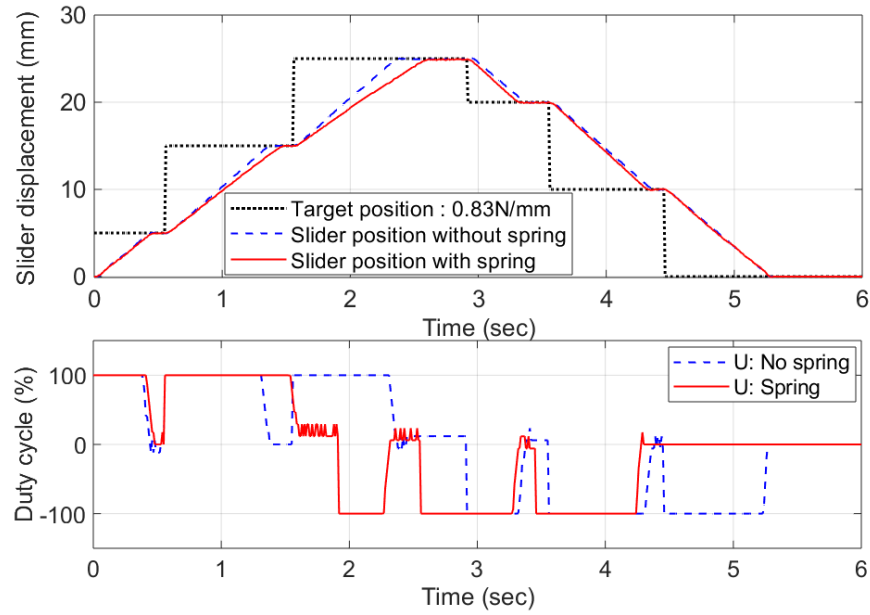


Figure C-5 Multiple-step response of the LA slider moving to the target positions with 0.83 N/mm extension spring payload: (top) the slider position and (bottom) the proportional control signal (u_p).

Table C-7 Experimental result summary of the multiple-step response of the LA slider movement with 0.83 N/mm extension spring payload.

Spring value (N/mm)	Direction	p_{ref} (mm)	$p_{s.s}$ (mm)	t_s (sec)	$e_{s.s}$ (mm)
0	Upwards	0 to 5	4.97	0.43	0.03
0.83			4.97	0.45	0.03
0		5 to 15	15	0.78	0
0.83			15	0.88	0
0		15 to 25	24.93	0.76	0.07
0.83			24.93	0.99	0.07
0	Downwards	25 to 20	19.97	0.42	0.03
0.83			19.97	0.36	0.03
0		20 to 10	10.03	0.78	-0.03
0.83			10.03	0.74	-0.03
0		10 to 0	0	0.8	0
0.83			0	0.8	0

The results reveal that the P-controller is able to control the LA-slider displacement when carrying inconstant-force payloads. The system has very small steady-state errors and without per cent overshoot.

C.5 Force Sensor Scaling Procedure

The first experiment involves finding a suitable location of the pressing tip. Nine locations on the circular active area are defined from point A to point I, as illustrated in Figure C-6 (a). Then, the pressing plate, which includes a pressing tip on the backside, is made by a Polylactic Acid (PLA) filament with a 3D printing

machine. The dimension of the pressing tip is 3mm in diameter and 3mm in height. For protecting the FSR surface, a 1mm-thickness rubber sheet is attached to the pressing tip (see Figure C-6(b)). The payload weight 100g or 0.98 Newton is employed to generate the physical pressures, which press on the FSR circular active areas at the nine locations. In this case, the pressing plate weight is neglected due to the lightweight part. The experimental results of the pressing tip location finding are summarised in Table C-8.

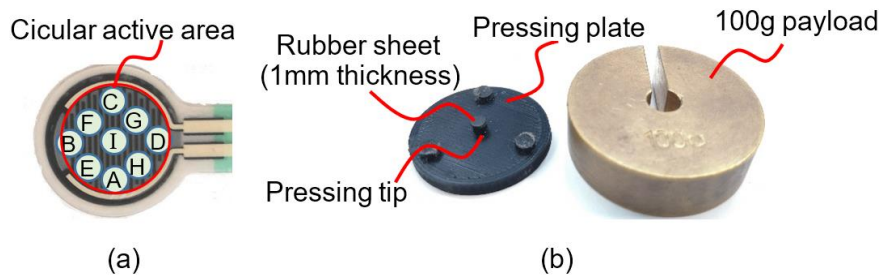


Figure C-6 Pressing tip location finding components: (a) positions of testing components and (b) pressing tip and 100g payload.

Table C-8 Experimental result summary of the pressing FSR position.

Pressing Positions	FSR (kilo ohm)
A	80.6
B	77.8
C	97
D	126
E	90
F	94.4
G	97
H	97.5
I	64

The results suggest that the pressed location “I”, which is a centre of the FSR active area, provides the lowest resistance of 64 Kilo ohm. Therefore, it is defined as the best position to press the pressing tip on the FSR active areas.

Another experiment involves finding a suitable diameter size of the pressing tip that is used to press on the FSR active areas appropriately. Different diameter sizes of the pressing tips are made, which are 3mm to 12mm. The payload weights between 20g to 2kg or 0.2N to 20N are utilised to produce physical pressure in this experiment. This payload weight range is defined based on the force-sensitive range of the selected FSR [92]. The eleven different diameter sizes of the pressing tip and the example of the payloads are shown in Figure C-7.

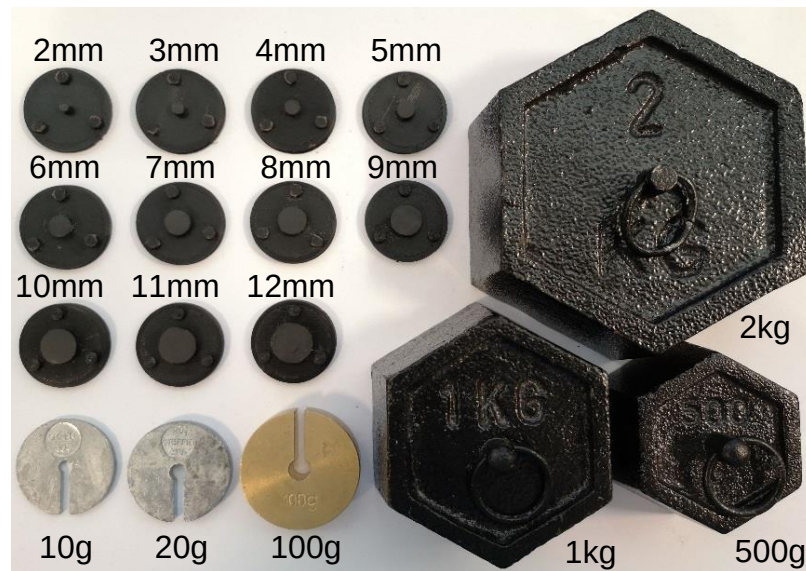
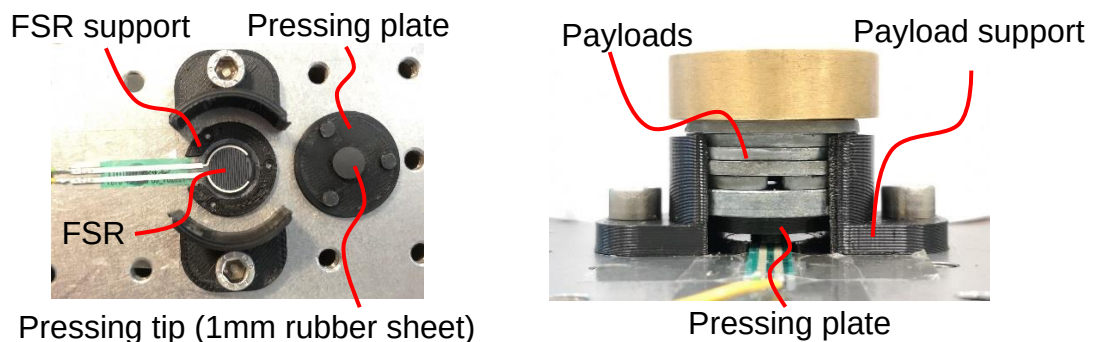


Figure C-7 Components for testing the FSR.

For making the experiment reliable, the FSR is attached to FSR support and fixed on a backplane (see Figure C-8(a)). Additionally, payload supports are used to maintain the payloads put on the pressing plate stably (see Figure C-8(b)). Also, the payload supports can force the pressing pin in the centre of the FSR active area.



(a) Pressing force testing equipment (b) Pressing force-generating method

Figure C-8 Pressing force demonstration equipment and method

A digital multimeter is used to measure the FSR resistance that is varied from the payload weight pressing on the FSR active area. The example of the force-resistance characteristic demonstration is shown in Figure C-9, and the FSR resistance characteristic experimental result is summarised in Table C-9.

In order to calculate the FSR output voltage, a voltage divider circuit for the FSR is shown in Figure C-10, and it can be calculated by Equation (C-6).

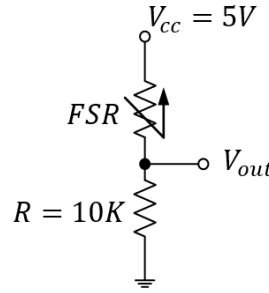


Figure C-10 The basic FSR schematic diagram.

$$V_{out} = V_{CC} \left(\frac{R}{R + FSR} \right) \quad (C-6)$$

This FSR output voltage relates to the force value [93] depending on how much pressure applying to the active area. The more pressure is applied, the more FSR voltage is generated due to the less resistance value. However, after initially testing the force value accuracy using the force and resistance characteristic graph in [93], the force value does not match the pressing forces practically due to some unexpected and unknown parameters.

In order to find a suitable solution, it can be assumed that the FSR output voltage (V_{FSR}) relates to the pressing force caused by the payload weight. Therefore, the FSR pressing force can be calibrated using the relationship between the measured FSR output voltage and the theoretical pressing force (F_{p1}), which relates to the payload weight. The procedure of the pressing force scaling is described below.

First, the theoretical pressing forces (F_{p1}) are calculated by the following formula:

$$F_{p1} = mg, \quad (C-7)$$

where m is the mass or weight of the payload (kg) and g is the gravity (9.8 m/s^2). The weights of the payloads are defined as 30g to 2kg, based on the force-sensitive range gathered from the pressing tip size experiments. Then, the referent pressing forces of each payload weight are shown in the third column of Table C-10.

The second step is to measure the FSR output voltage (V_{FSR}) by a digital multimeter. The different payload weights are put on the pressing plate to press the FSR active area. At the same time, the FSR output voltage is measured and gathered, as summarised in the second column of Table C-10.

Table C-10 FSR scaling parameters and experimental results.

Payload (m) (g)	Reference value and calculated data					Experimental data		
	V_{FSR} (V)	F_{p1} (N)	K_F	D_{dout}		D_{dout}	F_{p2} (N)	F_{p3} (N)
				Lower range	Upper range			
30	0.177	0.294	0.001661	0	190	179	0.29	0.25
40	0.342	0.392	0.001146	191	334	334	0.38	0.47
50	0.525	0.49	0.000933	335	518	518	0.48	0.6
60	0.735	0.588	0.0008	519	732	732	0.57	0.74
70	0.84	0.686	0.000817	733	842	842	0.69	0.76
80	0.92	0.784	0.000852	843	917	917	0.78	0.77
90	1.139	0.882	0.000774	918	1141	1141	0.88	0.82
100	1.225	0.98	0.0008	1142	1226	1226	0.98	0.92
200	1.54	1.96	0.001273	1227	1900	1550	1.97	2.05
300	1.946	2.94	0.001511	1901	2320	1949	2.95	2.98
400	2.5	3.92	0.001568	2321	2600	2522	3.96	4.01
500	2.73	4.9	0.001795	2601	2771	2771	4.97	4.8
600	2.86	5.88	0.002056	2772	2891	2891	5.94	5.75
700	2.924	6.86	0.002346	2892	2961	2961	6.95	6.78
800	2.988	7.84	0.002624	2962	3026	3026	7.94	7.81
900	3.022	8.82	0.002919	3027	3110	3056	8.92	8.95
1000	3.094	9.8	0.003167	3111	3160	3130	9.91	9.89
1500	3.223	14.7	0.004561	3161	3280	3270	14.91	15.13
2000	3.313	19.6	0.005916	3281	3360	3355	19.85	20.18

The third step is to convert the FSR output voltage (V_{FSR}) to the FSR output voltage data (D_{dout}). While demonstrating the second step, the FSR output voltage is sent to the ADC pin in the control board and converted to the FSR 10-bit data (D_{vin}). After that, the FSR 10-bit data is scaled, covering a range of the FSR output voltage data using the following mapping function:

$$D_{dout} = \frac{(D_{vin} - In_{vmin})(Out_{dmax} - Out_{dmin})}{(In_{vmax} - In_{vmin})} + Out_{dmin}, \quad (C-8)$$

where D_{dout} is the FSR voltage data output (0 to 5100, meaning 0v to 5.1v), D_{vin} is the FSR data 10-bit gathered by ADC module, In_{vmin} is the minimum FSR data 10-bit (always zero), In_{vmax} is the maximum FSR data 10-bit (always 1023), Out_{dmin} is the minimum FSR voltage data output (always zero) and Out_{dmax} is the maximum FSR voltage data output (always 5100, which is the FSR power supply (5.1V)). Then, the FSR voltage data output (D_{dout}) of each payload weights are gathered in the experimental data, as shown in the seventh column of Table C-10. However, it is observed that the increased rate of the FSR voltage data and the payload weights do not linear.

Therefore, the fourth step is to compute an additional gain (K_F) that is used to multiply by the FSR voltage data to calculate the calculated-actual pressing force

(F_{p2}). Thus, the additional gain (K_F) of each payload weight and the actual pressing force can be calculated by the following equations:

$$K_F = \frac{F_{p1}}{V_{FSR}} \quad (C-9)$$

and

$$F_{p2} = K_F D_{dout} \quad (C-10)$$

Moreover, another unexpected issue occurs during a repetitive demonstration. The FSR voltage data (D_{dout}) are a bit different, comparing to other experiments, even though the same payload weight presses the FSR. It is because the pressing tip, which touches on the FSR active area, is not the same position and angle in each repetitive experiment. This situation will happen inevitably in practical applications.

Therefore, in order to calculate the FSR pressing force correctly, the FSR voltage data (D_{dout}) needs to be classified by the upper and lower range to be multiplied by the suitable additional gain (K_F). Thus, the upper and lower range of the FSR voltage data in each payload weight can be found experimentally using the first demonstration of the FSR voltage data, as detailed in the fifth and sixth columns of Table C-10.

For example, If the 1000g payload presses the FSR active area, the FSR voltage data output (D_{dout}) will be calculated by Equation (C-8), which is 3130 (green highlighting in Table C-10.). After that, the data output (D_{dout}) is verified by the lower and upper range. In this case, the data output (D_{dout}) is within the range of 3111 and 3160 (blue highlighting in Table C-10). Thus, the data output is multiplied by 0.003167 (yellow highlighting in Table C-10.). Eventually, the actual pressing force (F_{p2}) is calculated as 9.91N (orange highlighting in Table C-10). The rest experimental results of the actual FSR pressing force pressed by different payload weights are shown in the eighth column in Table C-10. The last column is the results of the repetitive experiment for the FSR pressing force (F_{p3}).

From the experimental result, it is evaluated that the proposed pressing force scaling method could be used to calculate the physical pressure pressing on the FSR to detect the pressing stage of an environmental surface. Also, the pressing tip and pressing plate size will be employed, attaching to other parts of the end cap.

Appendix D

D.1 Braking Delay Time Compensation

This section describes the braking delay time compensation for the PRM. To restrict the cable at the desired length is one of the challenging tasks. The delay time of the braking parts occurs during the locking stage because the braking mechanisms cannot restrict the rotational parts suddenly after receiving the locking command. A DC-geared motor can rotate the locking guide with the maximum speed of 31.4 rpm with constant times between 0.5 and 0.8 seconds depending on the responding time of the braking parts in each PRM, as shown in Table D-1.

Table D-1 Braking delay time of all (PRMs)

	PRM-A	PRM-B	PRM-C	PRM-D	PRM-E	PRM-F
Braking delay time	0.5s	0.6s	0.5s	0.6s	0.7s	0.8s

These delay times cause the locked-cable length error (e_{CRM}). These errors also depend on spooled-cable speeds (v_{CRM}). Therefore, the relationship between the spooled-cable speeds and the locked-cable length error should be investigated doing the experimentation.

A simple structure is built for this experiment. A LA module is used to spool the cable of a PRM module. An extension spring 0.17N/mm is connected between a restrictor mechanism cable, to protect the locking mechanism inside the PRM module in case of the overwhelming-spooling forces during the locking stage, and the aluminium profile platform fixed on the backplane. The extension spring value is selected because it is less than the maximum braking force of the PRM module, according to Table 5.10. The 3mm plastic ball nut is attached to the cable tip. It is used to screw up with the 3mm screw, which is mounted on the LA slider tip, as shown in Figure D-1(a). The LA module case is fixed on the aluminium profile platform to allow the slider to extend and retract its lengths leading to spool and unspool the PRM cable, as shown in Figure D-1(b).

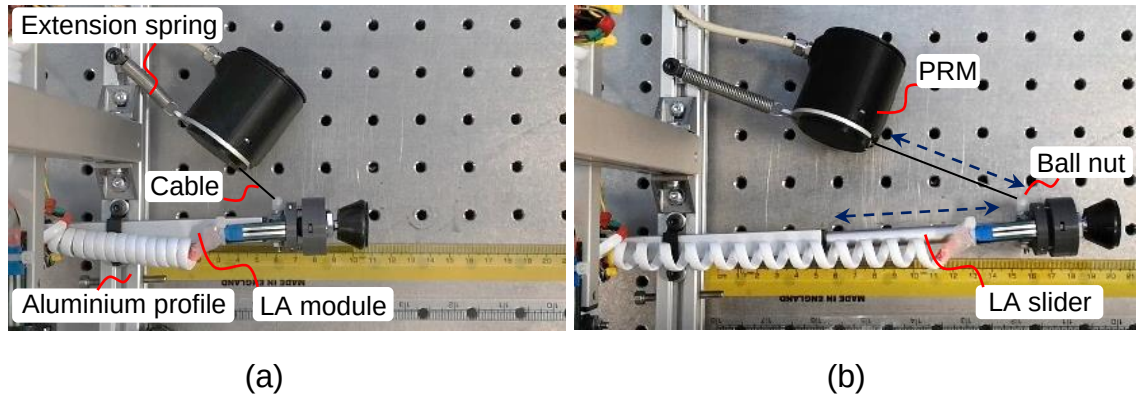


Figure D-1 Cable-locking experiment setup: (a) the initial length of the LA slider, (b) the LA slider and cable length extension and retraction.

The parameter values in this experiment are defined. The different duty cycle values (80, 140, and 255) are initially applied for the LA module to spool the PRM cable. They are defined based on the slow, medium and fast speed which cover the moving speed of the LA slider (v_f). The locked-cable length target (CRM_{ref}) for a spooling stage defines as 50mm that is the middle length of the maximum LA stroke, and the locked-cable length target for an unspooling stage defines as 15mm which is closed to the initial length. The controller module is used to gather both the LA-slider position and the PRM cable length (l_{CRM}). The experimental result is shown in Figure D-2.

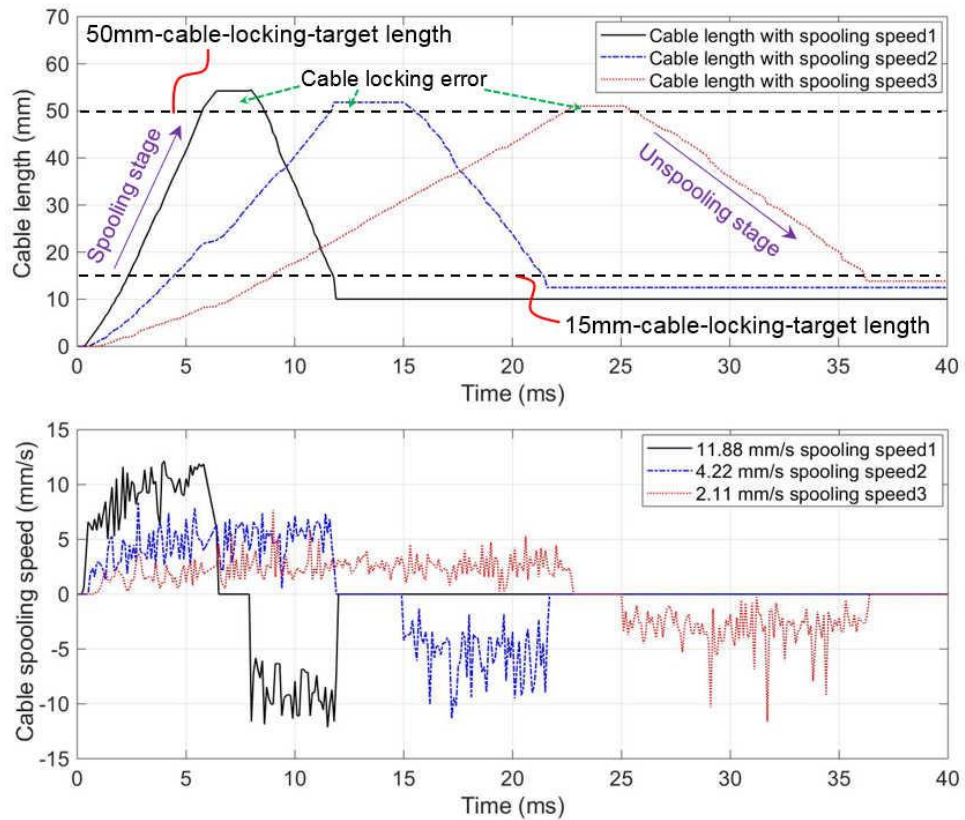


Figure D-2 Cable-locking experimental results.

The experimental results suggest that the locked-cable length error increases when the spooled cable speed increases. For example, for the 50mm of the cable-locking target, the cable length error is 0.4mm when the spooled-cable speed is 1.05mm/s, and the cable length error increases to 4.23mm when the spooled-cable speed is 10.13mm/s. The locked-cable length target does not depend on the locked-cable length error because the braking delay time of the braking parts is equal and stable mechanically. The summary of the experimental parameters and results are shown in Table D-2.

Table D-2 Relationship between the spooled-cable speeds and the locked-cable length error at the 50mm and 15mm of the locked-cable length target.

LA duty cycle	v_f (mm/s)	$CRM_{ref} = 50\text{mm}$ (extension)			$CRM_{ref} = 15\text{mm}$ (retraction)		
		v_{CRM} (mm/s)	l_{CRM} (mm)	e_{CRM} (mm)	v_{CRM} (mm/s)	l_{CRM} (mm)	e_{CRM} (mm)
15.7	1.58	1.05	50.4	0.4	-1.215	14.39	-0.61
31.4	3.77	2.36	51	1.0	-2.493	13.83	-1.17
47.1	5.86	4.96	51.64	1.64	-5.523	12.59	-2.41
54.9	7.14	5.75	51.8	1.8	-5.991	12.49	-2.51
62.7	8.24	6.84	52.11	2.11	-6.44	12.17	-2.83
70.6	9.03	7.36	52.67	2.67	-7.92	11.22	-3.78
86.3	11.21	9.67	53.35	3.35	-8.39	10.77	-4.23
100	12.9	10.13	54.23	4.23	-9.79	10.03	-4.97

To improve the cable restriction performance, the locking command should be compensated and modified considering the spooled-cable speed and the cable displacement in order to break the cable at the desired length.

The cable length target modification (l_m) for the locked-cable stage can be calculated by Equation (D-1).

$$l_m = \begin{cases} CRM_{ref} - (|v_{CRM}|t_{dly}) - k_{cs} & \text{if } (l_{CRM} < CRM_{ref}) \\ CRM_{ref} + (|v_{CRM}|t_{dly}) - k_{cs} & \text{if } (l_{CRM} > CRM_{ref}) \end{cases} \quad (D-1)$$

Where t_{dly} represents braking delay time and k_{cs} represents a compensation constant value obtained by the trial and error method. Thus, the spooled-cable speed can be calculated by Equation (D-2).

$$v_{CRM} = \frac{l_{CRM} - l_{CRM-1}}{t_i - t_{i-1}} \quad \left(\frac{mm}{sec}\right) \quad (D-2)$$

Where l_{CRM-1} represent a previous cable length (mm), t_i represents present time (sec) and t_{i-1} represents previous time (sec).

The second experimentation involves demonstrating the cable compensation performance using Equation (D-1). The cable length targets for the locking stages and the spooling/unspooling speed from the LA module are defined as the first experimentation. For the reliable-experimental results, each experiment is repeated three times, as illustrated in Table D-3 and Table D-4.

Table D-3 Experimental results of the locked-cable length accuracy using the cable compensation equation, 50mm locking target length.

LA duty cycle	v_f (mm/s)	Repeatability test	$CRM_{ref} = 50\text{mm}$		
			v_{CRM} (mm/s)	l_{CRM} (mm)	e_{CRM} (mm)
15.7	1.58	1st	1.32	50.79	-0.79
		2nd	1.32	50.48	-0.48
		3rd	1.32	50.29	-0.61
31.4	3.77	1st	5.28	50.27	-0.27
		2nd	3.17	50.32	-0.32
		3rd	5.02	50.11	-0.11
47.1	5.86	1st	4.75	50.79	-0.79
		2nd	5.02	50.82	-0.82
		3rd	4.44	50.77	-0.77
54.9	7.14	1st	6.07	50.34	-0.34
		2nd	7.13	49.98	0.02
		3rd	6.27	50.37	-0.37
62.7	8.24	1st	8.45	50.19	0.19
		2nd	8.18	49.92	-0.08
		3rd	7.66	50.34	0.34
70.6	9.03	1st	8.98	50.37	0.37
		2nd	8.98	50.77	0.77
		3rd	8.71	50.37	0.37
86.3	11.21	1st	10.56	49.87	-0.13
		2nd	9.93	49.61	-0.39
		3rd	10.46	49.37	-0.63
100	12.9	1st	12.55	50.66	0.66
		2nd	12.67	50.29	0.29
		3rd	12.14	50.32	0.32

Table D-4 Experimental results of the locked-cable length accuracy using the cable compensation equation, 15mm locking target length.

LA duty cycle	v_f (mm/s)	Repeatability test	$CRM_{ref} = 15\text{mm}$		
			v_{CRM} (mm/s)	l_{CRM} (mm)	e_{CRM} (mm)
15.7	1.58	1st	-0.79	14.39	0.61
		2nd	-2.11	14.81	0.19
		3rd	-2.36	15.68	-0.68
31.4	3.77	1st	-3.17	15.15	-0.15
		2nd	-2.64	15.1	-0.1
		3rd	-3.17	14.6	0.4
47.1	5.86	1st	-3.7	14.47	0.53
		2nd	-5.02	15.79	-0.79
		3rd	-5.81	15.84	-0.84
54.9	7.14	1st	-4.75	14.73	0.27
		2nd	-5.54	14.52	0.48
		3rd	-5.54	15.18	-0.18
62.7	8.24	1st	-5.81	14.52	0.48
		2nd	-7.39	50.13	-0.13
		3rd	-8.71	49.92	0.08
70.6	9.03	1st	-6.34	14.41	0.59
		2nd	-7.38	15.26	-0.26
		3rd	-6.07	14.26	0.74
86.3	11.21	1st	-6.07	14.36	-0.64
		2nd	-7.66	15.05	0.05
		3rd	-8.18	14.49	-0.51
100	12.9	1st	-7.602	14.18	0.82
		2nd	-7.655	15.42	-0.42
		3rd	-7.22	15.02	-0.02

The results suggest that the cable compensation equation is able to generate locking commands to restrict the cable within $\pm 1\text{mm}$ locked-cable length error. However, the error increases reaching $\pm 2\text{mm}$ in the case of unsmooth spooling and unspooling situations due to the unexpected rolling of rotational parts.

Different target lengths are also tested to ensure that the cable compensation equation can be performed effectively for other target lengths. The 30mm, 25mm and 15mm locked-cable target lengths are defined for the spooled cable stage. 20mm, 10mm and 5mm locked-cable target lengths are defined for the unspooled cable stage. The different spooling and unspooling speeds forced by the LA slider between 1.58mm/sec and 12.9 mm/sec are applied. The experimental results are shown in Figure D-3, and the experimental data are summarised in Table D-5 and Table D-6.

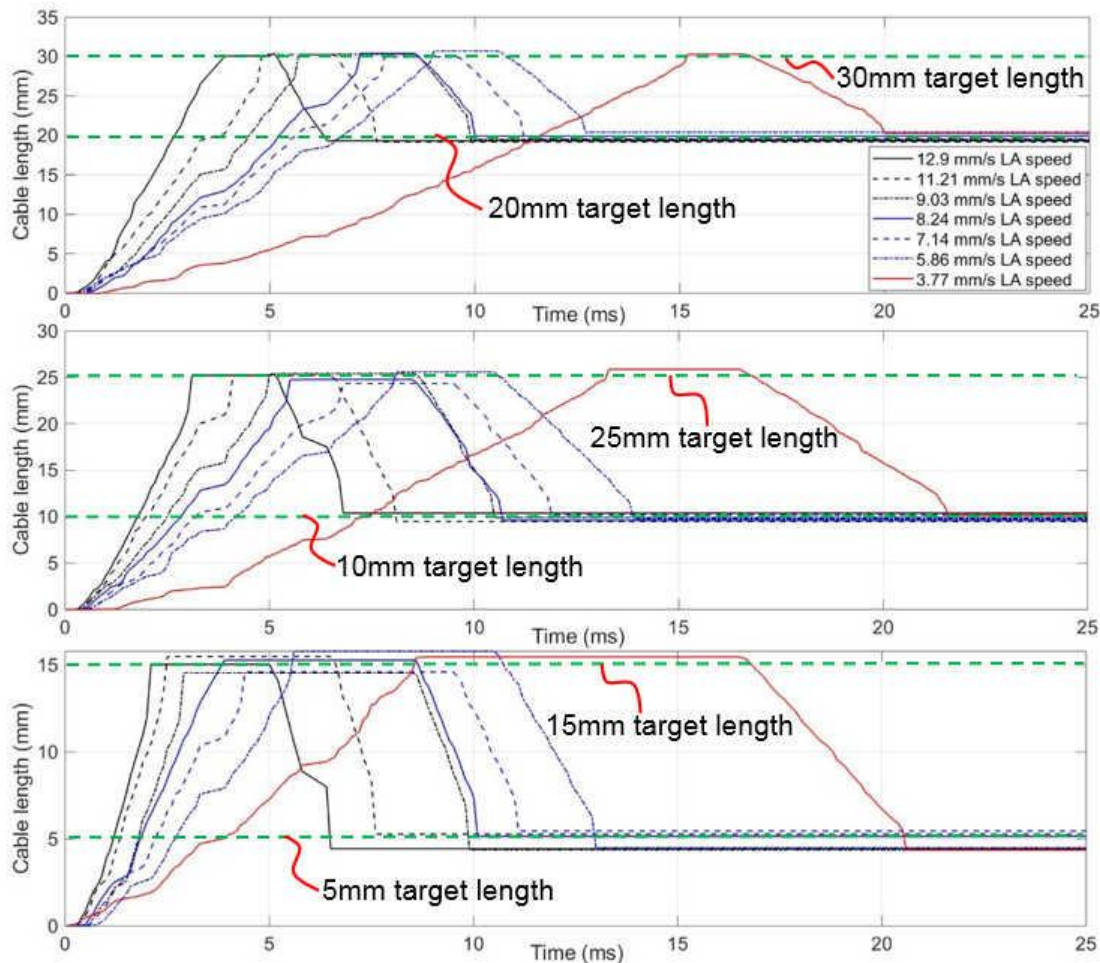


Figure D-3 Time response of different locked-cable target lengths: (top) 30mm and 20mm locked-cable target lengths, (middle) 25mm and 10mm locked-cable target lengths and (bottom) 15mm and 5mm locked-cable target lengths.

The results suggest that the locked-cable length accuracy of the PRM is $\pm 2\text{mm}$ that is the acceptable value that has little effect on robot configurations. The cable compensation method is also used and tested with all the rest PRM modules.

Table D-5 Experimental results of the locked-cable length accuracy using the cable compensation equation (30mm, 25mm and 12mm target lengths).

LA duty cycle	Moving speed of LA slider (mm/s)	Cable spooling speed (mm/s)	Spooled cable		e_{CRM} (mm)
			CRM_{ref} (mm)	l_{CRM} (mm)	
40	1.58	1.32	30	30.65	-0.65
		1.32	25	25.16	-0.58
		2.11	15	15.36	-0.36
80	3.77	3.17	30	30.28	-0.28
		2.09	25	25.87	-0.87
		3.17	15	15.47	-0.47
120	5.86	4.75	30	30.7	-0.7
		5.28	25	25.56	-0.56
		6.34	15	15.79	-0.79
140	7.14	5.81	30	29.96	0.04
		6.73	25	24.34	0.66
		6.07	15	14.6	0.4
160	8.24	6.53	30	30.41	-0.41
		6.34	25	24.76	0.24
		5.54	15	15.29	-0.29
180	9.03	8.18	30	30.28	-0.28
		6.34	25	25.4	-0.4
		6.6	15	14.55	0.45
220	11.21	9.24	30	30.25	-0.25
		9.5	25	25.19	-0.19
		9.88	15	15.5	-0.5
255	12.9	11.04	30	30.1	-0.1
		11	25	25.21	-0.21
		10.03	15	15.05	-0.05

Table D-6 Experimental results of the locked-cable accuracy using the cable compensation equation (20mm, 10mm and 5mm target lengths).

LA duty cycle	Spooling speed of LA slider (mm/s)	Cable spooling speed (mm/s)	Unspooled cable		Locked cable length error (mm)
			Target length (mm)	Locked cable length (mm)	
40	1.58	-2.64	20	20.14	-0.14
		-1.04	10	9.72	0.28
		-1.06	5	4.86	0.14
80	3.77	-3.17	20	20.28	-0.28
		-2.64	10	10.16	-0.16
		-3.66	5	4.36	0.64
120	5.86	-5.28	20	20.41	-0.41
		-5.28	10	9.77	0.23
		-3.96	5	4.49	0.51
140	7.14	-5.02	20	19.56	0.44
		-5.28	10	10.19	-0.19
		-4.22	5	5.46	-0.46
160	8.24	-5.28	20	19.93	0.07
		-6.6	10	9.61	0.39
		-5.81	5	5.15	-0.15
180	9.03	-5.54	20	19.48	0.52
		-5.75	10	9.9	0.1
		-5.81	5	4.38	0.62
220	11.21	-7.66	20	19.19	0.81
		-6.93	10	9.48	0.52
		-7.66	5	5.28	-0.28
255	12.9	-11.88	20	19.32	0.68
		-12.45	10	10.38	-0.38
		-8.98	5	4.44	0.56

Appendix E

E.1 Custom-Circular Scale Development and Test

A standard CAD software design, SolidWorks for education version, is used to design a large-circular scale with different diameters between 10mm to 120mm radius. A laser cutting machine is then used to engrave a custom scale on the 3mm transparent acrylic sheet (see Figure E-1 (a)). The angular accuracy of the custom-circular scale is compared with a commercial circular scale (see Figure E-1(b)). Also, different diameter sizes of the custom-circular scale are compared with a commercial cutting mat, as shown in Figure E-1(c).

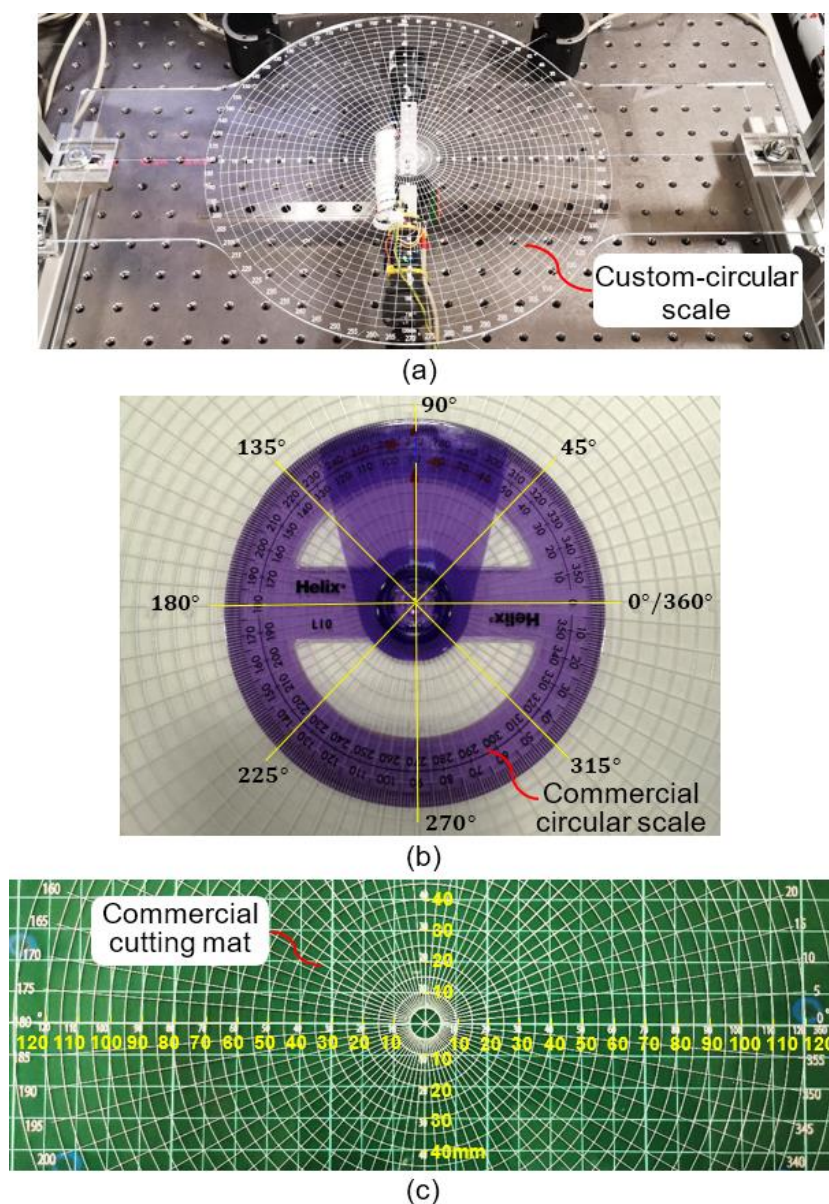


Figure E-1 Image of the custom-circular scale created by the laser engraving machine. After comparing both scales, the commercial circular scale and the custom-circular scale are equal with the angle error $\pm 0.3^\circ$ due to the laser edge line width.

Also, the linear scales between the commercial cutting mat and the custom-circular radius are equal with radius error ± 0.3 mm. Although the linear scale on the left and right side (see Figure E-1 (c)) do not entirely overlap, it occurs due to the slope angle of the camera position. For these comparisons, the custom-circular scale can be employed to measure the end-effector positions accurately and reliably.

E.2 Forward Kinematic Accuracy Experimentations

The end-effector angles and distance calculated from the kinematics equations are gathered to compare with the custom scale physically at all desired target positions. The 108-selected target positions are shown in Figure E-2, and the experimental result data are shown in Table E-1.

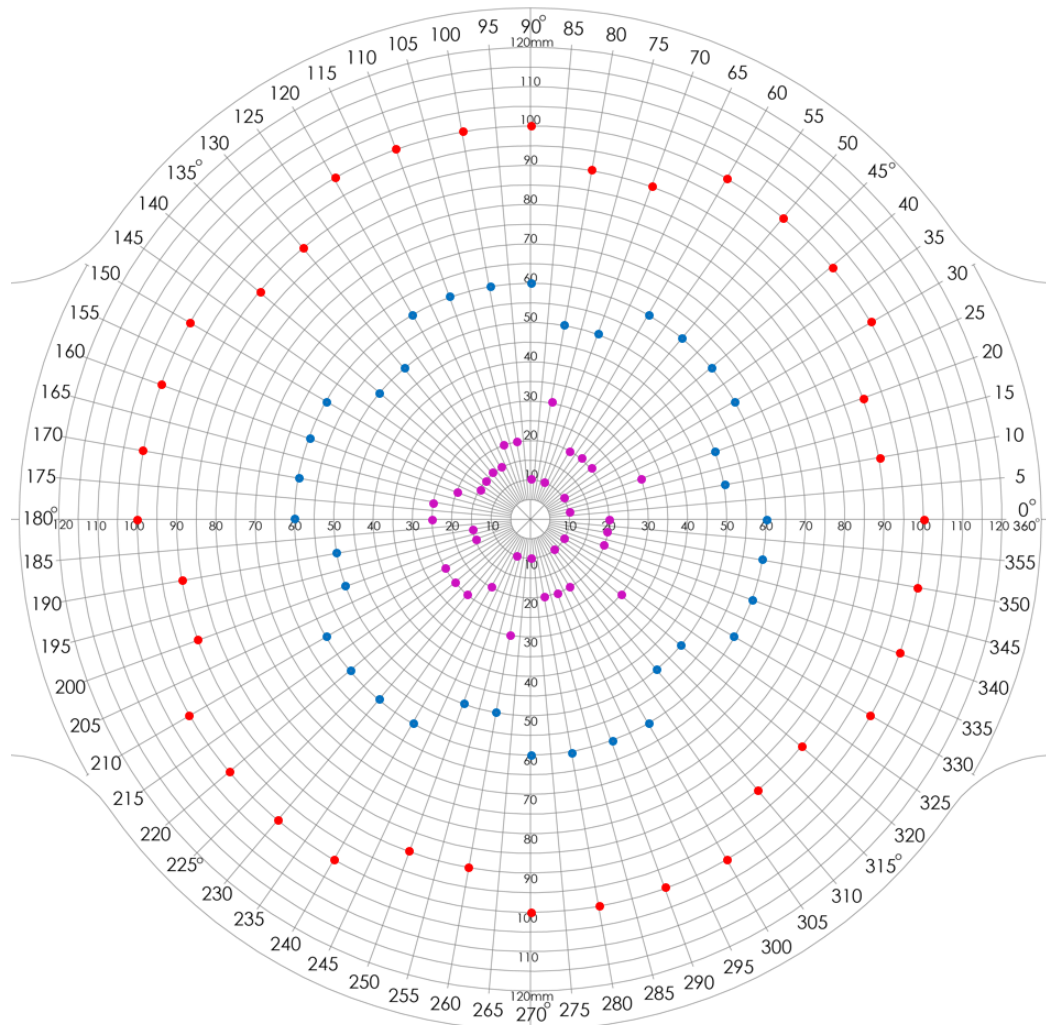


Figure E-2 Selected target positions of the end-effector plotted on the custom scale drawing. Red dots are long distances. Blue dots are medium distances, and purple dots are short distances.

Table E-1 Experimental result data of the end-effector position accuracy demonstrations.

Custom scale		Kinematics equation		Error	
θ_f (°)	d_f (mm)	θ_f (°)	d_f (mm)	$e.e_{\theta_f}$ (°)	$e.e_{d_f}$ (mm)
0	20	0.97	20.75	0.97	0.75
	60	0.31	59.91	0.31	-0.09
	100	0.09	98.9	0.09	-1.1
10	10	9.67	9.26	-0.33	-0.74
	50	9.37	49.48	-0.63	-0.52
	90	9.97	89.56	-0.03	-0.44
20	30	19.86	30.32	-0.14	0.32
	50	19.47	50.25	-0.53	0.25
	90	19.69	89.31	-0.31	-0.69
30	10	29.39	9.74	-0.61	-0.26
	60	30.27	60.34	0.27	0.34
	100	29.63	99.95	-0.37	-0.05
40	20	39.22	20.95	-0.78	0.95
	60	40	59.72	0	-0.28
	100	39.6	100.02	-0.4	0.02
50	20	48.9	19.46	-1.1	-0.54
	60	50.07	59.86	0.07	-0.14
	100	49.65	100.16	-0.35	0.16
60	20	58.11	19.3	-1.89	-0.7
	60	59.57	59.96	-0.43	-0.04
	100	59.26	100.35	-0.74	0.35
70	10	70.45	9.37	0.45	-0.63
	50	70.3	49.46	0.3	-0.54
	90	69.2	90.89	-0.8	0.89
80	30	79.13	29.79	-0.87	-0.21
	50	79.76	49.08	-0.24	-0.92
	90	79.28	90.64	-0.72	0.64
90	10	89.05	9.54	-0.95	-0.46
	60	90.17	59.98	0.17	-0.02
	100	88.91	101.25	-1.09	1.25
100	20	99.19	19.09	-0.81	-0.91
	60	99.72	59.37	-0.28	-0.63
	100	98.94	100.77	-1.06	0.77
110	20	110.65	19.28	0.65	-0.72
	60	110.03	59.02	0.03	-0.98
	100	109.08	100.4	-0.92	0.4
120	15	121.97	14.88	1.97	-0.12
	60	120.29	60.22	0.29	0.22
	100	119.76	100.14	-0.24	0.14
130	15	130.31	15.5	0.31	0.5
	50	130.7	50.03	0.7	0.03
	90	129.79	90.53	-0.21	0.53
140	15	140.46	14.74	0.46	-0.26
	50	140.84	50.02	0.84	0.02
	90	139.94	90.1	-0.06	0.1
150	15	151.23	14.62	1.23	-0.38
	60	149.91	59.47	-0.09	-0.53
	100	149.38	99.75	-0.62	-0.25
160	20	160.31	20.05	0.31	0.05
	60	160.56	60.64	0.56	0.64
	100	159.39	100.38	-0.61	0.38

Custom scale		Kinematics equation		Error	
θ_f (°)	d_f (mm)	θ_f (°)	d_f (mm)	$e.e_{\theta_f}$ (°)	$e.e_{d_f}$ (mm)
170	25	170.78	24.63	0.78	-0.37
	60	170.6	60.59	0.6	0.59
	100	169.78	100.51	-0.22	0.51
180	25	180.48	25.25	0.48	0.25
	60	180.48	60.11	0.48	0.11
	100	180.01	100.91	0.01	0.91
190	15	190.1	16.02	0.1	1.02
	50	191.5	51.29	1.5	1.29
	90	190.05	91.03	0.05	1.03
200	15	202.02	16.28	2.02	1.28
	50	202.07	51.67	2.07	1.67
	90	200.17	90.26	0.17	0.26
210	25	211.18	25.09	1.18	0.09
	60	211.39	61.01	1.39	1.01
	100	210.33	100.53	0.33	0.53
220	25	219.8	26.22	-0.2	1.22
	60	220.56	61.59	0.56	1.59
	100	219.84	100.55	-0.16	0.55
230	25	230.04	26.41	0.04	1.41
	60	230.6	61.55	0.6	1.55
	100	230.11	101.41	0.11	1.41
240	20	239.69	19.97	-0.31	-0.03
	60	240.32	60.02	0.32	0.02
	100	239.94	100.33	-0.06	0.33
250	10	250.02	9.97	0.02	-0.03
	50	250.35	50.47	0.35	0.47
	90	249.91	89.48	-0.09	-0.52
260	30	260.59	30.81	0.59	0.81
	50	260.55	51.03	0.55	1.03
	90	260.31	90.2	0.31	0.2
270	10	270.03	10.06	0.03	0.06
	60	269.68	60.97	-0.32	0.97
	100	269.62	99.9	-0.38	-0.1
280	20	279.51	20.99	-0.49	0.99
	60	280.03	60.74	0.03	0.74
	100	279.4	101.36	-0.6	1.36
290	20	290.09	20.15	0.09	0.15
	60	289.05	61.16	-0.95	1.16
	100	289.27	99.17	-0.73	-0.83
300	20	299.74	20.87	-0.26	0.87
	60	299.74	60	-0.26	0
	100	300.28	98.32	0.28	-1.68
310	10	310.84	10.07	0.84	0.07
	50	308.96	50.53	-1.04	0.53
	90	309.71	89.75	-0.29	-0.25
320	30	319.72	30.16	-0.28	0.16
	50	319.02	49.86	-0.98	-0.14
	90	319.56	89.79	-0.44	-0.21
330	10	330.7	10.46	0.7	0.46
	60	329.19	59.47	-0.81	-0.53
	100	330.51	98.88	0.51	-1.12
340	20	339.44	20.51	-0.56	0.51

Custom scale		Kinematics equation		Error	
θ_f (°)	d_f (mm)	θ_f (°)	d_f (mm)	$e.e_{\theta_f}$ (°)	$e.e_{d_f}$ (mm)
	60	339.22	59.83	-0.78	-0.17
	100	340.56	99.25	0.56	-0.75
350	20	349.36	20.84	-0.64	0.84
	60	349.15	59.31	-0.85	-0.69
	100	350.35	99.58	0.35	-0.42

The results suggest that the end-effector angles and distances calculated by the kinematics equations are close to custom scale values. The red number shows the errors which are between ± 1 and ± 2 values of both distance and angle. Overall, the calculated angle errors are in the range of $\pm 2^\circ$ approximately, and the distance errors are in the range of $\pm 2mm$, which are acceptable. Therefore, these forward kinematic equations are suitable and reliable to calculate the end-effector position in the closed-loop control system.

Appendix F

F.1 One Degree of Freedom (1-DOF) System Experiments

This section demonstrates a basic 1-DOF system of a retractable-cable structure. Figure F-1 shows the experimental setup of the 1-DOF system. It consists of a linear actuator (LA) module mounted on a miniature linear guide, model GS02740-02, to reduce frictions between LA module contact points and backplane surface while moving. Two modules of a passive-retractable joint with a cable locking mechanism (PRM) are placed on both sides of the LA module. PRM-A is placed on the right, and PRM-B is placed on the left. PRM cables connect between the PRMs and the LA module. The cables are able to adjust using the change in length of the LA slider that produces push and pull forces. The cable length can also be adjusted by applying the locking and unlocking stage to PRMs to enable and disable cable-pulling forces of the PRM-A (F_{RA}) and PRM-B (F_{RB}). Two tension springs are connected between the PRM anchor and screw fixed on the panel. The tension springs of 0.16 N.mm are used. It is selected because the spring rate value should be higher than the rotational torque of the power spring to prevent the spring coil extension while pulling the cable in the unlocking stage. However, the spring rate value should be lower than the maximum braking force of the PRMs to allow a little extension during the overwhelming-spooling force in the locking stage to protect the braking part damage.

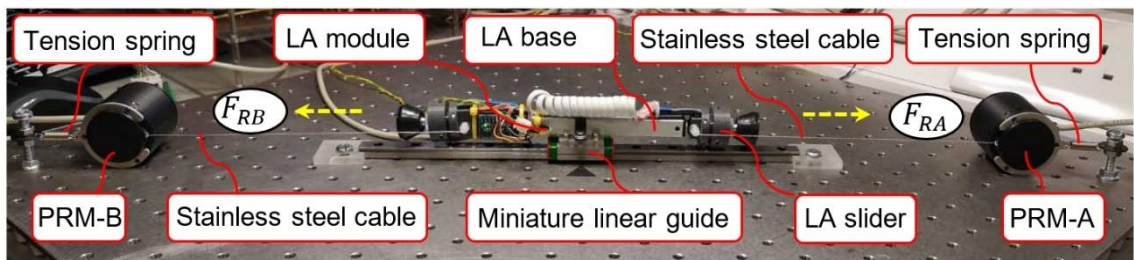


Figure F-1 Experimental setup of one, two and three degrees of freedom system of the retractable-cable structure.

To move the end-effector or the LA base of the 1-DOF system, the LA module is only defined as an independent movement that is the active actuator of the system. It can exert two directional forces: push force and pull force, which interacts with the cable-pulling forces of both PRM-A and PRM-B.

Before doing experiments, the forward kinematics of the LA-base position is first calculated to identify LA-base positions. It can be computed using subtraction of current PRM-B cable length (L_B) from initial PRM-B cable length ($L_{B_{ini}}$) because

the PRM-B cable is directly connecting to the LA-base. Therefore, the forward kinematic of the LA-base can be calculated from the following Equation:

$$LA_f = LA_{ini} + (L_{B_{ini}} - L_B), \quad (F-1)$$

where LA_f is the LA-base feedback position or current position (mm) and LA_{ini} is the initial LA-base position (mm) defined as 0mm at the centre of the linear guide bar. This forward kinematic Equation will be used for 1-DOF, 2-DOF and 3-DOF system experimentations.

For the experiment procedure, the repetitive LA-slider length target is defined as 90mm, which is the distance that the LA-base movement behaviour can be observed. The unlocking stage (U) is only applied to the PRM-A and PRM-B while extending and retracting LA length without closed-loop position control. The experiment procedure includes five steps: the initial stage (A) to the final stage (E). All experiment parameters are summarised in Table F-1, and the video frames of the 1-DOF system experiments are illustrated in Figure F-2 (step A to E).

Table F-1 LA slider length pattern of the 1-DOF system demonstration.

Stage	LA slider length (mm)	Locking procedure	
		PRM-B	PRM-A
A	0	U	U
B	90	U	U
C	0	U	U
D	90	U	U
E	0	U	U

N/A is the unlocking stage by default.

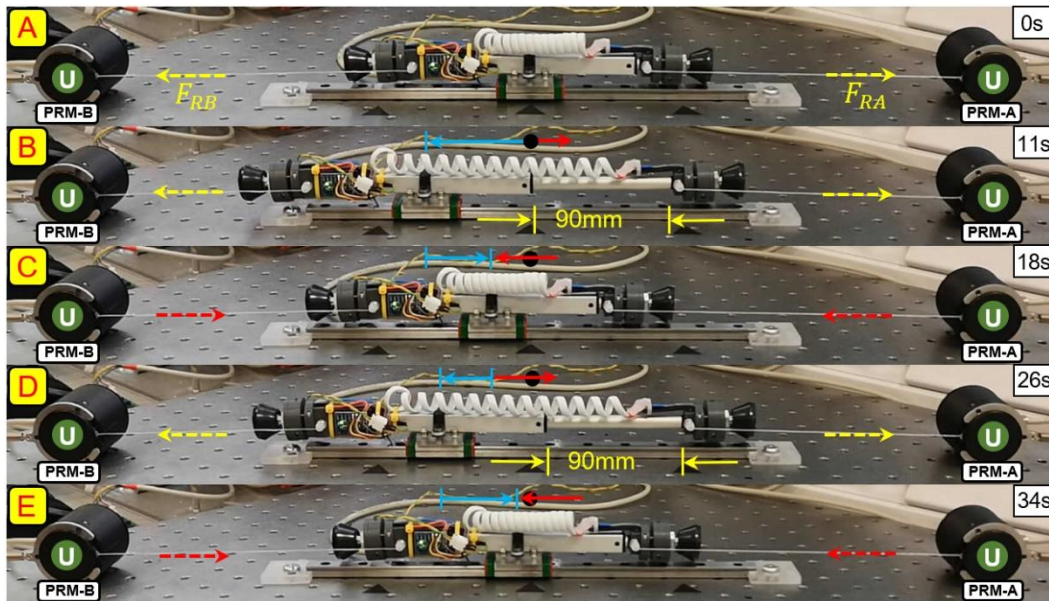


Figure F-2 Video frames of the 1-DOF system experimentations. The yellow arrow indicates the PRM cable direction, which is followed by the PRM pulling force, and the red arrow indicates the LA dragging force to pull the cable out from the PRM module.

The results suggest that the LA base can be moved only on the left side randomly depending on the PRM-A and PRM-B spooling forces, which directly relates to the PRM cable lengths. The more PRM cable length is spooled, the more cable-pulling force occurs. For example, in stage B, after the LA slider extending the length to 90mm, the LA-base centre is pulled to the left around 80mm, while the LA-slider end cap extends to the right around 10mm from the the initial position. It is because that the F_{RA} is larger than the F_{RB} . A head direction of the yellow arrow indicates the direction of cable-pulling force (see Figure F-2).

On the other hand, in stage C, the F_{RB} is larger than the F_{RA} while retracting the LA-slider lengths resulting in the LA-base centre is dragged mostly to the right. However, the LA-base does not return to the initial position, as shown in Figure F-3 (red line).

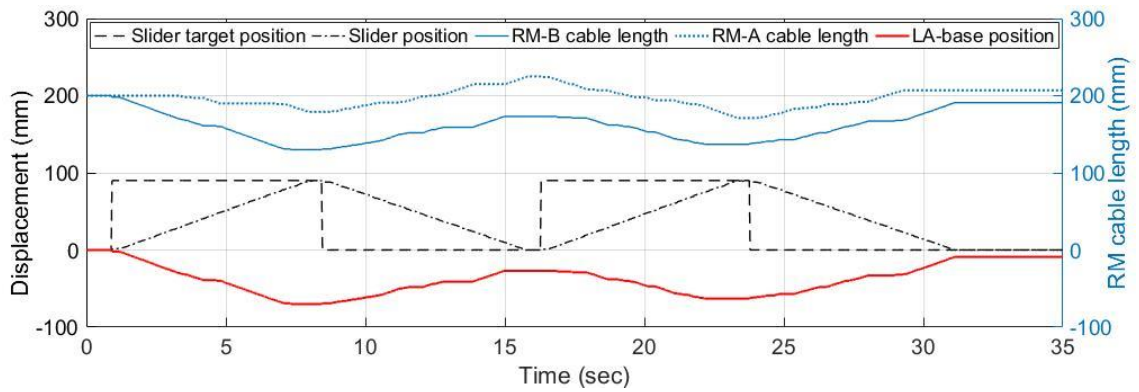


Figure F-3 Experimental results of the 1-DOF system. The PRM on the graph represents the PRM.

From the unstable LA-base movement, the 1-DOF system is not suitable to control the LA-base movements due to the lack of a locking and unlocking stage of the PRM-A or PRM-B. Therefore, a more independent motion must be used, as presented in the next section.

F.2 Two Degrees of Freedom (2-DOF) System Experiments

This section describes the improvement of the LA-base movement control using a 2-DOF system. It comprises a LA module that exerts a force against the cable-pulling force produced from the PRM-A or PRM-B. However, the PRM-A or PRM-B is defined as the second independent motion, which increases the LA-base movement capability. A PRM is employed to restrict and release a cable while changing LA-slider lengths.

In the 2-DOF system, the PRM-A and PRM-B do not control at the same time. Therefore, this experiment is divided into two conditions. The first condition is to define the PRM-A as a controllable locking and unlocking stages, while the PRM-

B is defined as the unlocking stage all the time. The 90mm slider length is determined as the maximum target length. The control procedures of the LA slider length and locking/unlocking stage of the PRM-A are summarised in Table F-2. The video frames of the demonstration are shown in Figure F-4.

Table F-2 LA-slider position and PRM-A locking and unlocking procedures for 2-DOF experimentation to move the end-effector that is the LA-base position.

Stage	LA slider length (mm)	Locking procedure	
		PRM-B	PRM-A
A	0	U	U
B	90	U	L
C	0	U	L
D	90	U	L
E	0	U	U
F	90	U	L
G	0	U	U

U is the unlocking stage, and L is the locking stage.

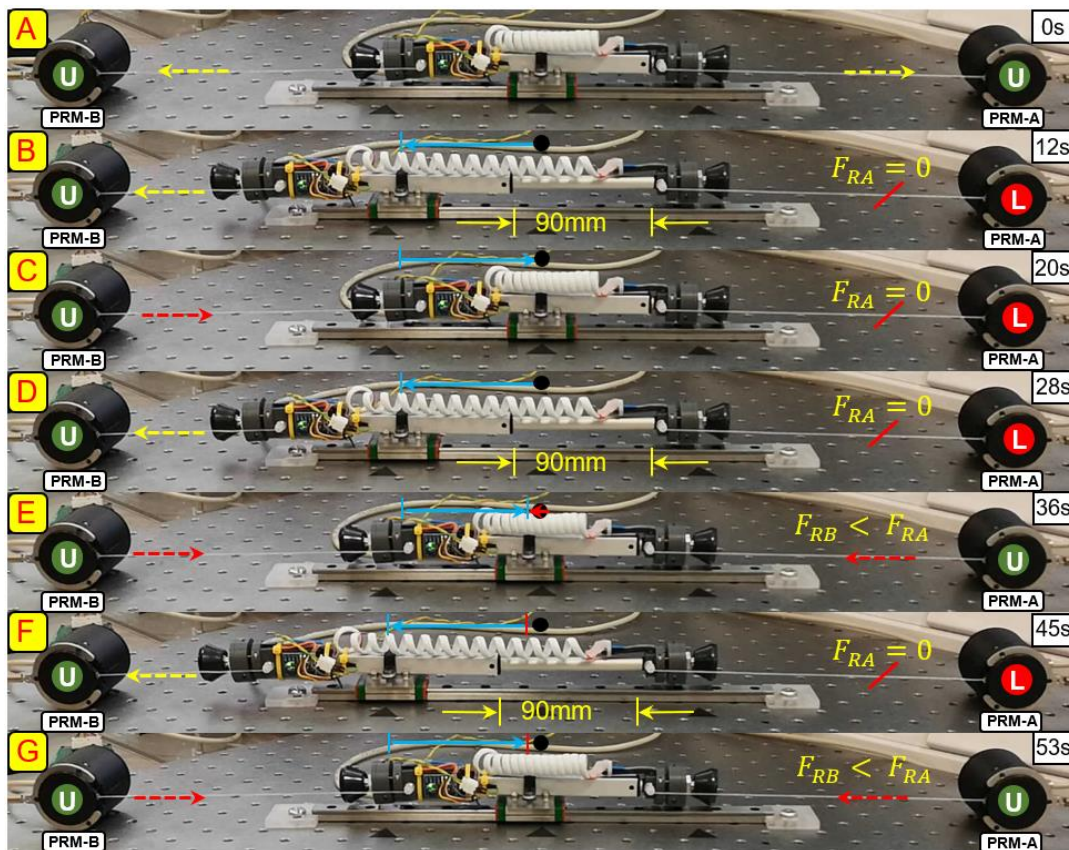


Figure F-4 Video frames of the 2-DOF system controlled using the LA module and PRM-A with locking and unlocking procedures.

The results suggest that the centre of the LA-base is moved to the left following the F_{RB} during extending the LA-slider lengths (see Figure F-4 (stage B)). It is because that the F_{RA} is disable (equal to zero) in the locking stage. For this movement behaviour, the centre of the LA-base positions is equal to the length

of the LA-slider extension or PRM-B cable retraction. It means that the 2-DOF system can control the LA-base position moving to the left direction by specifying the LA-slider length. However, the LA-base motion is still restricted due to the lack of cable locking stage of the PRM-B resulting in uncontrollable motion on the right side. The maximum distance that the LA-base can be moved is 102mm, as shown in Figure F-5.

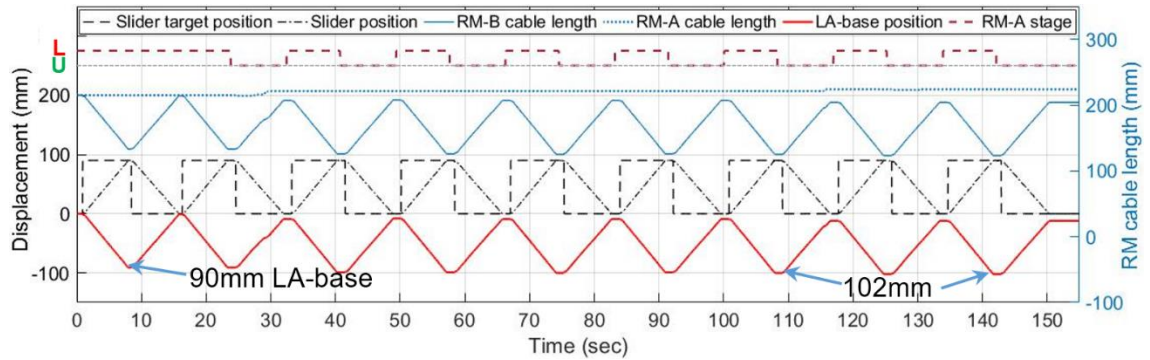


Figure F-5 Multiple-cycle-experimental results of the 2-DOF system with LA slider movement and locking/unlocking procedure of the PRM-A.

The second condition is to define the PRM-B as controllable locking and unlocking stages. Whereas, the PRM-A is defined as the unlocking stage only. The 90mm slider length is determined as the maximum target length. The control procedures of the LA slider length and the locking/unlocking stages of the PRM-B are summarised in Table F-3, and the video frames of the demonstrations are shown in Figure F-6.

Table F-3 LA slider position and PRM's locking and unlocking pattern for 2-DOF system experimentation.

Stage	LA slider length (mm)	Locking procedure	
		PRM-B	PRM-A
A	0	U	U
B	90	L	U
C	0	L	U
D	90	L	U
E	0	U	U
F	90	L	U
G	0	U	U

The results suggest that the centre of the LA-base cannot move while extending and retracting the LA slider length because the LA-base position is restricted due to the PRM-B cable restriction (see Figure F-6 (step B, C and D)). The LA slider may be randomly moved to the right following the F_{RA} while applying the unlocking stage of the PRM-B, as shown in Figure F-6 (step E, F and G). This movement occurred due to the F_{RB} being lower than the F_{RA} at a short time.

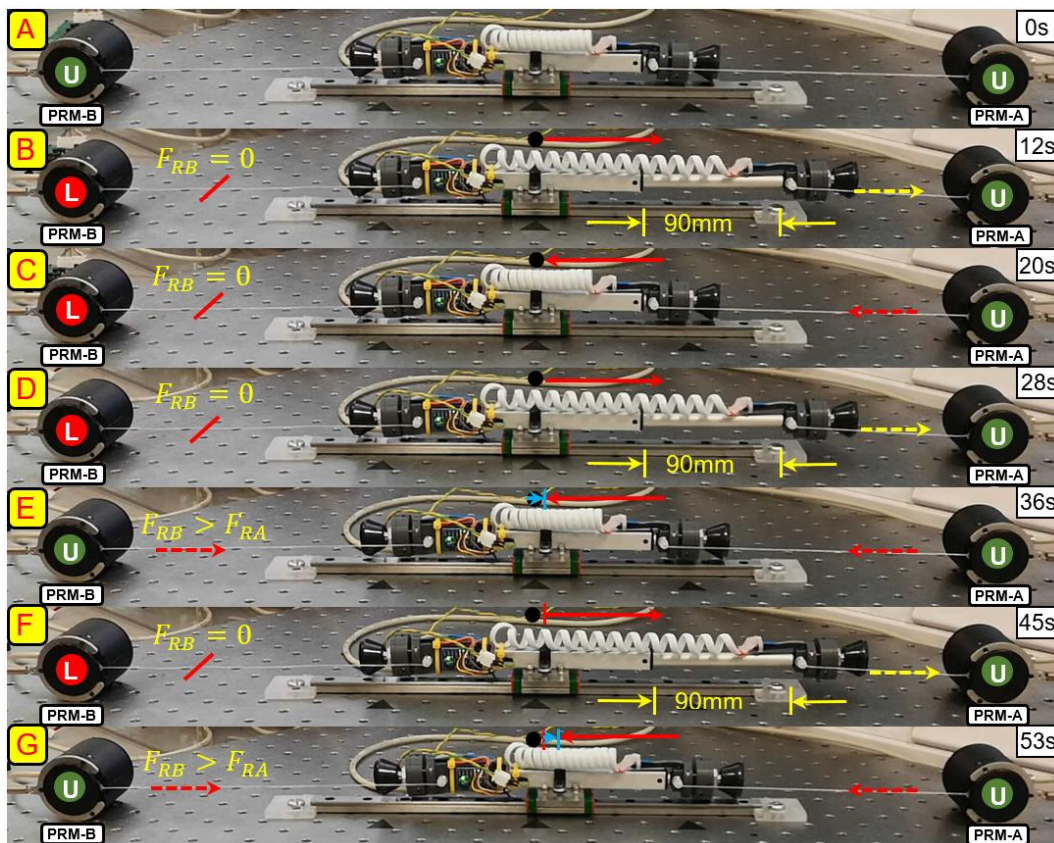


Figure F-6 Video frames of the 2-DOF system controlled using the LA module and PRM-B with locking and unlocking procedures.

To increase the LA-base distance on the right side, another four cycles of control procedures are applied to control the LA-base position moving in the right. Each control cycle consists of the PRM-B locking stage while extending the LA-slider length and the PRM-B unlocking stage while retracting the LA-slider length. The LA-base position is eventually dragged to the right around 15mm maximum, as shown in Figure F-7 (red line).

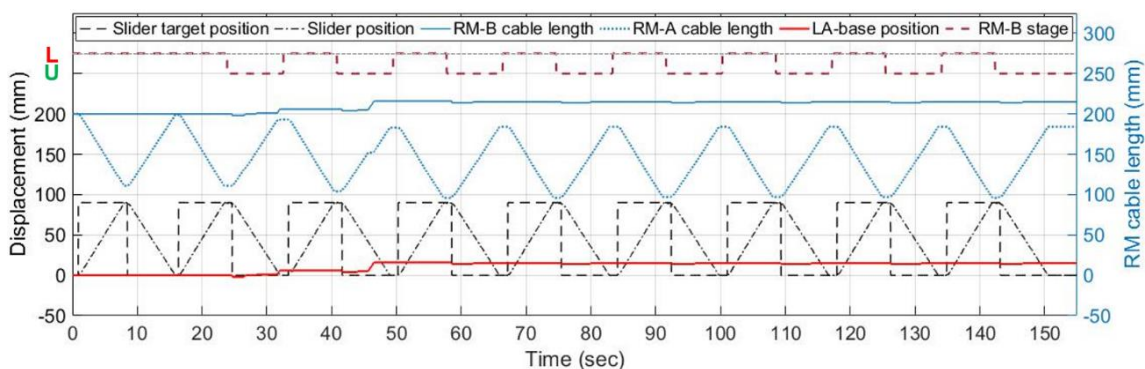


Figure F-7 Experimental results of the 2-DOF system with LA slider movement and locking and unlocking procedure of the PRM-B.

The results suggest that two problems are found in the 2-DOF system experimentations. Firstly, although the LA-base positions can be moved to the

left using the proposed technique, the LA-base distance is restricted due to the cable-pulling force against each other. Secondly, the LA-base position cannot be controlled to the right because the PRM-A cannot enable and disable F_{RA} to control the slider tip positions. Therefore, it is concluded that the 2-DOF system cannot be suitable to control the LA-base movements due to the lack of another independent motion to lock and unlock the PRM cables on both sides. Therefore, the minimum number of individual elements to control LA-base positions should be three.

F.3 Five Degree of Freedom (5-DOF) System Experiments

This section demonstrates further experiments mentioned in Chapter 6 to ensure that the proposed control rules can be used to control end-effector positions to target points. The experiments can be divided into two sub-sections. The first sub-section involves controlling the end-effector point, including angle and distance. Two sets of the target angles and distances of the end-effector ($LA_{ref}(\theta_{ref}, d_{ref})$) are defined as 255° , 30mm and 310° , 55mm. The experimental results are shown in Figure F-8 to Figure F-13.

The results suggest that the proposed control rules is able to control the end-effector position to target points with small steady-state error. The PRM perform effectively to restrict and release cables while adjusting LA-slider length to move the end-effector to target points.

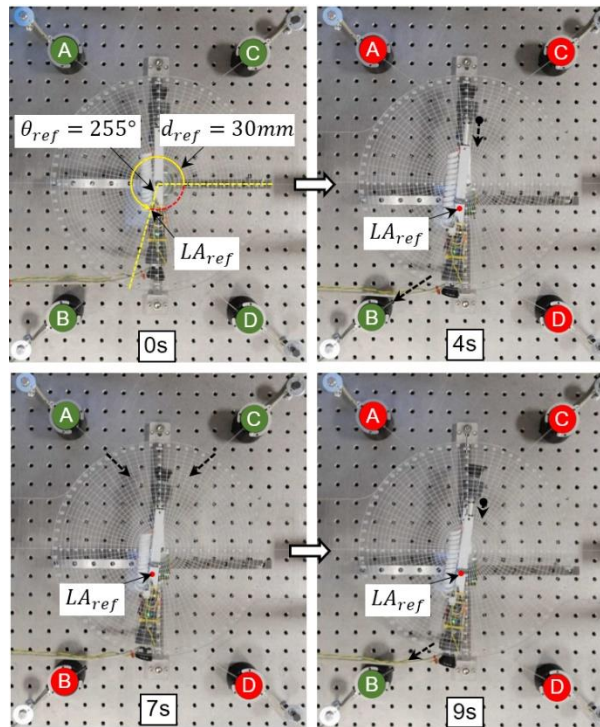


Figure F-8 Video frames of the end-effector position control experimentations ($LA_{ref}(255^\circ, 30mm)$).

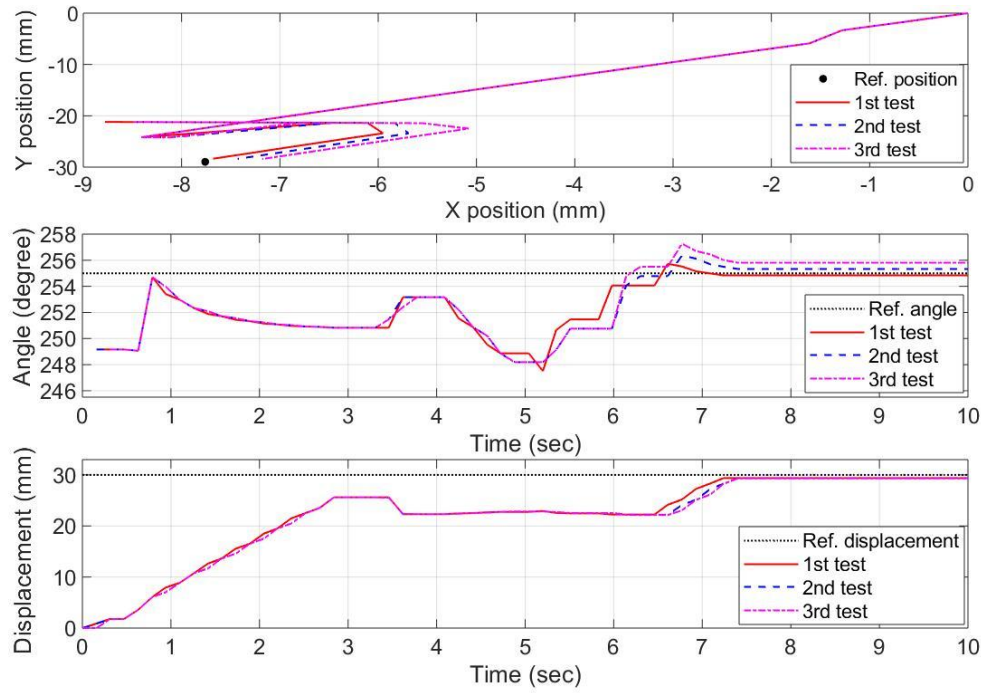


Figure F-9 Experimental results of the end-effector position control ($LA_{ref}(255^\circ, 30mm)$): (top) the end-effector movements in X-Y plane, (middle) the end-effector moving to the target angle and (bottom) the end-effector moving to the target position.

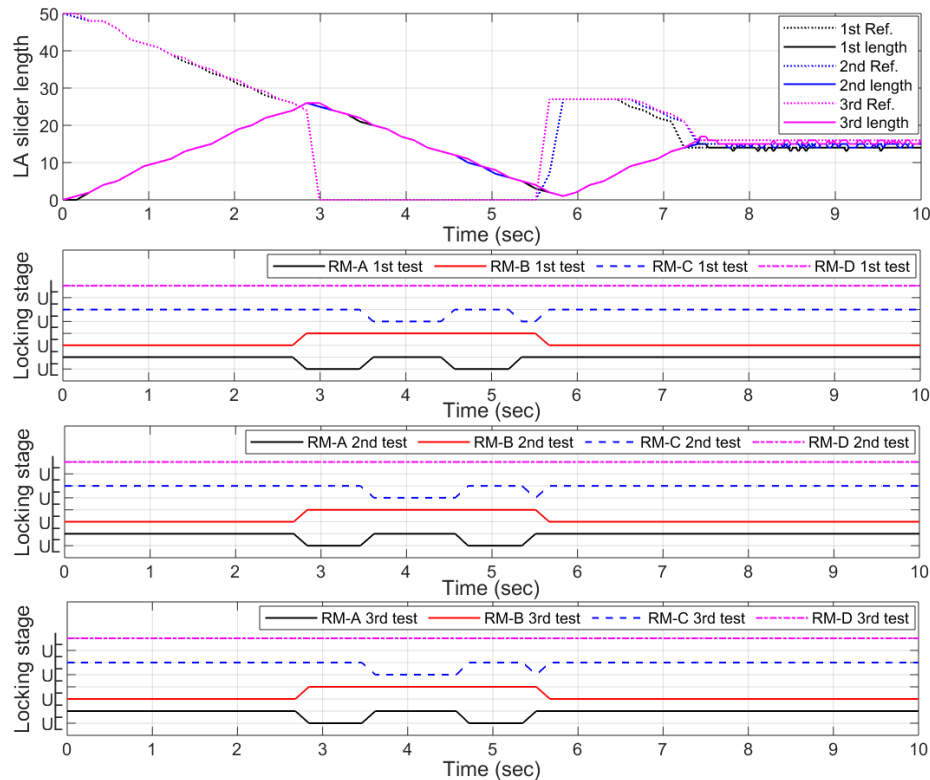


Figure F-10 Control signal comparison of the three repetitive tests generated by the proposed control rule for moving the end-effector to the target position ($LA_{ref}(255^\circ, 30mm)$):(top) the LA-slider targets and movement, (three-bottom) the first, second and third locking and unlocking control procedures of the PRMs or RMs (A to D).

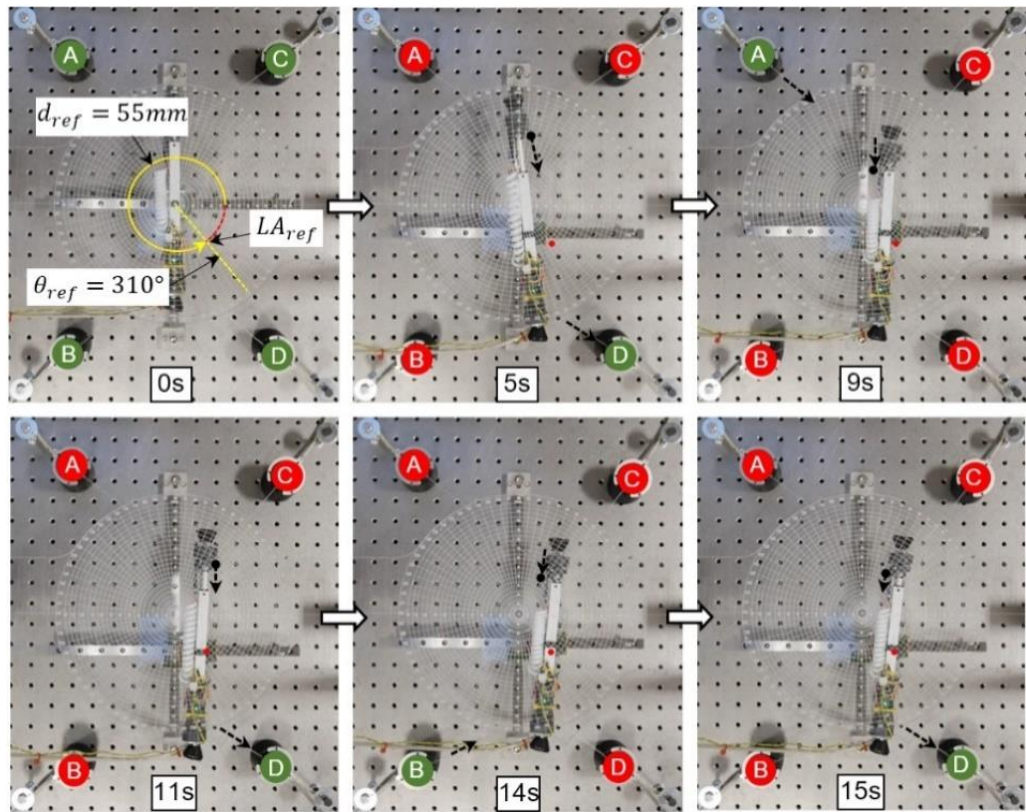


Figure F-11 Video frames of the end-effector position control experimentations ($LA_{ref}(310^\circ, 55mm)$).

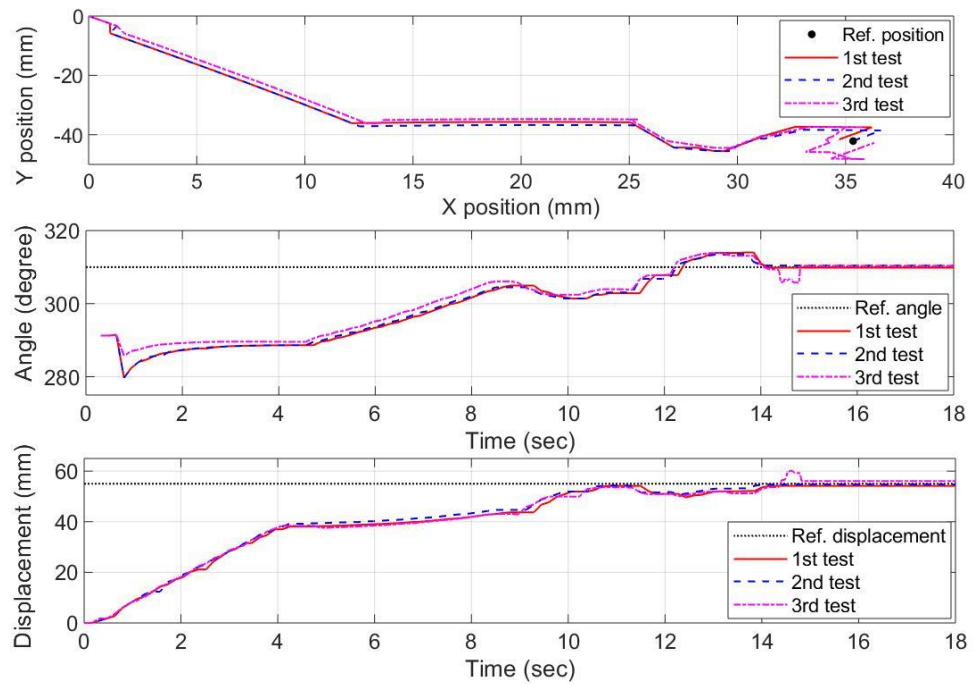


Figure F-12 Experimental results of the end-effector position control ($LA_{ref}(310^\circ, 55mm)$): (top) the end-effector movements in X-Y plane, (middle) the end-effector moving to the target angle and (bottom) the end-effector moving to the target position.

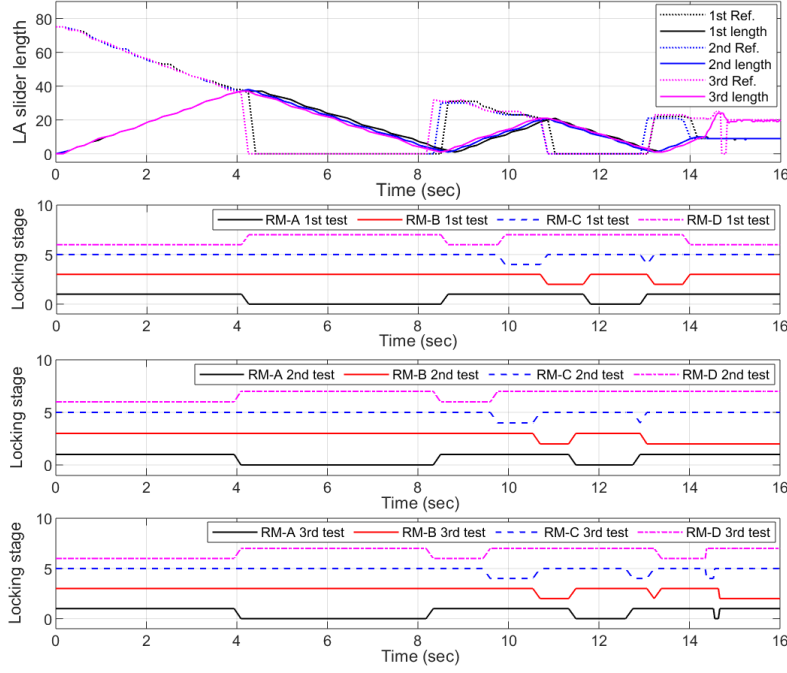
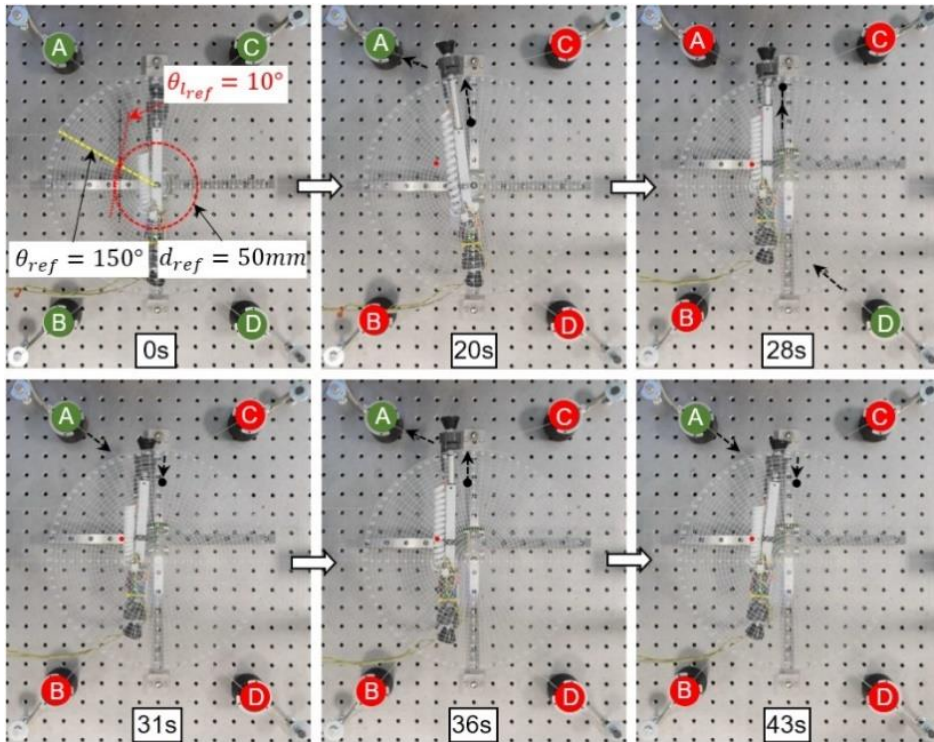


Figure F-13 Control signal comparison of the three repetitive tests generated by the proposed control rule for moving the end-effector to the target position ($LA_{ref}(310^\circ, 55mm)$):(top) the LA-slider targets and movement, (three-bottom) the first, second and third locking and unlocking control procedures of the PRMs or RMs (A to D).

The second sub-section involves controlling the end-effector points, including the angle, distance and LA-base angle ($LA_{ref}(\theta_{ref}, d_{ref}, \theta_{lref})$). Three sets of target points are selected as $(150^\circ, 50mm, 10^\circ)$, $(210^\circ, 35mm, -8^\circ)$ and $(305^\circ, 60mm, 5^\circ)$, respectively. The video frames and experimental results are shown in Figure F-14 to Figure F-22.



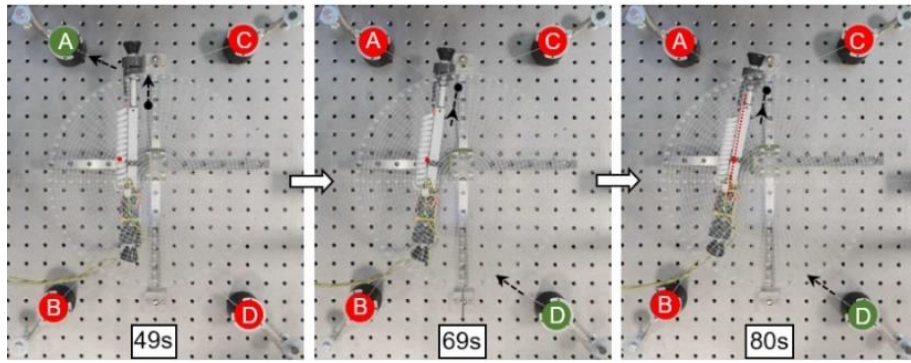


Figure F-14 Video frames of the end-effector position and angle control experimentations ($LA_{ref}(150^\circ, 50mm, 10^\circ)$).

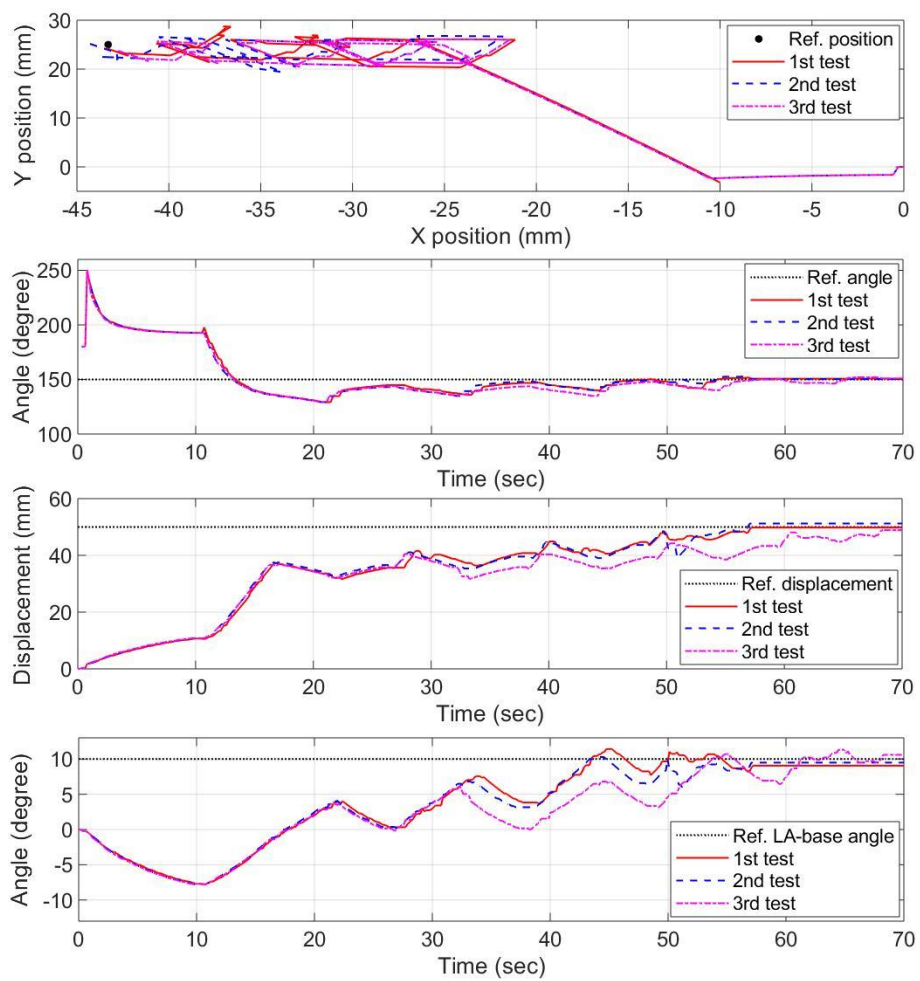


Figure F-15 Experimental results of the end-effector position and angle control ($LA_{ref}(150^\circ, 50mm, 10^\circ)$): (top) the end-effector movements in X-Y plane, (middle) the end-effector moving to the target angle and (bottom) the end-effector moving to the target position.

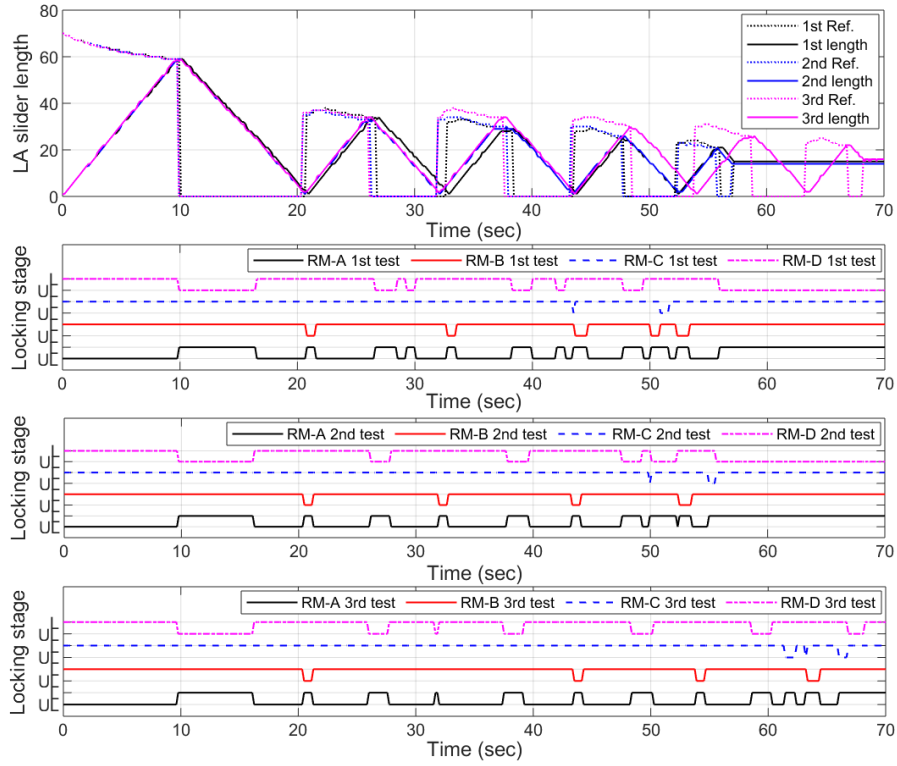


Figure F-16 Control signal comparison of the three repetitive tests generated by the proposed control rule for moving the end-effector to the target position and angle ($LA_{ref}(150^\circ, 50mm, 10^\circ)$):(top) the LA-slider targets and movement, (three-bottom) the first, second and third locking and unlocking control procedures of the PRMs or RMs (A to D).

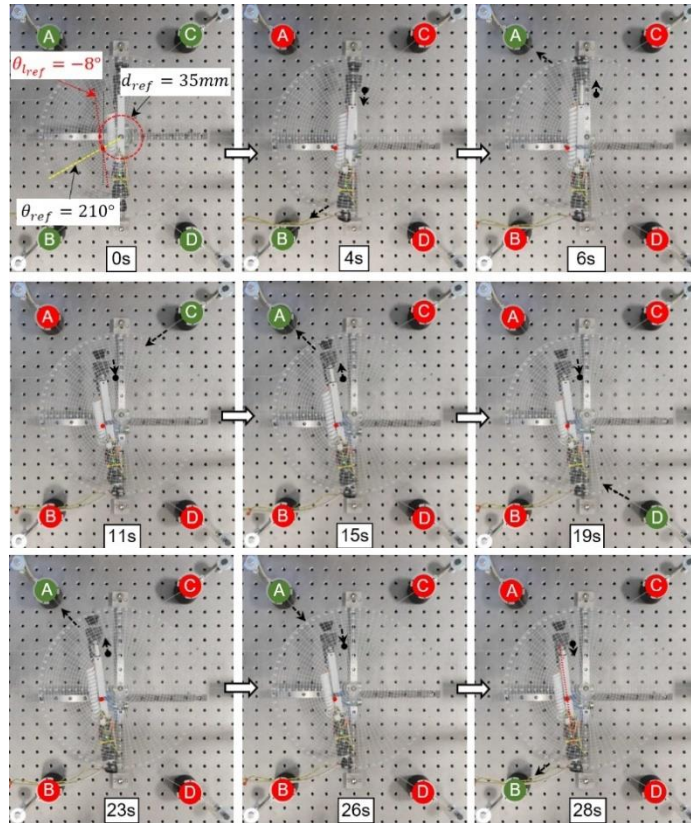


Figure F-17 Video frames of the end-effector position and angle control experimentations ($LA_{ref}(210^\circ, 35mm, -8^\circ)$).

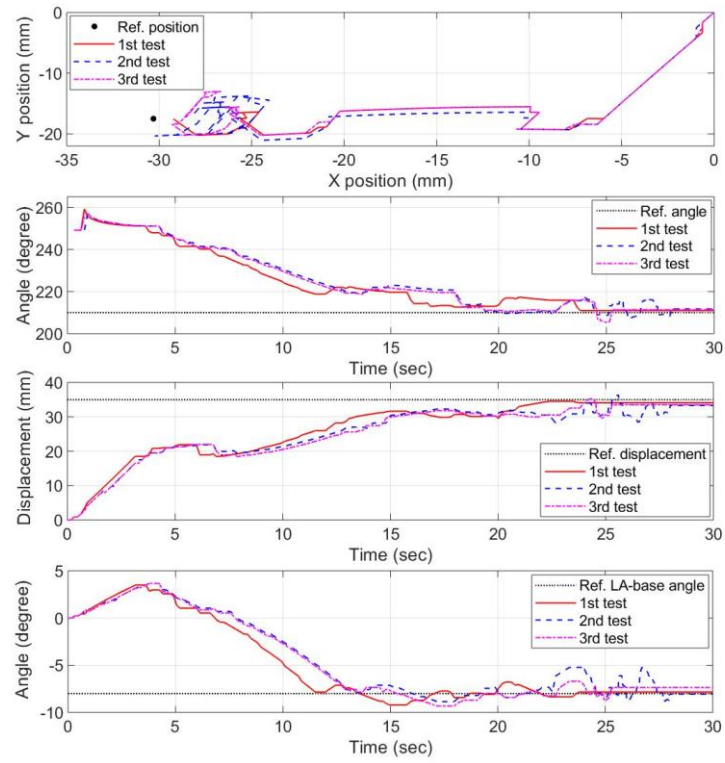


Figure F-18 Experimental results of the end-effector position and angle control ($LA_{ref}(210^\circ, 35mm, -8^\circ)$): (top) the end-effector movements in X-Y plane, (middle) the end-effector moving to the target angle and (bottom) the end-effector moving to the target position.

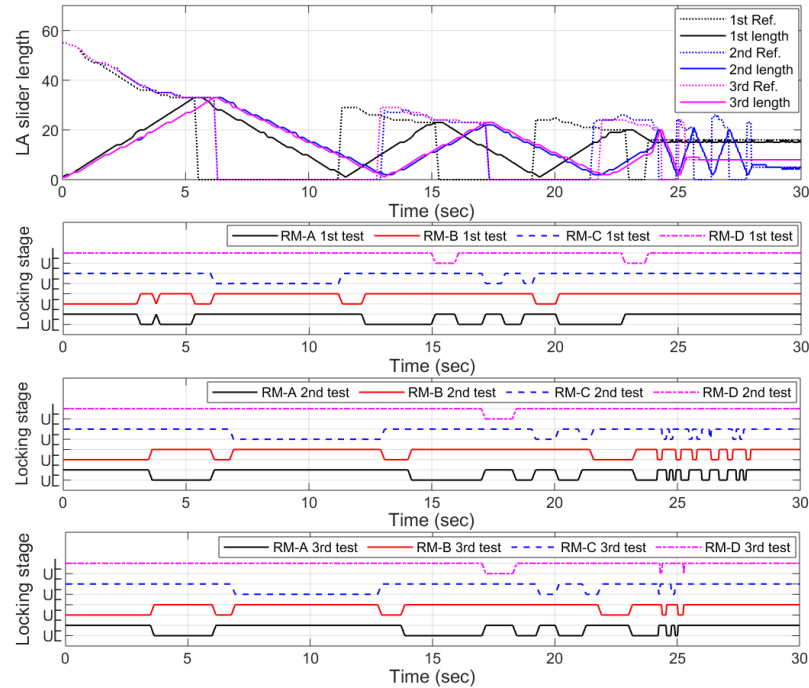


Figure F-19 Control signal comparison of the three repetitive tests generated by the proposed control rule for moving the end-effector to the target position and angle ($LA_{ref}(210^\circ, 35mm, -8^\circ)$): (top) the LA-slider targets and movement, (three-bottom) the first, second and third locking and unlocking control procedures of the PRMs or RMs (A to D).

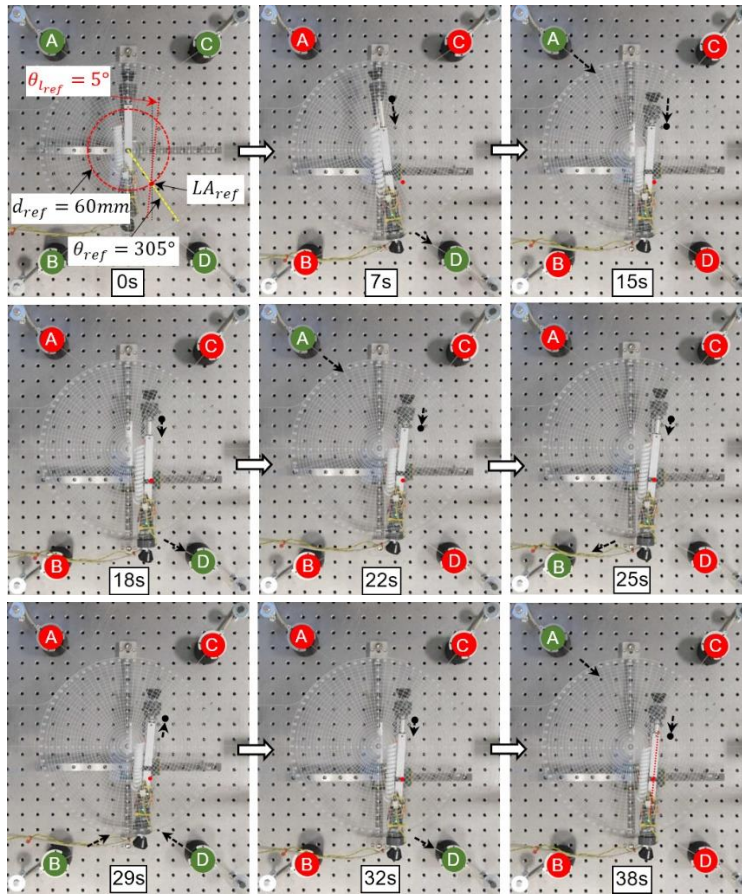


Figure F-20 Video frames of the end-effector position and angle control experimentations ($LA_{ref}(305^\circ, 60mm, 5^\circ)$).

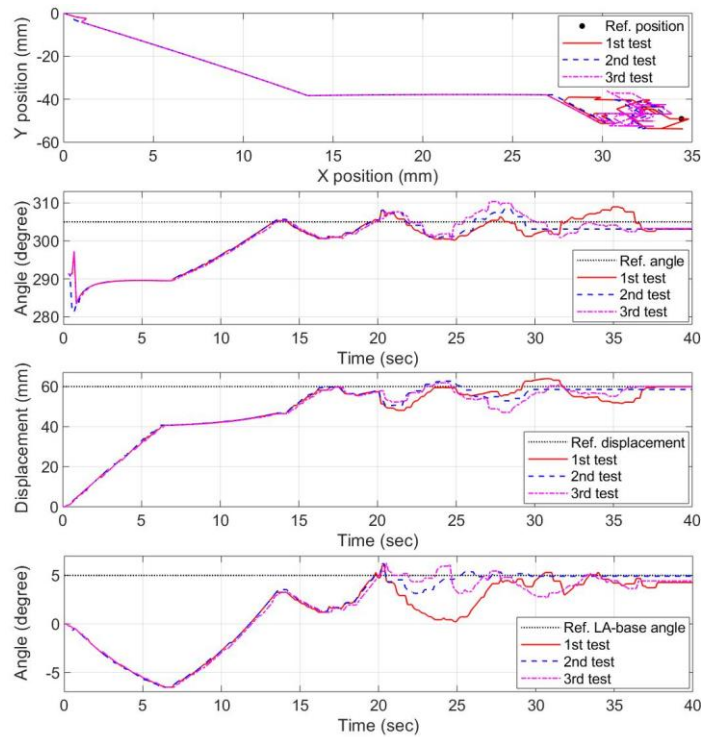


Figure F-21 Experimental results of the end-effector position and angle control ($LA_{ref}(305^\circ, 60mm, 5^\circ)$): (top) the end-effector movements in X-Y plane, (middle) the end-effector moving to the target angle and (bottom) the end-effector moving to the target position.

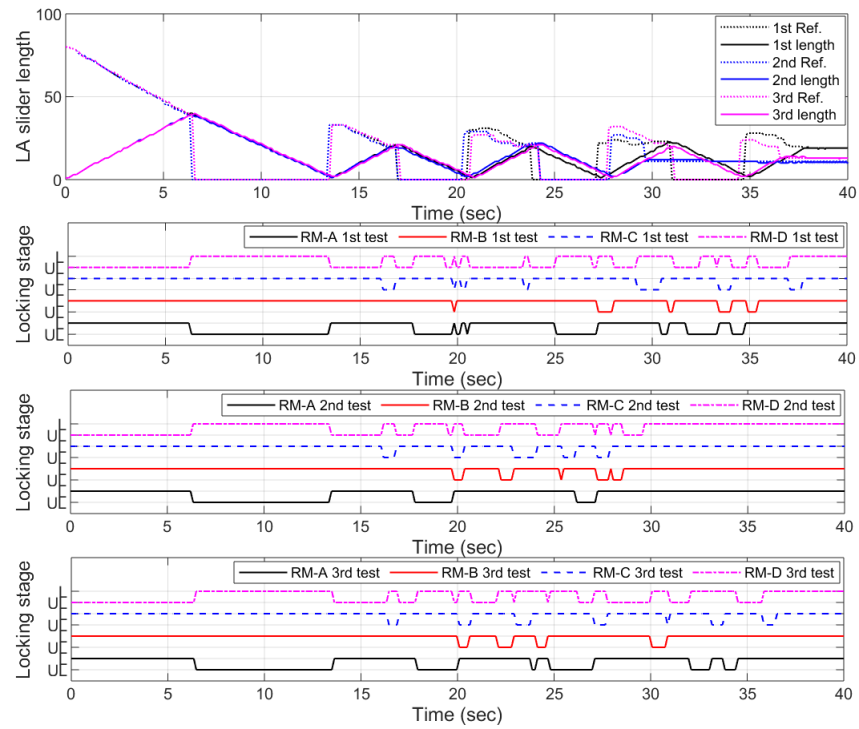


Figure F-22 Control signal comparison of the three repetitive tests generated by the proposed control rule for moving the end-effector to the target position and angle ($LA_{ref}(305^\circ, 60mm, 5^\circ)$): (top) the LA-slider targets and movement, (three-bottom) the first, second and third locking and unlocking control procedures of the PRMs or RMs (A to D).

References

- [1] A. Tantaworrasilp and R. C. Richardson, "Metamorphic tensegrity structure for pipe inspection," In IOP Conference Series: Materials Science and Engineering, 2020, vol. 715, no. 1, p. 012087.
- [2] R. Fuller, "Tensile-integrity structures," U. S. Patent 3063521, April, 1962.
- [3] K. Snelson, "Continuous tension, discontinuous compression structures," U. S. Patent 3169611, Feb., 1965.
- [4] A. Pugh, *an introduction to tensegrity*. United States of America: University of California Press, 1976.
- [5] R. E. Skelton and M. C. de Oliveira, *Tensegrity systems*. University of California, USA: Springer, 2009.
- [6] V. SunSpiral, G. Gorospe, J. Bruce, A. Iscen, G. Korbelt, S. Milam, A. Agogino and D. Atkinson, "Tensegrity based probes for planetary exploration: Entry, descent and landing (EDL) and surface mobility analysis," *International Journal of Planetary Probes*, vol. 7, 2013.
- [7] K. Kim, A. K. Agogino, D. Moon, L. Taneja, A. Toghyan, B. Dehghani and V. SunSpiral, "Rapid prototyping design and control of tensegrity soft robot for locomotion," In IEEE International Conference on Robotics and Biomimetics (ROBIO), 5-10 Dec. 2014, pp. 7-14.
- [8] L.-H. Chen, K. Kim, E. Tang, K. Li, R. House, E. L. Zhu, K. Fountain, A. M. Agogino, A. Agogino, V. SunSpiral and E. Jung, "Soft spherical tensegrity robot design using rod-centered actuation and control," In ASME International Design Engineering Technical Conferences & Computers and Information in Engineering Conference (IDETC/CIE 2016), Charlotte, North Carolina, 21-24 Aug. 2016.
- [9] A. Luo, H. Xin, P. Cao, X. Hao, Y. Yu, P. Sun and W. Tian, "Motion simulation of six-bar tensegrity robot based on Adams," In IEEE International Conference on Mechatronics and Automation, 7-10 Aug. 2016, pp. 264-269.
- [10] V. Bohm, T. Kaufhold, F. Schale, and K. Zimmermann, "Spherical mobile robot based on a tensegrity structure with curved compressed members," In IEEE International Conference on Advanced Intelligent Mechatronics (AIM), 12-15 July 2016, pp. 1509-1514.
- [11] V. SunSpiral, A. Agogino, and D. Atkinson, "Super Ball Bot-Structures for Planetary Landing and Exploration, NIAC Phase 2 Final Report," National Aeronautics and Space Administration (NASA), Intelligent Systems Division, USA, Sep. 2015.

- [12] B. T. Mirletz, I.-W. Park, R. D. Quinn, and V. SunSpiral, "Towards bridging the reality gap between tensegrity simulation and robotic hardware," In IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2015, pp. 5357-5363.
- [13] B. T. Mirletz, I.-W. Park, T. E. Flemons, A. K. Agogino, R. D. Quinn, and V. SunSpiral, "Design and control of modular spine-like tensegrity structures," In Proc. of The 6th World Conference of the International Association for Structural Control and Monitoring (6WCSCM), Barcelona, Spain, July 2014.
- [14] J. M. Friesen, P. Glick, M. Fanton, P. Manovi, A. Xydes T. Bewley and V. Sunspirai, "The second generation prototype of a Duct Climbing Tensegrity robot, DuCTTv2," In IEEE International Conference on Robotics and Automation (ICRA), 16-21 May 2016, pp. 2123-2128.
- [15] J. Friesen, A. Pogue, T. Bewley, M. d. Oliveira, R. Skelton, and V. Sunspirai, "DuCTT: A tensegrity robot for exploring duct systems," In IEEE International Conference on Robotics and Automation (ICRA), 31 May-7 June 2014, pp. 4222-4228.
- [16] Y. S. Chung, J.-H. Lee, J. H. Jang, H. R. Choi, and H. Rodrigue, "Jumping Tensegrity Robot Based on Torsionally Prestrained SMA Springs," *ACS applied materials & interfaces*, vol. 11, no. 43, pp. 40793-40799, 2019.
- [17] J. Rieffel, F. Valero-Cuevas, and H. Lipson, "Automated discovery and optimization of large irregular tensegrity structures," *Computers & Structures*, vol. 87, no. 5, pp. 368-379, 2009.
- [18] A. Tibert and S. Pellegrino, "Deployable tensegrity reflectors for small satellites," *Journal of Spacecraft and Rockets*, vol. 39, no. 5, pp. 701-709, 2002.
- [19] D. E. Ingber, "Cellular tensegrity: defining new rules of biological design that govern the cytoskeleton," *Journal of cell science*, vol. 104, no. 3, pp. 613-627, 1993.
- [20] N. Wang, K. Naruse, D. Stamenovic, J. J. Fredberg, S. M. Mijailovich, I. M. T-Norrelykke, T. Polte, R. Mannix and D. E. Ingber, "Mechanical behavior in living cells consistent with the tensegrity model," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 98, no. 14, pp. 7765-7770, Jul 2001.
- [21] S. Lessard, J. Bruce, E. Jung, M. Teodorescu, V. SunSpiral, and A. Agogino, "A lightweight, multi-axis compliant tensegrity joint," In IEEE International Conference on Robotics and Automation (ICRA), 16-21 May 2016, pp. 630-635.
- [22] S. Lessard, D. Castro, W. Asper, S. D. Chopra, L. B. B-Admony, M. Teodorescu, V. SunSpiral and A. Agogino, "A bio-inspired tensegrity manipulator with multi-DOF, structurally compliant joints," In IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 9-14 Oct. 2016, pp. 5515-5520.

- [23] J. Zhang and M. Ohsaki, "Adaptive force density method for form-finding problem of tensegrity structures," *International Journal of Solids and Structures*, vol. 43, no. 18-19, pp. 5658-5673, 2006.
- [24] M. Masic, R. E. Skelton, and P. E. Gill, "Algebraic tensegrity form-finding," *International Journal of Solids and Structures*, vol. 42, no. 16-17, pp. 4833-4858, Aug 2005.
- [25] A. Tibert and S. Pellegrino, "Review of form-finding methods for tensegrity structures," *International Journal of Space Structures*, vol. 26, no. 3, pp. 241-255, Sep. 2011.
- [26] J. Y. Zhang and M. Ohsaki, "Adaptive force density method for form-finding problem of tensegrity structures," *International Journal of Solids and Structures*, vol. 43, no. 18-19, pp. 5658-5673, Sep 2006.
- [27] R. Connelly and A. Back, "Mathematics and Tensegrity: Group and representation theory make it possible to form a complete catalogue of "strut-cable" constructions with prescribed symmetries," *American Scientist*, vol. 86, no. 2, pp. 142-151, 1998. [Online]. Available: <http://www.jstor.org/stable/27856980>.
- [28] J. M. M. Tur and S. H. Juan, "Tensegrity frameworks: Dynamic analysis review and open problems," *Mechanism and Machine Theory*, vol. 44, no. 1, pp. 1-18, Jan 2009.
- [29] C. Sultan, M. Corless, and R. E. Skelton, "Linear dynamics of tensegrity structures," *Engineering Structures*, vol. 24, no. 6, pp. 671-685, June 2002.
- [30] A. Iscen, K. Caluwaerts, J. Bruce, A. Agogino, V. SunSpiral, and K. Tumer, "Learning Tensegrity Locomotion using Open-Loop Control Signals and Coevolutionary Algorithms," *Artificial Life Journal*, vol. 21, no. 2, pp. 119-140. May 2015.
- [31] J. Bruce, K. Caluwaerts, A. Iscen, A. P. Sabelhaus, and V. SunSpiral, "Design and evolution of a modular tensegrity robot platform," In IEEE International Conference on Robotics and Automation (ICRA), 31 May-7 June 2014, pp. 3483-3489.
- [32] G. Mishra, "Tensegrity structures- benefits and applications in civil engineering. The Constructor- Civil Engineering Home.", [Online]. Available: <https://theconstructor.org/structures/tensegrity-structures-benefits-applications/14181/>. [Accessed 22 March, 2017].
- [33] C. Paul, F. J. Valero-Cuevas, and H. Lipson, "Design and control of tensegrity robots for locomotion," *IEEE Transactions on Robotics*, vol. 22, no. 5, pp. 944-957, 2006.
- [34] J. Rieffel, R. J. Stuk, F. J. Valero-Cuevas, and H. Lipson, "Locomotion of a tensegrity robot via dynamically coupled modules," In Proc. of the International Conference on Morphological Computation, 2007.

- [35] A. Iscen, A. Agogino, V. SunSpiral, and K. Tumer, "Controlling tensegrity robots through evolution," In Proc. of the 15th annual conference on Genetic and evolutionary computation, Amsterdam, Netherlands, 2013.
- [36] C. Paul, J. W. Roberts, H. Lipson, F. J. V. Cuevas and IEEE, "Gait production in a tensegrity based robot," In 12th International Conference on Advanced Robotics, 2005, pp. 216-222.
- [37] C. Paul, H. Lipson, and F. J. V. Cuevas, "Evolutionary form-finding of tensegrity structures," In Proc. of the 7th Annual Conference on Genetic and Evolutionary Computation Conference (GECCO), June 2005, pp. 3-10.
- [38] J. Rieffel, B. Trimmer, and H. Lipson, "Mechanism as Mind-What Tensegrities and Caterpillars Can Teach Us about Soft Robotics," In ALIFE, 2008, pp. 506-512.
- [39] J. A. Rieffel, F. J. Valero-Cuevas, and H. Lipson, "Morphological communication: exploiting coupled dynamics in a complex mechanical structure to achieve locomotion," *Journal of the Royal Society Interface*, vol. 7, no. 45, pp. 613-621, 2009.
- [40] A. Iscen, A. Agogino, V. SunSpiral, and K. Tumer, "Learning to control complex tensegrity robots," In Proc. of the International Conference on Autonomous Agents and Multi-Agent Systems, 2013, pp. 1193-1194.
- [41] B. R. Tietz, R. W. Carnahan, R. J. Bachmann, R. D. Quinn, and V. SunSpiral, "Tetraspine: Robust terrain handling on a tensegrity robot using central pattern generators," In IEEE/ASME International Conference on Advanced Intelligent Mechatronics, 9-12 July 2013, pp. 261-267.
- [42] T. Bliss, T. Iwasaki, and H. Bart-Smith, "Central Pattern Generator Control of a Tensegrity Swimmer," *IEEE/ASME Transactions on Mechatronics*, vol. 18, no. 2, pp. 586-597, 2013.
- [43] T. Bliss, J. Werly, T. Iwasaki, and H. Bart-Smith, "Experimental Validation of Robust Resonance Entrainment for CPG-Controlled Tensegrity Structures," *IEEE Transactions on Control Systems Technology*, vol. 21, no. 3, pp. 666-678, 2012.
- [44] T. K. Bliss, T. Iwasaki, and H. Bart-Smith, "CPG control of a tensegrity morphing structure for biomimetic applications," In *Advances in Science and Technology*, vol. 58, pp. 137-142, 2008.
- [45] O. Orki, "A Model of Caterpillar Locomotion Based on Assur Tensegrity Structures," M. S. thesis, TEL AVIV UNIVERSITY, Tel Aviv, Israel, 2012.
- [46] O. Orki, A. Ayali, O. Shai, and U. Ben-Hanan, "Modeling of caterpillar crawl using novel tensegrity structures," *Bioinspiration & biomimetics*, vol. 7, no. 4, p. 046006, 2012.

- [47] K. W. Moored, S. A. Taylor, T. K. Bliss, and H. Bart-Smith, "Optimization of a tensegrity wing for biomimetic applications," In Proc. of the 45th IEEE Conference on Decision and Control, 2006, pp. 2288-2293.
- [48] K. Kim, L.-H. Chen, B. Cera, M. Daly, E. Zhu, and J. Despois, "Hopping and Rolling Locomotion with Spherical Tensegrity Robots," In IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Daejeon, Korea, 9-14 Oct. 2016, pp. 4369-4376.
- [49] J. M. M. Tur, "On the Movement of Tensegrity Structures: November 1, 2009," *International Journal of Space Structures*, vol. 25, no. 1, pp. 1-13, 2010.
- [50] M. Shibata, F. Saijyo, and S. Hirai, "Crawling by body deformation of tensegrity structure robots," In IEEE International Conference on Robotics and Automation ICRA '09., 12-17 May 2009, pp. 4375-4380.
- [51] A. P. Sabelhaus, J. Bruce, K. Caluwaerts, P. Manovi, R. F. Firoozi, S. Dobi, A. M. Agogino and V. SunSpiral, "System design and locomotion of SUPERball, an untethered tensegrity robot," In IEEE International Conference on Robotics and Automation (ICRA), 26-30 May 2015, pp. 2867-2873.
- [52] Y. Koizumi, M. Shibata, and S. Hirai, "Rolling tensegrity driven by pneumatic soft actuators," In IEEE International Conference on Robotics and Automation (ICRA), 2012, pp. 1988-1993.
- [53] S. Hirai, Y. Koizumi, M. Shibata, M. Wang, and L. Bin, "Active shaping of a tensegrity robot via pre-pressure," In IEEE/ASME International Conference on Advanced Intelligent Mechatronics, 9-12 July 2013, pp. 19-25.
- [54] K. Caluwaerts, "Design and Computational Aspects of compliant tensegrity robots," PhD. thesis, University of Gent, Gent, Netherlands, 2014.
- [55] K. Caluwaerts, J. Despraz, A. Iscen, A. P. sabelhaus, J. Bruce, B. Schrauwen and V. SunSpiral, "Design and control of compliant tensegrity robots through simulation and hardware validation," *Journal of The Royal Society Interface*, vol. 11, no. 98, p. 20140520, 6 Sep. 2014.
- [56] M. Vespignani, J. M. Friesen, V. SunSpiral, and J. Bruce, "Design of superball v2, a compliant tensegrity robot for absorbing large impacts," In IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2018, pp. 2865-2871.
- [57] K. Kim, D. Moon, J. Y. Bin, and A. M. Agogino, "Design of a spherical tensegrity robot for dynamic locomotion," In IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 24-28 Sept. 2017, pp. 450-455.
- [58] T. J. Chen, C. C. Wu, M. J. Tang, J. S. Huang, and F. C. Su, "Complexity of the Tensegrity Structure for Dynamic Energy and Force Distribution of Cytoskeleton during Cell Spreading," *Plos One*, vol. 5, no. 12, Dec 2010.

- [59] D. Ingber, "In search of cellular control: Signal transduction in context," *Journal of Cellular Biochemistry*, pp. 232-237, 1998.
- [60] C. S. Chen and D. E. Ingber, "Tensegrity and mechanoregulation: from skeleton to cytoskeleton," *Osteoarthritis and Cartilage*, vol. 7, no. 1, pp. 81-94, Jan 1999.
- [61] N. Hogan, "Impedance control: An approach to manipulation," In American Control Conference, 1984, pp. 304-313.
- [62] T. Flemons, "The Bones of Tensegrity", [Online]. Available: http://www.intensiondesigns.com/bones_of_tensegrity.html. [Accessed 12 June, 2017].
- [63] A. J. Ijspeert, A. Crespi, D. Ryczko, and J.-M. Cabelguen, "From swimming to walking with a salamander robot driven by a spinal cord model," *science*, vol. 315, no. 5817, pp. 1416-1420, 2007.
- [64] E. Coumans, "Bullet physics library," 30 July 2015. [Online]. Available: <https://dl.acm.org/doi/10.1145/2776880.2792704>. [Accessed 12 June, 2017]
- [65] A. P. Sabelhaus, H. Ji, P. Hylton, Y. Madaan, C. Yang, A. M. Agogino, J. Friesen and V. SunSpiral, "Mechanism design and simulation of the ULTRA Spine: a tensegrity robot," In Proc. International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, 2015, Vol 5a.
- [66] T. White, N. Hower, B. Luk, and J. Hazel, "The design and operational performance of a climbing robot used for weld inspection in hazardous environments," In Proc. of the IEEE International Conference on Control Applications, 1998, vol. 1, pp. 451-455.
- [67] W. Neubauer, "A spider-like robot that climbs vertically in ducts or pipes," in *Intelligent Robots and Systems' 94. 'Advanced Robotic Systems and the Real World', IROS'94. Proceedings of the IEEE/RSJ/GI International Conference on*, 1994, vol. 2: IEEE, pp. 1178-1185.
- [68] J. Friesen, "DuCTT color tracking for data.", [Online]. Available: <https://www.youtube.com/watch?v=p0ZOIWt7Rhs>. [Accessed 12 June, 2017].
- [69] J. Friesen, "DuCTT Robot, First Climb of a Short Duct Section.", [Online]. Available: <https://www.youtube.com/watch?v=WuRCIqdhj0o>. [Accessed 6 June, 2017].
- [70] A. Plummer and G. Lai, "New concepts for parallel kinematic mechanisms using fluid actuation," In 7th International conference on Fluid Power and Mechatronics, University of Bath, 2015.
- [71] G. Lai, A. Plummer, D. Cleaver, and H. Zhou, "Parallel kinematic mechanisms for distributed actuation of future structures," *Journal of Physics: Conference Series*, 2016, vol. 744, p. 012169.

- [72] A. Luo, S. Che, and H. Liu, "The driving of the six-bar tensegrity robot," In IEEE International Conference on Robotics and Biomimetics (ROBIO), 5-8 Dec. 2017, pp. 640-645.
- [73] J. Friesen, "DucTT, a tensegrity robot developed at UC San Diego.", [Online]. Available: <https://www.youtube.com/watch?v=TKANwv6u4SA>. [Accessed 16 May, 2017].
- [74] R. L. Williams and P. Gallina, "Planar Cable-Direct-Driven Robots: Part I—Kinematics and Statics," In International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, vol. 80234: American Society of Mechanical Engineers, 2001, pp. 1233-1240.
- [75] K. Caluwaerts, M. D'Haene, D. Verstraeten, and B. Schrauwen, "Locomotion Without a Brain: Physical Reservoir Computing in Tensegrity Structures," *Artificial Life*, vol. 19, no. 1, pp. 35-66, 2013.
- [76] L.-H. Chen, B. Cera, E. L. Zhu, R. Edmunds, F. Rice, A. Bronars, E. Tang, S. R. Malekshahi, O. Romero, A. K. Agogino and A. M. Agogino, "Inclined surface locomotion strategies for spherical tensegrity robots," In IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 24-28 Sept. 2017, pp. 4976-4981.
- [77] L.-H. Chen, O. Romero, E. L. Zhu, M. C. Daly, B. Cera, F. Ghahani, S. R. Malekshahi, C. U. Spangenberg, G. Emmendorfer, E. Tang, Y. W. Chau, A. K. Agogino and A. M. Agogino, "Modular elastic lattice platform for rapid prototyping of tensegrity robots," In International Design Engineering Technical Conferences and Computers and Information in Engineering Conference (ASME), Aug. 2017.
- [78] K. Kim, A. K. Agogino, A. Toghyan, D. Moon, L. Taneja, and A. M. Agogino, "Robust learning of tensegrity robot control for locomotion through form-finding," In IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Oct. 2015, pp. 5824-5831.
- [79] M. Vespignani, C. Ercolani, J. M. Friesen, and J. Bruce, "Steerable locomotion controller for six-strut icosahedral tensegrity robots," In IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2018, pp. 2886-2892.
- [80] K. Kim, A. K. Agogino, A. Toghyan, D. Moon, L. Taneja and A. M. Agogino, "Robust Learning of Tensegrity Robot Control for Locomotion through Form-Finding," In IEEE/RSJ International Conference on Intelligent Robots and Systems, 2015, pp. 5824-5831.
- [81] A. Iscen, A. Agogino, V. SunSpiral, and K. Tumer, "Flop and roll: Learning robust goal-directed locomotion for a Tensegrity Robot," In IEEE/RSJ International Conference on Intelligent Robots and Systems, 14-18 Sept. 2014, pp. 2236-2243.

- [82] A. Iscen, A. Agogino, V. SunSpiral, and K. Tumer, "Controlling Tensegrity Robots through Evolution," In Proc. of the Genetic and Evolutionary Computation Conference (Gecco)'13, 2013, pp. 1293-1300.
- [83] V. Bohm and K. Zimmermann, "Vibration-driven mobile robots based on single actuated tensegrity structures," In IEEE International Conference on Robotics and Automation (ICRA), 6-10 May 2013, pp. 5475-5480.
- [84] J. M. Mirats-Tur and J. Camps, "A three-dof actuated robot," *IEEE robotics & automation magazine*, vol. 18, no. 3, pp. 96-103, 2011.
- [85] K. Caluwaerts *et al.*, "Design and control of compliant tensegrity robots through simulation and hardware validation," *Journal of The Royal Society Interface*, vol. 11, no. 98, 2014.
- [86] R. L. Williams, P. Gallina, and A. Rossi, "Planar cable-direct-driven robots, part i: Kinematics and statics," In Proceedings of the 27th ASME Design Technical Conference, 2001, no. 26, pp. 178-186.
- [87] ATC., "Material Contact Properties Table.", [Online]. Available: http://atc.sjf.stuba.sk/files/mechanika_vms_ADAMS/Contact_Table.pdf [Accessed 26 April, 2020].
- [88] C. A. Queener and G. E. Wood, "Spiral Power Springs. Part 1—Theory," *Journal of Engineering for Industry*, vol. 93, no. 2, pp. 667-675, 1971.
- [89] C. A. Queener and G. E. Wood, "Spiral Power Springs. Part 2—Design," *Journal of Engineering for Industry*, vol. 93, no. 2, pp. 676-682, 1971.
- [90] M. Plooi, G. Mathijssen, P. Cherelle, D. Lefeber, and B. Vanderborght, "Lock Your Robot: A Review of Locking Devices in Robotics," *IEEE Robotics & Automation Magazine*, vol. 22, no. 1, pp. 106-117, 2015.
- [91] Anonymous, "PIVOTED BLOCK OR SHOE BRAKE ", [Online]. Available: <http://mechdesign21.blogspot.com/2013/07/pivoted-block-or-shoe-brake.html>. [Accessed 27 April, 2020].
- [92] Pololu, "Force-Sensing Resistor.", [Online]. Available: <https://www.pololu.com/product/1696>. [Accessed 22 April, 2020].
- [93] I. electronics, "Force Sensing Resistor Integration Guide and Evaluation Parts Catalog." [Online]. Available: <https://cdn-learn.adafruit.com/assets/assets/000/010/126/original/fsrguide.pdf>. [Accessed 22 April, 2020].
- [94] Arduino, "MPU-6050 Accelerometer + Gyro", [Online] Available: <https://playground.arduino.cc/Main/MPU-6050/>. [Accessed 11 October, 2016].
- [95] D. Fedorov, A. Y. Ivoilov, V. Zhmud, and V. Trubin, "Using of measuring system MPU6050 for the determination of the angular velocities and linear accelerations," *Automatics & Software Enginry*, vol. 11, no. 1, pp. 75-80, 2015.

- [96] C. Mischke, "A method of relating factor of safety and reliability," [Online] Available: 1970, pp. 537-541. [Accessed 11 October, 2016].
- [97] C. Mischke, "Factor of Safety in Design and Engineering: The Basics.", [Online]. Available: <https://www.creativemechanisms.com/blog/factor-of-safety-in-design-and-engineering-the-basics>. [Accessed 11 October, 2016].
- [98] A. Spring, "Initial Tension", [Online]. Available: <https://www.acxesspring.com/initial-tension-in-extension-springs.html>. [Accessed 27 April, 2020].
- [99] RLS, "RM08 super small non-contact rotary encoder", [Online] Available: <https://www.rls.si/en/products/rotary-magnetic-encoders/incremental-encoders/rm08-super-small-non-contact-rotary-encoder>. [Accessed 10 April, 2020].
- [100] Simplify3D, "Filament Properties Table.", [Online]. Available: <https://www.simplify3d.com/support/materials-guide/properties-table/>. [Accessed 10 April, 2020].
- [101] Stratasys, "ABS-M30.", [Online]. Available: <https://www.stratasys.com/materials/search/abs-m30>. [Accessed 10 April, 2020].
- [102] A. m. d. Inc., "Miniature Linear Motion Series L12, " [Online]. Available: <https://s3.amazonaws.com/actuonix/Actuonix+L12+Datasheet.pdf>. [Accessed 18 April, 2020].
- [103] S. Tiwari, A. Bhatt, A. C. Unni, J. G. Singh, and W. Ongsakul, "Control of DC Motor Using Genetic Algorithm Based PID Controller," In International Conference and Utility Exhibition on Green Energy for Sustainable Development (ICUE), 24-26 Oct. 2018, pp. 1-6.
- [104] K. Ogata and Y. Yang, *Modern control engineering*. Prentice-Hall, 2002.
- [105] M. Abdellatif, H. Mohamed, M. Hesham, A. Abdelmoneim, A. Kamal, and A. Khaled, "Mechatronics design of an autonomous pipe-inspection robot," In MATEC Web of Conferences, 2018, vol. 153, p. 02002.
- [106] A. website, "Arduino," [Online]. Available: <https://www.arduino.cc/>. [Accessed 18 April, 2020].
- [107] Raspberrypi.org., "Raspberry Pi," [Online]. Available: <https://www.raspberrypi.org/>. [Accessed 18 April, 2020].
- [108] Beagleboard.org., "Beagleboard," 10 Sep. 2019, [Online]. Available: <https://beagleboard.org/>. [Accessed 18 April, 2020].
- [109] PJRC.com/teensy., "Teensy USB Development Board," [Online]. Available: <https://www.pjrc.com/teensy/>. [Accessed 18 April, 2020].

- [110] Z. KHAN, "How to choose a safety factor so a motor design lasts?", [Online]. Available: <https://www.motioncontroltips.com/faq-choose-safety-factor-motor-design-lasts/>. [Accessed 20 April, 2020].
- [111] F. Leens, "An introduction to I2C and SPI protocols," *IEEE Instrumentation & Measurement Magazine*, vol. 12, no. 1, pp. 8-13, 2009.
- [112] Y. L. Karnavas, A. S. Topalidis, and M. Drakaki, "Development and Implementation of a Low Cost μ C-Based Brushless DC Motor Sensorless Controller: A Practical Analysis of Hardware and Software Aspects," *Electronics*, vol. 8, no. 12, p. 1456, 2019.