Design of Spatial Interfaces for Engineering Assembly within a Virtual Environment

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The candidate confirms that the work submitted is her own and the appropriate credit has been given where reference has been made to the work of others.

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Abstract

This thesis presents studies on the design of a novel two-handed spatial interface for engineering assembly, informed by a number of qualitative studies using a realistic assembly model within a fully working virtual environment (VE). The results show that the two-handed spatial interface has the potential to reduce task-performance times by more than 25%, over an existing one-handed spatial interface. The VE is the IVPS (Interactive Virtual Prototyping System) at University of Leeds, which supports interactive engineering assembly. The main contribution of this research is to demonstrate an improved understanding of task performance for engineering assembly.

By understanding the assembly task-performance through the evaluation of the existing IVPS using a desktop-based interface, the strengths and weakness of the existing interaction techniques are studied. The results strongly suggest that there is a need to know if more expressive spatial interaction could improve the task-performance for engineering assembly within a VE.

By understanding the assembly task-performance through an evaluation of a one-handed spatial interaction model within the IVPS, a number of problems in spatial selection and positioning have been identified. They are the problems of *scale* (such as selecting a very small feature from a component), *slide* (such as manipulating constrained components in an assembly), *global precision* (such as manipulating the entire scene in which some components are long way from the centre of rotation) and *related precision* (such as manipulating the selected component related to the other components).

A novel cube-based two-handed spatial interface has therefore been designed to overcome these problems in spatial selection and positioning. It assigns to the non-dominant hand tasks such as positioning that can be performed by a sequence of 1DOF sub-tasks. This leaves the dominant-hand to perform the tasks such as 6DOF manipulation of assemblies, selection and attachment. This interface uses a physical cube to provide the user with a spatial frame of reference. The evaluation results show that the cube-based two-handed spatial interface has the potential to reduce the task-performance time by more than 25%, over the existing one-handed spatial interface. A tentative hypothesis is finally generalized and offers opportunities for further research.

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Chapter 1
Introduction

1.1 Motivation

Most engineered products – from pencil sharpeners to aircraft engines – are assembled units which consist of individual *components* or *parts*. *Assembly* is defined as joining and fastening of single, manufactured parts in a specified sequence into a complete product or a unit that is part of a product [Willemse 1997]. Assembly is one of the most important industrial processes in product development. It is estimated that a full 50% of manufacturing costs are tied up in the assembly process [Bedworth et al 1991]. Further, up to 70% of product development cost is committed by decisions made in the early stages of the design process [Lombardo et al 1996]. When evaluating alternate designs, ease of assembly is a key element in successful product development [Boothroyd & Dewhurst 1983]. Therefore, the great potential for increased productivity and significant reduction in production costs lies in the consideration of assembly requirements during the design stage of the product cycle. At this stage, prototypes, which represent important features of a product, are used to investigate assembly-related problems and prove design alternatives [Dai et al 1996].

Making physical prototypes is very time consuming and expensive. Recently, manufacturing industry has started to investigate the potential for replacing physical prototypes with *virtual prototypes* to reduce design time in manufacturing [Haug 1993, Anderson 1999]. A virtual prototype is defined as a computer based simulation of a prototype system or subsystem with a degree of functional realism that is comparable to that of a physical prototype [Haug 1993]. *Virtual prototyping* is therefore the process of using a virtual prototype, instead of a physical one. It enables simulation and functional experimentation of mechanical features (such as hinges, assemblies etc) of candidate designs. Hence the designs could be evaluated and modified at the conceptual design.

As CAD systems are widely used, a lot of product data are digitally available. This provides a good basis for virtual prototyping. However, early CAD (Computer Aided Design) systems as geometric modelers are used to perform the detailed design of individual components [Sodhi & Turner 1994]. The data structure is designed to store and manipulate geometric data and individual parts only. Such systems, therefore, facilitate the analysis of individual parts and components. However, in practice, the designer often wishes to consider an assembly rather than the individual components. *Assembly modelers* represent the newest trend in the world of CAD [Vasilash 1998]. Assembly modelers are defined [Zeid 1991] as advanced geometric modelers in which the data structure is extended to allow representation and manipulation of *assemblies* (including components and subassemblies) and *mating conditions (*or *assembly constraints)*. Mating conditions or assembly constraints define how components or subassemblies fit together. Constraints are used to align and orient parts in an assembly model with respect to each other [Howell 1998]. Assembly modelers, which facilitate the construction, modification and analysis of complex assemblies, are a critical component in engineering assembly. These modules are found in many widely used commercial CAD systems, including Pro-Engineer, Unigraphics, Catia, I-DEAS and Solidworks.

With the development of assembly modelers, a lot of design evaluations are already done in the form of virtual prototypes. But physical prototypes are still used in most cases. The benefits of physical prototypes rise from their spatial presence. Especially for conceptual design and product presentation, one can touch it, take it into the hand, and manipulate it to investigate assembly-related problems. Therefore, assembly modelers ask for better *user interfaces*. A user interface is the hardware and software that mediates the interaction between humans and computers [Hix & Hartson 1993]. Virtual environment (VE) is the enabling technology providing realistic presentation and intuitive, direct manipulation of virtual prototypes [Dai et al 1996].

A VE is a computer generated three dimensional (3D) model, where a participant can interact intuitively in real time with the environment or objects within it, and to some extent have a feeling of actually ‘being there’ [Wilson 1999]. Many modern VE display devices employ head tracking and stereoscopic projection (e.g. flat or curved screens, VE-desks and head-mounted displays), which have the potential to improve a user’s depth perception and sense of position and orientation within the three-dimensional environment. There are now a large number of VE interaction devices, both tracked and stationary, that enable users to navigate and manipulate artefacts within a VE with six degree of freedom (6DOF). Examples include the CyberGlove^{TM}, Stylus, VR Wand and Space Mouse. In additional, a range of general-purpose haptic feedback devices have also emerged, such as the PHANToM^{TM}, and the CyberGrasp^{TM} and CyberTouch^{TM} extensions to standard CyberGloves, that enhance the feedback to the user during interaction tasks [Jayaram et al 2001].

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A VE offers the potential for engineering assemblies to be viewed, manipulated and maintained in a three dimensional, interactive, synthetic environment [Jayaram et al 2001]. A VE also changes the way the engineers work by placing them inside the design and reducing, even eliminating, the need for physical prototypes. Within a VE [Dewar et al 1997], designers can interactively assemble and disassemble the components and analyze the assembly in *virtual space*, much the same way as they would explore a physical prototype in real space. Based on the interactive feedback, engineers can evaluate if and how the components fit, simplify the assembly structure, verify the assembly sequence, explore design alternatives, examine “what-if” situations and make changes more cheaply at an early stage of development. In this thesis, our interest is in modeling and manipulating engineering assemblies within a VE.

Many complex VEs remain in research laboratories, because while their functionality is impressive, their interfaces to that functionality are inconsistent, imprecise, inefficient, and perhaps unusable [Chu et al 1998]. User interface design is a critical component of any VE application. It plays a central role with respect to usability, usefulness and accuracy [Chu et al 1998]. The traditional desktop-based interfaces are still prevalent. However, they have started to show limitations when interacting with 3D models [Conner et al 1992, Gobbetti & Balaguer 1995]. With the rapid development of *spatial input* devices, spatial interfaces have been widely used for variety of 3D applications including engineering assembly [Jayaram et al 1999, Gomes & Zachmann 1999]. The term *spatial input* refers to interfaces based upon free-space 3D input technologies such as a magnetic tracker (stylus, glove, etc), as opposed to a desktop 2D or 3D mouse. Spatial interfaces enable the user to interact with the design by visualizing and moving around in 3D space. Positioning the components in 3D space is straightforward since the spatial input devices return six dimensions of input data. However, 3D positioning is difficult in the traditional interface. Either multiple views are needed or multiple reorientations of the 3D space have to be performed to get the 3D positioning just right.

However with spatial interfaces, new problems have also been revealed. People often find it inherently difficult to understand 3D spaces and to perform actions in free space [Zachmann & Rettig 2001]. The difficulties increase when dealing with complex engineering assembly environments that demand high precision and accuracy. In the real world, a worker utilizes natural constraints to obtain precise and efficient manipulation of components and tools. However, the natural constraints cannot currently be presented completely and accurately in a computer simulation. Therefore, great care must go into the design of more efficient and intuitive spatial interfaces for engineering assembly tasks.

1.2 An Interactive Virtual Prototyping System (IVPS) for Assembly

An Interactive Virtual Prototyping System (IVPS) has been designed and developed at University of Leeds over a number of years to support interactive assembly and the simulation of kinematic behaviour for component assemblies within a virtual environment [Fa et al 1993, Munlin 1995, Thompson et al 1998, Maxfield et al 2000]. It provides a suitable environment for the studies undertaken in this thesis. The software architecture of the IVPS used in this research is shown in Figure 1-1. The architecture integrates an *assembly model* and *interaction model*. The assembly model represents and maintains assembly constraints between components and supports the interactive assembly and disassembly of the product within the environment. The interaction model used in the IVPS enables the user to steer the simulation within the environment.

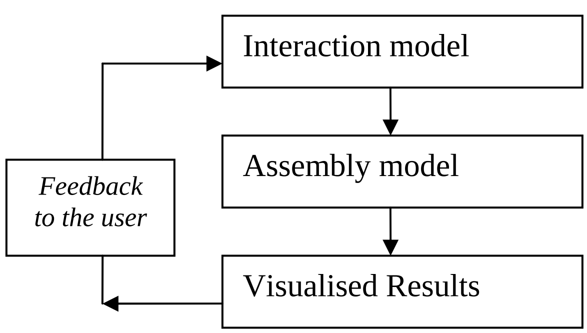

Figure 1-1 The IVPS software architecture

The assembly model allows different levels of geometry detail to be used as shown in Figure 1-2. A virtual prototype is represented as an *assembly* (or group) of *components* in a 3D *scene*. A component model is a more general representation than a solid model as it can be described geometrically as either a set of surface patches, a skin model, or as a solid model. One of the representations of component geometry within the IVPS is the *geometric features*. It represents a set of geometric shapes with specific quantifiable properties. This data can be exported from most popular CAD systems (e.g. CATIA, Pro-engineer, and I-DEAS) on a per component basis, and imported into the IVPS. During the import process the IVPS automatically analyses the data to extract and build a list of geometric features. Such features include basic geometric primitives, such as planar, cylindrical and spherical faces, as well as more complex geometric features, such as gears or helical surfaces (e.g. screw threads). All features have a number of basic quantifiable properties, for example dimensions, center point, axis, normal etc. Complex features contain more specialized properties, such as pitch diameter, number of teeth and gear type for gear features. The concept of geometric features provides the foundation for creating mechanical assemblies using feature matching techniques to automatically identify valid *mating conditions* or *assembly constraints* between compatible features. Currently, the assembly model supports against (between planar features), concentric (between cylindrical features), cylindrical fit (between opposing cylindrical features), spherical (between opposing spherical features) and gear fit (between gear features). Constraints can be created to locate components within the assembly. The interaction model uses the constraint relationship to support the interactive construction and dynamic manipulation of mechanical assemblies.

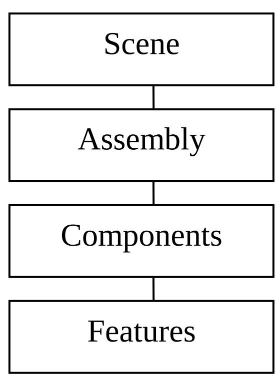

Figure 1-2 Assembly scene structure

The architecture of the IVPS interaction model is shown in Figure 1-3. The model is informed by the IVPS user interfaces. The model controls the interaction between the physical environment (input devices such as a mouse, stylus or gloves; output devices such as screens) and the virtual environment (interaction with the scene, sub-assemblies, components or features within the assembly model). With respect to output, the interaction model can be configured to support both mono and stereoscopic display on a wide variety of visual devices, from desktop monitors to multi-projection display systems. With respect to the input, the original interface presented by the interaction model has used a combination of mouse and keyboard input (see Chapter 2). In particular, the interaction model has been successfully tested on numerous NT and Unix-based workstations, the BMW Group Electronic Build Theatre (a dual screen stereo power wall), various Reality Centers™ and a dual-plane TAN Holobench (an L-shaped 3D projection table with two orthogonal projection surfaces). In this research, the interaction model has been enriched with two one-handed spatial interfaces using two spatial interaction devices (see Chapter 4): stylus and CyberGlove™, and a cube-based two-handed spatial interface (see Chapter 6).

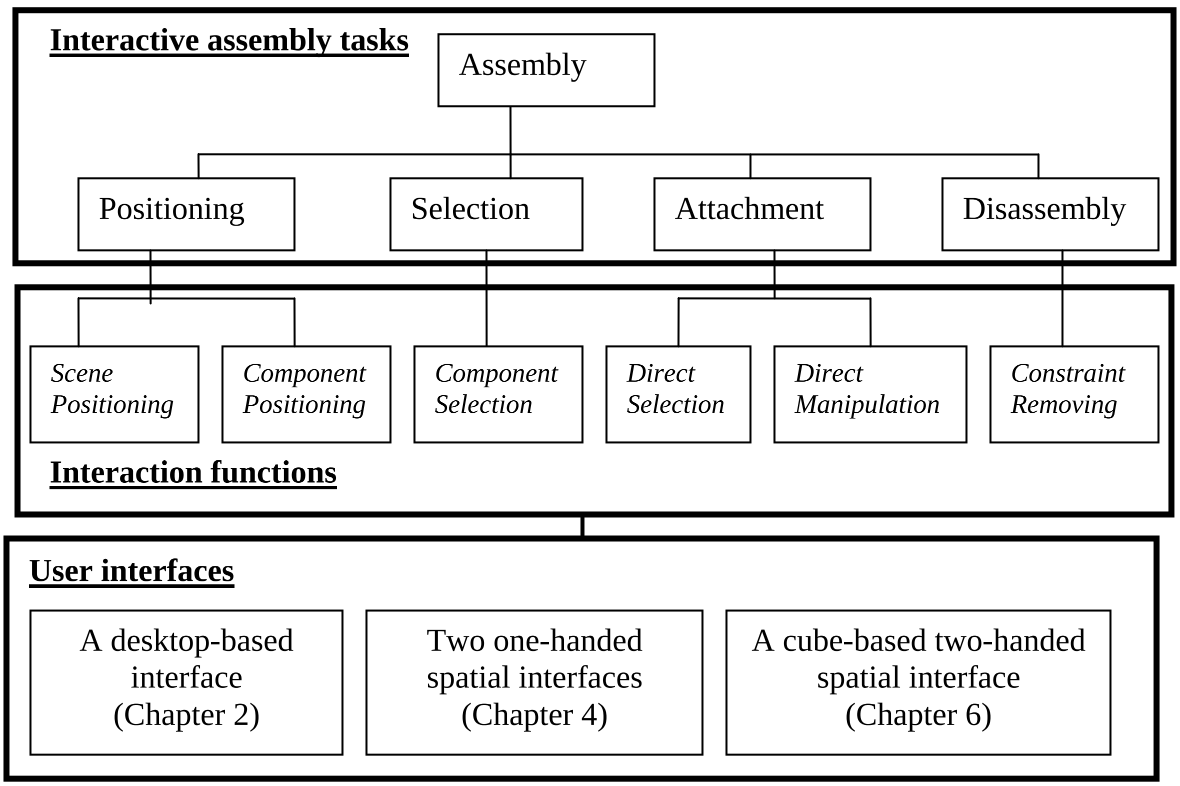

Figure 1-3 Architecture of the IVPS interaction model

The interaction model allows the user to perform the interactive assembly tasks including **selection**, **positioning**, **attachment** and **disassembly**. Positioning is also called *manipulation*. The model invokes a number of *interaction functions or techniques* for these tasks (Figure 1-4). To navigate within the environment, the user can manipulate the entire scene by *Scene Positioning.* The center of rotation is the center of the entire scene. This method is also called "scene-in-hand" [Dai et al 1996]. By *Component Selection*, the user can select a component within the environment using the "ray-casting" technique [Bowman & Hodges 1997]. In this technique, the user points at objects using a virtual ray emanating from the virtual representation (such as a virtual pointer or virtual hand) of the interaction devices. When the virtual ray intersects an object, the object can be selected and manipulated by *Component Positioning*. In *Component Positioning*, if the selected component is unconstrained, the user can manipulate (move or rotate) it freely within the environment. The centre of rotation is the centre of the *bounding box* of the selected component. A bounding box describes the tightest box which includes a component. This method is called object-centered manipulation [Mine 1997]. If the component is constrained with one or more mating conditions, its movement will be restricted so that the structural integrity of the parent assembly is maintained (i.e. a door is only able to rotate about its hinges) [Jayaram et al 1999].

In addition to selection and positioning, the interaction model also supports more advanced interactive attachment tasks. Mating conditions and constraints between components can be defined interactively in one of two ways; either *Direct Selection* or *Direct Manipulation*. *Direct Selection* requires the user to explicitly choose which geometric features to mate. After one feature has been selected, the interaction model provides some assistance by indicating features on other components that could form valid mating conditions. This method of constraint formation is most useful if the geometric features involved in the assembly process are known in advance. If the user wishes to experiment with the components to see what potential constraints can be formed or does not know how to assemble the components, then an alternative method is the *Direct Manipulation* approach. With *Direct Manipulation* the user is required to select a particular component and to move it within the environment. The interaction model then predicts all possible mating conditions that exist between the selected component and the nearest component to it in the assembly model. A valid mating condition is then highlighted using an appropriate color (depending on the type of mating condition).

The interaction model automatically repositions the components to precisely satisfy any selected mating condition and a new constraint is added to the assembly model. Each new constraint is maintained by the system during any subsequent manipulation. Thus the kinematic behaviour of an assembly is automatically simulated. This involves propagating the motion of a component to the components connected to it through constraints. The effect of this strategy is best illustrated with a simple example. Consider a cylindrical fit between a torus and a cylinder, the torus is allowed to translate along the length of the cylinder and to rotate about the cylinder's axis. This is the constraint's allowable motion. Moving the cylinder in a direction consistent with the constraint's allowable motion would have no effect on the torus. However, if the cylinder was translated in a direction perpendicular to the allowable motion of the constraint, then the torus must follow to maintain the constraint.

To disassemble two components, *Constraint Removing* is used to remove constraints between them, one by one in the reverse order to which they are applied.

1.3 Problem Space

There is the increasing use of the spatial interaction devices in many VE applications including engineering assembly. These devices return six degree-of-freedom (DOF) data. This allows the user to directly manipulate 3D virtual objects within a VE. The 6DOF spatial input facilitates the coarse manipulation of virtual objects [Mine et al 1997], but precise positioning of virtual objects is still hard. The difficulties of precise positioning increase when dealing with complex engineering assembly environments that demand high precision and accuracy [Zachmann & Rettig 2001]. The IVPS can be used to illustrate some of these limitations of existing approaches in spatial interaction. They include the following problems of precision. These problems are also demonstrated in the attached CD.

- the problem of *scale* (see Video 1 in the CD)

It is found difficult to position and select a geometric feature (or finding a feature within a whole scene) when the feature is very small compared with the total assembly. The user often needs to perform a sequence of "select-pull-release" [Mine et al 1997] steps to navigate to the required position using *Component Positioning* or *Scene Positioning*, which is inconvenient and time consuming [Mine et al 1997]. Moreover, the user needs more careful control of the tracked devices due to unavoidable electromagnetic interference in the environment [Jayaram et al 1999, Gomes & Zachmann 1999].

- the problem of *slide* (see Video 2 in the CD)

Manipulation of a constrained component in an assembly is thought as a natural and accurate manipulation in the IVPS as the system can simulate the kinematic behaviour of the assembly by maintaining any previously formed constraints. However, the constrained component easily slides out of its proper position when the mating conditions associated with the component are not fully specified during assembly process. Therefore the user cannot maintain the current precise position of the constrained component.

- the problem of *global precision* (see Video 3 in the CD)

The user often needs to position a virtual object to get proper view of the object. There is the *global precision* between the position of the virtual object and the user's point of view.

It is desirable to position the entire scene because this avoids having to switch models or select a component. However, precisely translating the entire scene can be problematic. It is natural that the user's hand would twist slightly when moving due to the biomechanical constraints of the hands and arms [Hinkley et al 1994b]. The slight twist would slightly rotate the entire scene. However, an object that is far from the centre of rotation would have a much greater angle of rotation. This makes it difficult to accurately position the object when translating the entire scene.

Viewing a feature which is on the inner side of a component (such as a hole, slot, etc) often requires the user finely rotating the component related to the user's viewpoint. However, precise rotation of an object is difficult by 6DOF input [Mine et al 1997].

- the problem of *related precision* (see Video 4 in the CD)

In an assembly, a component is often required to be positioned precisely related to another one [Zachmann & Rettig 2001]. There is the related precision between the position of two components. For example, to attach two components by *Direct Manipulation*, the selected component should be manipulated close to the other one. Moreover, the related position of the two components should be adjusted close to the final position determined by a mating condition between them. Thus the valid mating condition can be detected. This is found to be a difficult task using 6DOF spatial input.

1.4 Research Goal and Objectives

This research addresses the problems of precision in spatial selection and positioning for engineering assembly. The goal is to design an effective spatial interface to improve human performance when performing a set of engineering assembly tasks within a VE. The experimental platform is the IVPS. The goal is achieved through the following objectives:

- To evaluate the usability of the provided interaction techniques for interactive assembly tasks within the IVPS using a desk-top based user interface.
- To evaluate a one-handed spatial interaction model for engineering assembly using two spatial interaction devices.
- To design a novel cube-based two-handed spatial interface to overcome the problems of precision in the one-handed spatial interaction.
- To evaluate the cube-based two-handed spatial interaction against the task-performance achieved by the one-handed spatial interaction.
- To make recommendations for the future spatial interfaces

This thesis therefore focuses on the design of a novel spatial interaction model that supports efficient and precise spatial selection and positioning for engineering assembly within a VE, and facilitates a demonstrable improvement in the task performance of its users, over an existing interaction model.

1.5 Value and Contribution

The overall contribution of the research is an improved understanding of human task-performance for engineering assembly within a VE. The contributions are made to the fields of engineering assembly and human computer interaction within a VE. In particular:

- Understanding human task-performance through the evaluation of a 2D interaction model using a case study of gearbox assembly within the IVPS.
- Understanding human task-performance through the evaluation of an one-handed spatial interaction model using a case study of gearbox assembly within the IVPS.

- Understanding human task-performance through the evaluation of a novel two-handed spatial interaction model using a case study of gearbox casing assembly within the IVPS.

1.6 Methodology Issues

1.6.1 Qualitative Research Methodology

A *methodology* is defined as 'a general approach to studying research topics' [Silverman 2000: 88]. Research methodologies can be classified in various ways, however one of the most common distinctions is between *qualitative research* and *quantitative research* [Silverman 2000].

Quantitative research [Robson 1993] was originally developed in the natural sciences to study natural phenomena such as physics and chemistry – indeed it is sometimes known as the 'scientific method'. It assumes the existence of universal laws in which cause gives rise to effect and seeks to verify them using objective, 'hard' evidence. Research completed using quantitative methods is usually deductive – a hypothesis is proposed, an experiment is devised, and the hypothesis is confirmed, rejected or reviewed on the basis of the results of that experiment. The results are based on numerically measured observation of one or more variables.

Qualitative research (also called interpretive research), broadly defined, means "any kind of research that produces findings not arrived at by means of statistical procedures or other means of quantification" [Strauss & Corbin 1990: 17]. Qualitative research has a philosophical basis in which reality is subjective, created as a product of individual responses to the world, and hence directs research methods towards understanding the behaviours and characteristics of individuals and groups rather than seeking global laws. Qualitative research is often inductive, seeking to observe patterns, theories and concepts from the data that is collected, rather than testing specific theories against the data – *hypothesis-generating* rather than *hypothesis–testing*. It is recognised as being subjective, and biased by the values, actions and context of the researcher, and these features become recognised and discussed aspects of the research process.

There are various qualitative research methods. The choice of method should reflect an 'overall research strategy' [Mason 1996: 19] as the methodology shapes which methods are used and how each method is used [Silverman 2000: 88]. One of the qualitative research methods discussed here is *case study research*.

Case study [Yin 1994, Robson 1993] refers to the collection and presentation of detailed information about a particular participant or small group, frequently including the accounts of subjects themselves. A form of qualitative descriptive research, the case study looks intensely at an individual or small participant pool, drawing conclusions only about that participant or group and only in that specific context. Researchers do not focus on the discovery of a universal, generalizable truth, nor do they typically look for cause-effect relationships; instead, emphasis is placed on exploration and description. Unlike quantitative methods of research, like the survey, which focus on the questions of who, what, where, how much, and how many, and archival analysis, which often situates the participant in some form of historical context, case studies are the preferred strategy when how or why questions are asked. Likewise, they are the preferred method when the researcher has little control over the events, and when there is a contemporary focus within a real life context. Case studies typically examine the interplay of all variables in order to provide as complete an understanding of an event or situation as possible. This type of comprehensive understanding is arrived at through a process known as *deep data* or *thick description*, which involves an in-depth description of the entity being evaluated, the circumstances under which it is used, the characteristics of the people involved in it, and the nature of the community in which it is located. In case study research, the researcher will often act as a participant-observer, both observing activities and participating in them. The degree of participation may vary from complete group member (where the other participants may not even be aware of the 'observer' role) to a minimal level of participation. The main strength of case studies is their usefulness in teasing out explanatory hypotheses in complex (typically human-centred) circumstances. Researchers are comparatively freer to discover and address issues as they arise in their experiments. In addition, the looser format of case studies allows researchers to begin with broad questions and narrows their focus as their experiment progresses rather than attempt to predict every possible outcome before the experiment is conducted. In addition, the emphasis on deep data can help bridge the gap between abstract research and concrete practice by allowing researchers to compare their firsthand observations with the quantitative results obtained through other methods of research. The main weaknesses of case studies are their lack of representation of the population as a whole and the subjective biases of the observer, especially if they are participants in the case study.

1.6.2 Choosing a Methodology

The choice of research methodology were formed after consultation with the supervisors (Professor P.M.Dew and Dr. J. Maxfield). Both have backgrounds in information technology. They suggested that methods closer to the qualitative rather than the quantitative would be most appropriate. On reflection, this suggestion was an appropriate one for the following reasons:

- The context of the research is application-specific rather than generic. Moreover, measuring and characterizing human performance is difficult: it is much harder to specify the properties of any living system than it is to characterize even the most complicated of devices made by human beings [Gawron 2000]. The qualitative research would provide an in-depth understanding of human performance in its own context than would be obtained from purely quantitative data.
- A small group of users would be available.
- Less control of experimental conditions would be required.
- The findings would possibly generate hypotheses, which could be developed and tested – an example of hypothesis-generating research.

The research is therefore informed by a number of qualitative studies of the design and evaluation of spatial interfaces for engineering assembly using realistic assembly case studies within the IVPS.

1.6.3 Evaluation Methods

The research is informed by a number qualitative evaluations to assess the *usability* of interaction for engineering assembly. Usability defined in ISO 9241-11 as ‘the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use’ [ISO 9241-11].

Effectiveness pertains to accuracy and completeness, efficiency involves time and effort needed, and satisfaction considers comfort and acceptability. *Usability evaluation* is defined as the assessment of a specific application's user interface (often at the prototype stage), an interaction metaphor or technique, or an input device, for the purpose of determining its actual or probable usability [Bowman et al 2002]. An evaluation is related to human performance in the specific tasks supported by the computer system and to the user's attitude towards the system [Lindgaard 1994].

Measurement of task performance typically involves dealing with a range of measures, including objective measures and subjective measures [Gabbard et al 1999]. Objective measures provide a measure of performance against quantifiable parameters. In this research, task completion time is recorded by computer. Subjective measures reflect subjective opinions that are collected from trial participants. These collected qualitative data has a significant effect, either positive or negative, on user task performance or user satisfaction with the interface. Quantitative data generally indicate that a problem has occurred; qualitative data indicate where (and sometimes) why it occurred. Several advantages of subjective measures have been identified: "inexpensive, unobtrusive, easily administered, and readily transferable" [Casali & Wierwille 1983: 640]. The subjective measures used in this research are shown in Table 1-1. They are widely used for human performance studies either for the assessment of pilot workload [Fadden 1982] or evaluations of computer interfaces [Foley et al 1984, Kalawsky et al 1999].

Table 1-1 Subjective measures

Subjective measures	**Endpoints**	**Descriptions**
Task Difficulty	Easy, Difficult	Whether the task was easy, demanding, simple or complex, exacting or forgiving.
Overall Satisfaction	Perfect, Failure	How satisfied you were with what you accomplished and how successful you think were in doing what we asked you to do
Mental Effort	Low, High	The amount of mental and/or perceptual activity that was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.).
Physical Effort	Low, High	The amount of physical activity that was required (e.g., pushing, pulling, turning, controlling, activating, etc.).
Fatigue	Alert, Exhausted,	How tired, weary, worn out, and exhausted or fresh, vigorous, and energetic you felt.
Stress Level	Relaxed, Tense	How anxious, worried, uptight, and harassed or calm, tranquil, placid, and relaxed you felt.
Learnability	Easy, Difficult	How difficult you felt to learn the techniques required to perform the required tasks

The following prevailing forms of data collection associated with qualitative studies are used in this research:

- *Interviews*: a technique for gathering information about users by talking directly to them. Interviews are good for getting subjective reactions, opinions, and insights into how people reason about issues [Hix & Hartson 1993]. Written notes are used to record interview data in this research.

- *Observation:* The classical form of data collection in case study research is observation of participants in the context of a natural scene. Observation data used for the purpose of description – of settings, activities, people, and the meanings of what is observed from the perspective of the participants. Observation can lead to deeper understandings than interviews alone, because it provides knowledge of the context in which events occur, and may enable the researcher to see things that participants themselves are not aware of, or that they are unwilling to discuss [Patton 1990]. This research monitors both verbal and nonverbal cues in close observation of each participant performing a set of engineering assembly tasks in the given environments. Videotapes are used as means of accurately capturing a setting.

- *Post-Questionnaire*: a written set of questions used to obtain demographic information and views and interests of users after they have participated in a usability evaluation session [Hix & Hartson 1993]. Questionnaires are good for collecting subjective data and are often more convenient and more consistent than personal interviews. In this research, the questionnaire is accompanied by a subjective scale. The subjective scale is used for the assessment of subjective measures in Table 1-1. The scale is a seven-point subjective evaluation scale which has been developed by Boeing for use in the pilot certification of the Boeing 767 aircraft [Fadden 1982]. The thresholds are from 1 to 7. One of the examples is shown in Figure 1-4. It is used to measure the mental effort relevant to a task. The participant is asked to rate a score by ticking one box. In comparison with a ten-point scale, ten-point scale might be suitable for more sensitive issues, such as assessment of the mood effects of a sleep-inducing drug for aircrews [Shachem 1983]. The seven-scale might be easier to score as the participant would spend less time on the selection of one box from an array of seven than ten. In comparison with a five-point scale, the seven-point could produce more sensitive in-depth data. Therefore, the seven-point is chosen for the research rather than the ordinary scale such as five- or ten- point. Finally, in order for the readers to understand the results, the output of the scores is re-scaled according to the ordinary five-point scale. For a comparison of the same measure in two different environments, the difference on the five-point scale is used. If the difference is more than 1.0, the difference between the two environments would be big. If the difference is between 0.5 and 1.0, it would be medium. If the difference was less than 0.5, it would be small. The detailed data analysis is described in Chapter 4 & 6.

The amount of mental effort required for completing the task is

1	2	3	4	5	6	7
Low			Medium			High

Figure 1-4 Mental effort rating scale

1.6.4 Valid Issues

The price for this in-depth understanding is the potential risk of lacking objectivity, partly because the researcher has a stake in effecting a successful outcome of the project, and partly because of the interoperation dilemma. The following issues are addressed in order for the reader to judge the validity of the findings from the thesis.

The author's role

Marshall and Rossman [Marshall & Rossman 1989] emphasize the importance of giving an account of the researcher's own role in qualitative studies. The entrance, management of role, etc. of the researcher may have a considerable influence on the project. At the outset of this research, the author had received the Master's degree in Mechanical Engineering in China and many years of interest in computer graphics. The author had little knowledge of research methods and techniques commonly used in HCI. During the first year of the PhD research, the author covered a substantial part of the HCI literature and VE literature. The author had also done some practical work to understand the techniques in the IVPS and built up some experience and knowledge in software development. After gaining some knowledge in HCI, the author conducted a usability evaluation of the existing IVPS using the desktop-based interface. The usability defects of the 2D input for 3D application, and the requirements of spatial input are discussed (Chapter 3). At about the same time, the School of Computing was purchasing VE input / output devices. After more than one year, the devices were finally arrived and installed at the school. During the waiting period, the author had focused on studying the literature on engineering assembly within a VE, 3D technologies, and HCI research methodologies. Once the interaction devices (such as the stylus and CyberGlove) were available, the author spent a lot of time in learning and setting up the devices, and implementing the IVPS to support these devices. As both the researcher and system developer, the author learned continuously during the research process. Finally, it should make it clear that the author has very little formal training in the social sciences, within which this type of study is normally conducted.

Criteria for judgment

- *Validity & reliability*

Validity refers to the degree to which a study accurately reflects or assesses the specific concept that the researcher is attempting to measure. *Reliability* is the extent to which an experiment, test, or any measuring procedure yields the same result on repeated trials. While reliability is concerned with the accuracy of the actual measuring instrument or procedure, validity is concerned with the study's success at measuring what the researchers set out to measure. Validity depends less on sample size than the richness of the information gathered and on the analytical abilities of the researcher [Denzin & Lincoln 1994].

In this research, the following ways are used in order to aim at more valid and reliable findings:

- *Triangulation*

Triangulation refers to the attempt to get a ‘true’ fix on a situation by combining different ways of looking at it or different findings [Silverman 2000: 177]. This research uses multiple methods (observation, interviews and questionnaire) to get many different aspects of human performance when performing a particular task.

- The constant comparative method

The comparative method means that the qualitative researcher should always attempt to find another case through which to test out a provisional hypothesis. This method is employed in this research by comparing human performance in different environments (in terms of the use of different interfaces). Some results are also compared with the related literature.

- Using appropriate quantification

As mentioned in the previous section, this research uses the rating scale for the quantification of subjective measures. This make it easy to quantify consistency in human judgment. Moreover, this enable the researchers to test and to revise their generalizations, removing nagging doubts about the accuracy of their impressions about the data [Silverman 2000].

- Providing raw data

In order to demonstrate the neutrality of the research interpretations, this thesis provides the raw data of the evaluation studies (see Appendix B, C & D). This includes observation notes, video clips, user comments and measured results.

- Consistently using some procedure and measures

Both objective measures (such as task completion time) and subjective measures (such as mental effort, physical effort, stress, fatigue etc.) are consistently used in the evaluation studies (Chapter 4 & 6).

- *Transferability*

In quantitative research the common notion of generalizability of results does obviously not apply to the qualitative research [Lincoln & Guba 1985]. Instead, one speaks of "*transferability*" or "*exportability*", referring to the possibility for the readers to understand the results reported and adapt them to their own contexts. According to Cronbach, "*when we give proper weight to local conditions, any generalization is a working hypothesis, not a conclusion*" [Cronbach 1975: 125]. The transferability of a working hypothesis to other situations depends on the degree of similarity between the original situation and the situation to which it is transferred. The researcher cannot specify the transferability of findings; he or she can only provide sufficient information that can then be used by the reader to determine whether the findings are applicable to the new situation.

Since this thesis is intended to be hypothesis generation, a hypothesis is put forward that summarises and offers opportunities for further research (Chapter 6). A number of recommendations are made for future spatial interfaces. Moreover, other problem domains to which the findings are applicable are suggested (Chapter 7). These make an attempt to answer some of questions the readers may have related to the transferability issues. But apart from that, the reader will have to draw his own conclusions as to the transferability of the results.

1.7 Thesis Organization

Chapter 2 presents the background and literature review for engineering assembly within a VE. It begins with a description of the detailed interaction techniques within the IVPS using a desktop-based interface, and then it reviews the state-of-the-art engineering assemblies using 3D VE technologies. A classification of these interaction techniques is given, with respect to the tasks in engineering assembly. The evaluation studies in engineering assembly is then reviewed. These studies indicate precise interaction is found difficult due to the limitations in the VE hardware and software.

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Chapter 3 describes a usability evaluation of the existing IVPS using the desktop-based interface. The evaluation results show how people perform the engineering assembly tasks including selection, positioning, attachment and disassembly both in the real world and within the VE. The evaluation results discuss the limitations in the use of 2D input for tasks involving 3D selection and positioning operations during the assembly process. A set of implications have been generalized to develop a more efficient and intuitive spatial interface.

Chapter 4 assesses the usability of a one-handed spatial interaction model for engineering assembly. This chapter firstly describes the architecture of the one-handed spatial interaction model. Two spatial interfaces, a one-handed stylus and a one-handed glove interface, are implemented. An evaluation is conducted to evaluate the impact of the one-handed spatial interfaces on the task-performance for engineering assembly within the

VE. A number of problems of *precision* arise from the evaluation in spatial selection and positioning using the 6DOF spatial input. They include the problems of scale, slide, related and global precision. This chapter finally indicates there is a need to develop a more efficient and intuitive spatial interface to overecome these problems in spatial selection and positioning.

Chapter 5 presents the overall context of two-handed spatial interaction within a VE. The motivation of the use of two-handed interfaces for spatial interaction within a VE is firstly given. This chapter then reviews the literature on two-handed spatial interaction, and then describes the two-handed theory and experiments. A summary of the literature review is given. A new two-handed spatial interaction model is then designed to overcome the problems of precision identified in Chapter 4. A table-based two-handed spatial interface is implemented. The user feedback from the use of the table-based two-handed spatial interface indicates that this interface has not the potential to significantly improve the task-performance for engineering assembly. A number of reasons are discussed, and a set of implications are generalized for the design of a more efficient two-handed spatial interface.

Chapter 6 describes the design and evaluation of a novel cube-based two-handed spatial interface to improve the task-performance of spatial positioning and selection operations in engineering assembly. This interface overcomes the problems of slide, scale and global precision identified in Chapter 4. It assigns to the non-dominant hand tasks such as positioning that can be performed by a sequence of 1DOF sub-tasks. This leaves the dominant hand to perform 6DOF tasks such as selection, positioning and attachment. A physical cube is used to provide the non-dominant hand with a spatial frame of reference. The evaluation results show that the new interface has the potential to reduce the task performance times for assembly tasks by more than 25%, over an existing one-handed spatial interface. As the next stage improvements, the extended design of the cube-based interface is presented to address the problems of related precision and global precision in engineering assembly. Finally, a tentative hypothesis is generalized for further test and development.

Chapter 7 summarizes the thesis and presents recommendations for future research.

Chapter 2

Engineering Assembly within a Virtual Environment

VE technologies offer the potential for engineering assemblies to be viewed, manipulated and maintained in a three dimensional, interactive, synthetic environment. A VE also changes the way the engineers work by placing them inside the design and reducing, even eliminating, the need for physical prototypes. To support engineering assembly within a VE, a number of interaction techniques have been developed, and a number of 3D input/output devices have been used. This chapter therefore describes the existing interaction techniques in engineering assembly by using the IVPS as an example in section 2.1. The state-of-the-art engineering assembly systems using advanced VE technologies are then reviewed in section 2.2. A classification of the existing spatial interaction techniques in engineering assembly is given in section 2.3. To investigate the usability issues of the interaction techniques and VE interfaces, a number of evaluation studies have been undertaken in engineering assembly. These studies are reviewed in section 2.4. Finally, section 2.5 draws a conclusion of this chapter.

2.1 Interactive Assembly Using the IVPS

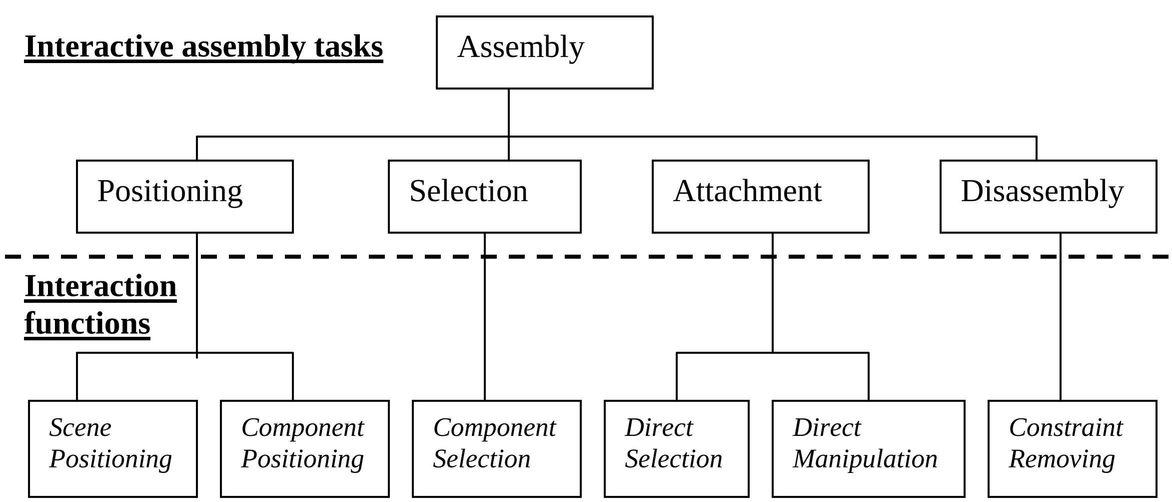


Figure 2-1 Architecture of the IVPS interaction model

As described in Chapter 1, the architecture of the IVPS interaction model is repeated in Figure 2-1. The original interface of the IVPS used a combination of mouse and keyboard input. In the desktop-based interaction model, 3D positioning operations are broken down into translation (2D translation in X, Y direction), zoom (1D translation in Z direction), and 3D rotation. Pressing mouse buttons or particular keys triggers events. These events are mapped onto interaction functions as shown in Table 2-1. The keys are largely used for changing the interaction mode. When the mode is changed, the text on the left top of the screen provides visual confirmation of the mode change to the user.

Table 2-1 Mouse and keyboard event mapping

Mouse Buttons & Keys	**Operations**
Left button (press and hold)	Rotate the scene in *Scene Positioning* mode; or rotate a selected component in *Component Selection* mode.
Left button (click and release)	Select a component in *Component Selection* mode, or select a feature in *Direct Selection* mode.
Middle button (press and hold)	Zoom the scene in *Scene Positioning* mode or a selected component in *Component Selection* mode.
Right button (press and hold)	Translate the scene or selected component in *Scene Positioning* or *Component Selection* respectively.
‘y’ key	Switch to *Component Selection* mode
‘n’ key	Switch to *Direct Selection* mode
‘m’ key	Switch to *Direct Manipulation* mode
‘u’ key	Switch to *Scene Positioning* mode
‘i' key	Accept constraint in *Direct Manipulation* mode
‘r’ key	Reset the scene back to the default position and orientation
‘o’ key	Undo and remove the last mating condition

Figure 2-2 The green box indicates the current component is selected by clicking the mouse left button

To positioning the entire scene in *Scene Positioning* mode, the user presses and holds the left, middle and right button for the operations of rotation, zooming and translating in X/Y direction. The center of rotation is the center of the scene. The scene can also be reset at anytime by pressing an appropriate key. The scene will then fly back to the default position when the screen window firstly opened. To select and position a component the user first presses the key to enter *Component Selection* mode, and then moves the mouse pointer over the component that the user wishes to select and click (press and release) the left mouse button once to confirm selection. Visual feedback is presented to the user during the selection process. While the user is selecting a component, a red bounding box is used to indicate which component the user is currently pointing to. When a component is actually selected the box changes to green as shown in Figure 2-2. When a component has been selected, the mouse is used to manipulate the selected component, rather than the scene. When the component is constrained with one or more mating conditions, manipulation of the constrained component will be propagated on to any connected component. Thus the kinematic behaviour of the constrained components can be simulated by manipulation of the selected component.

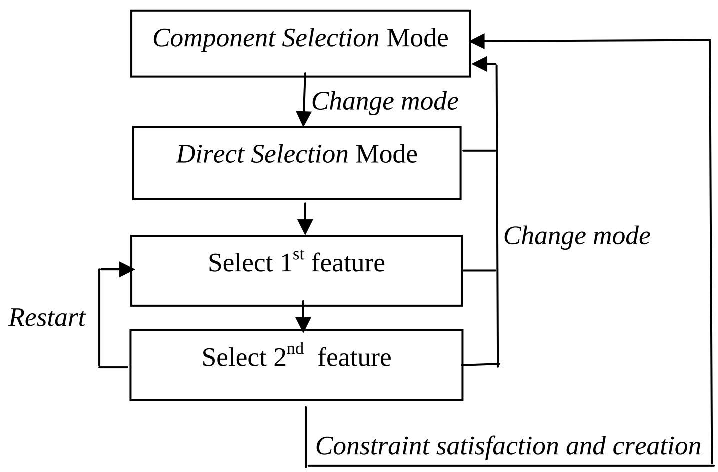
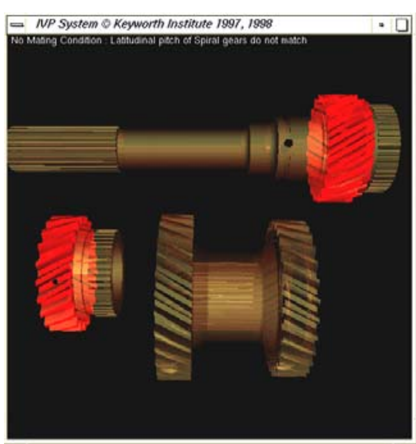
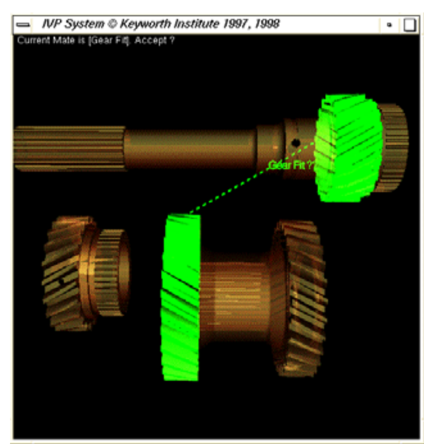


Figure 2-3 Process of using *Direct Selection*



a) The user selects two spiral gear entities that cannot be mated successfully



b) The user selects two spiral gear entities that can be mated successfully

Figure 2-4 Attaching two components using *Direct Selection*

To attach two components by creating a constraint using *Direct Selection* mode, the user must point to and select the features on the components using the mouse. Figure 2-3 shows the process of attaching two components with *Direct Selection*. In this mode the entire model becomes transparent so that the highlighted or selected geometric features can easily be distinguished from the rest of the model. When a feature is under mouse pointer, it is highlighted in red. Once selected, the first geometric feature remains highlighted and the system remains in *Direct Selection* mode, while a second feature is selected. Before selection, potential mating features are highlighted either in red or green to indicate whether a valid mating condition exists between them. If both features are highlighted in red then the IVPS cannot detect a valid mating condition between them as illustrated in Figure 2-4a. If a valid mating condition exists between the geometric features then both will be highlighted in green and linked by a dotted green line as illustrated in Figure 2-4b. This constraint can be accepted by selecting the second feature (i.e. click the left mouse button once while the second entity is under the mouse pointer). The IVPS will then satisfy and create the mating constraint, and switch back into the *Component Selection* mode. Leaving *Direct Selection* mode at any time can be achieved by pressing a key to revert back to the default *Component Selection* mode.

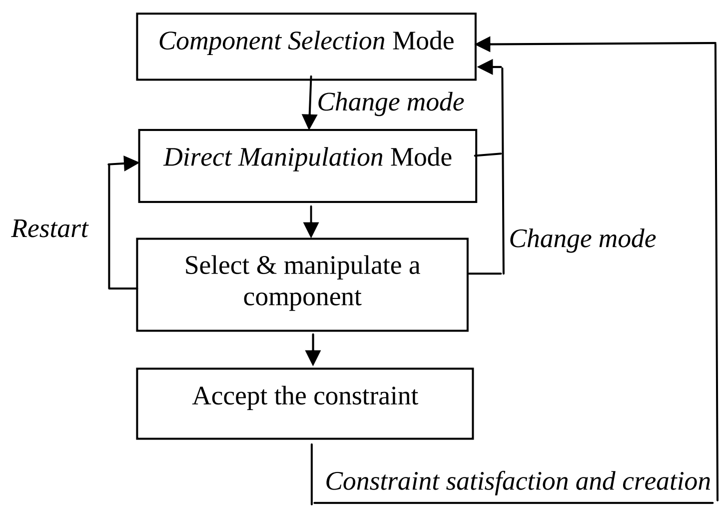


Figure 2-5 Process of using *Direct Manipulation*

Alternatively, to attach two components by forming a constraint using *Direct Manipulation* mode, the user must select a particular component and manipulate it while the system attempts to predict all possible mating conditions that exist given the current position and orientation of the selected component and its nearest components in the model. Figure 2-5 shows the process of constraining two components with *Direct*

Manipulation. In this mode, all components become transparent so that the highlighted geometric entities can be distinguished from the rest of the model. The selected component can be manipulated using the mouse. Each time the component is manipulated, the system will predict all valid mating conditions between the selected component and the nearest component to it in the model. The system assigns a probability to each potential mating condition to indicate how close it is to being satisfied and will display all of the predicted mating conditions by highlighting the geometric entities in a colour and shade dependent on the type of mating condition and its probability. An example of this is illustrated in Figure 2-6. At each step of the manipulation, the most likely constraint is offered to the user. This can be accepted by pressing a particular key to release the component. The system will then satisfy and create the necessary assembly constraint, and switch back into the *Component Selection* mode. The IVPS allows the user to remove a constraint which is last formed by pressing a key.

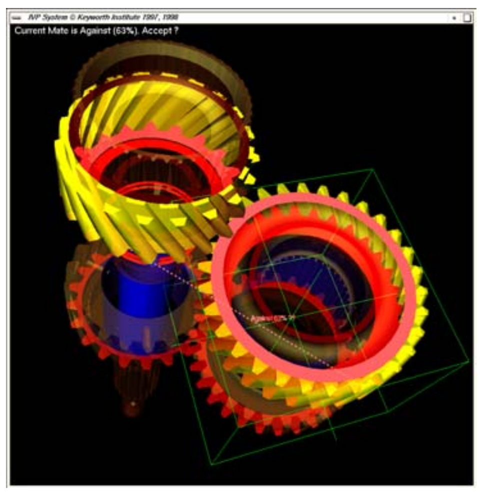


Figure 2-6 Mating condition detection with *Direct Manipulation*

2.2 Engineering Assembly Using Advanced VE Technologies

A number of academic research groups in different parts of the world have developed engineering assembly systems using advanced VE input / output devices. This section reviews some of these systems.

VADE - Washington State University

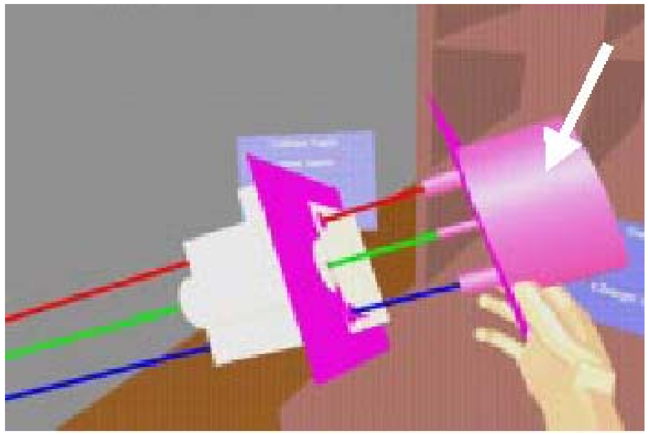


Figure 2-7 A constrained motion simulation. The grabbed part is only allowed to move along the highlighted axes during an insertion.

A Virtual Assembly Design Environment (VADE) has been designed and implemented at Washington State University in collaboration with NIST (National Institute of Standards and Technology) [Jayaram et al 1995, 1997, 1999, 2000]. The VADE focuses on utilizing an immersive virtual environment tightly coupled with a commercial CAD system. It allows engineers to evaluate, analyze, and plan the assembly of mechanical systems. The VE presents users with an assembly scene. The various parts and tools (screw driver, wrench, and so on) used in the assembly process are initially located where they would be in the real assembly facility. The VADE supports both one-handed and two-handed assembly within an HMD-based immersive VE. The virtual hand is based on an instrumented glove device (such as the CyberGlove™) and a graphical model of a hand. Each hand is checked for individual gripping of virtual objects as well as for two-handed gripping. The process of grabbing and manipulating parts is based on physics-based algorithms (involving friction, number of contacts, direction of force, and so on). This attempts to let users grip the parts realistically and perform fine-motor manipulations (such as twirling the objects using the fingertips) just as in the real world. This facilitates modelling assembly processes that involve handling intricate parts and tools. The geometry part motion in the VADE is driven by the combined dynamics of the user's hand, gravity, and collision with other objects. Using the assembly constraints, the VADE simulates kinematic motion of sub-assembly during the assembly process. When a part is brought close to the base part, VADE checks the constraints on the two parts. If any of the assembly constraints are satisfied, the motion is restricted based on the constraint. This allows effective simulation of sliding, rotating, and so on, without computationally expensive numerical methods (Figure 2-7). The VADE has been successfully used in several studies, for example using models from the truck, engine, machine tools, and construction equipment industry.

Design of Spatial Mechanisms - Iowa State University

Figure 2-8 Placing locations

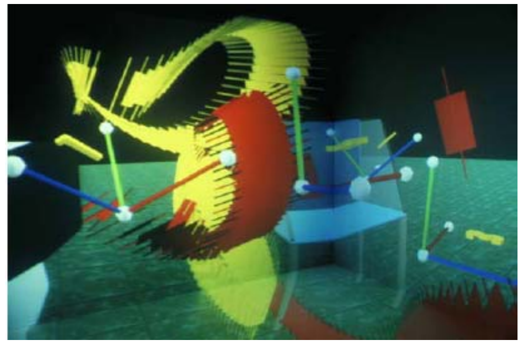


Figure 2-9 Congruence planes

An immersive environment for the design of spatial mechanisms has been developed at Iowa State University [Osborn & Vance 1995, Furlong et al 1999, Vance et al 2002]. This allows the user to move around in 3D space, synthesize a spherical mechanism and examine the movement of the mechanism. In the VE, placing objects in the desired location relative to other parts in the area is straightforward (Figure 2-8). Following the 'design in context' approach geometric models of the objects in the work area can be loaded into the design environment. This provides the user with the ability to investigate interaction of the mechanism with other objects in the work environment, and to design mechanisms within the physical constraints imposed by the work environment. While looking though the stereo viewing device, the user moves to the desired location and uses the position tracked device to release a virtual part in the correct location. Adjustments are made by picking up the part and moving it until the user is satisfied with the position and orientation of the design locations. The information, which consists of the positions and orientations of the specified locations, generates all possible design solutions. There are two methods that are used to pick a solution: selection from the 2D type map, and selection from the fixed and moving congruences. Congruences are spatial entities. They are infinite planes of lines that represent all possible solutions. These planes are placed in their spatial orientation with respect to the mechanism design locations (Figure 2-9). A designer can move around the space and selects from various congruences until an acceptable design has been achieved. The designed mechanism can move throughout the work area for examination. Small adjustments might be needed during the examination.

The same issues of placement of design locations and selection of possible designs are present in the iteration process.

Virtual Prototyping – Frauhofer Institute

A virtual prototyping system has been developed to verify assembly and maintenance process in Fraunhofer Institute [Dai et al 1996, Zachmann 1998]. The system has been used for a number of applications in the automotive industry. A virtual prototype has been developed for VW to present different ways of positioning and adjusting components in the engine compartment, and allow simulation of alternative assembly procedures. Further, a scenario of exchanging an alternator has been presented for evaluation of design alternatives, clash-and clearance analysis, assembly / disassembly simulation, and simulation of working conditions. Robust and efficient interaction with the system is achieved by utilizing all input channels available, namely gesture recognition, tracking, voice input, and menus [Zachmann & Rettig 2001]. A number of natural grab gestures are used for grasping objects using a glove-based device. Some types of grasping involve the whole hand in particular the palm, while some types involve the fingers. For navigation, three classic techniques have been used for positioning the viewpoint (or virtual camera) which is mounted on a virtual cart (sometimes referred to as a flying carpet [Ware & Osborne 1990]). They are *point-and-fly*, *eyeball-in-hand* and *scene-in-hand*. In the point-and-fly mode the user moves the cart by pointing in the desired direction with the navigation device (e.g., glove or cricket) and making a certain gesture or pressing a certain button. If a glove is being used, then the speed of the motion can be controlled by the flexion value. If head tracking is enabled, the camera will be controlled by the head tracker. As the user is allowed to fly in any direction with complete freedom, this method has a lack of constraint: the user can easily get lost or disoriented if given complete freedom [Brooks et al 1992]. The eyeball-in-hand allows the user to navigate the scene by moving a hand held device as a virtual camera through the scene. This method is most appropriate for close examination of single objects from different viewpoints, e.g., interior design [Dai et al 1996]. The scene-in-hand interprets the movement of the interaction device as a movement of the entire scene. This technique is not suited for navigating inside an object but is suited for movement around a closed object. Sometimes it can be quite useful for coarse object placement [Ware & Osborne 1990]. Precise positioning of parts is made possible by constraining interactive object motions and by abstract positioning via command interfaces [Zachmann & Rettig 2001]. By abstract commands given via voice input, menu, or keyboard, an object can be translated, rotated, or scaled about one coordinate axis. In addition to this, the user can specify constraints by selecting a point, axis, or plane. This will constrain the object's degree of freedom. Then, the object is linked to the user's hand so that it follows the hand's motion but only within the constraint. However, this method was disliked by the users because it was thought unnatural [Gomes & Zachmann 1999]. Two kinds of snapping paradigms have been developed [Gomes & Zachmann 1999]: the first one makes objects snap in place when they are released by the user and when they are sufficiently close to their final position. The second snapping paradigm makes tools snap onto screws when sufficiently close and while they are being utilized (Figure 2-10). The second paradigm is implemented by a 1DOF rotational constraint which can be triggered by events. During the assembly simulation, a variety of feedback can be combined which will be given if the user tries to move an object to an invalid position: acoustic feedback, tactile feedback by a Cybertouch™ glove, and visual feedback. Visual feedback comes in several flavours: the whole part can be highlighted, or the polygons which would have intersected at the invalid position can be highlighted.

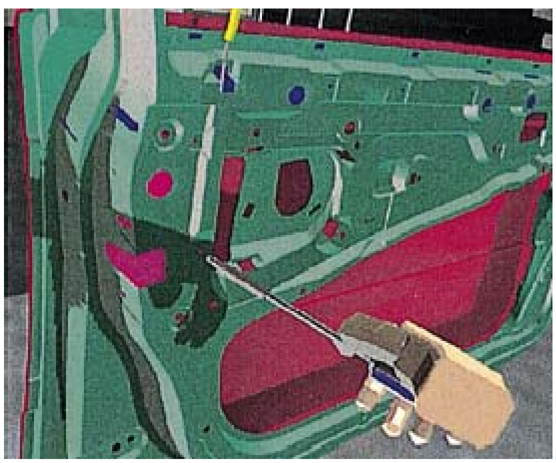


Figure 2-10 Tools snap onto screws and are constrained. Also, they are placed automatically at an ergonomic position within the hand by the system

MAESTRO – Aachen University of Technology

A software called MAESTRO (Multimodal Interaction Techniques for Assembly Simulation in Virtual Environment) has been developed at Aachen University of Technology [Steffan & Kuhlen 2001]. PHANToM 1.5 from Sensable Technolgies

[Massie & Salisbury 1994] is used for 6DOF input and a simple force vector as output. A pencil-like manipulator of the PHANToM is represented by a graphical counterpart in the VE. Its motions are adequately scaled due to the rather small interaction volume of the PHANToM. In combination with the PHANToM, a TAN HoloBench (table-like display consisting of a horizontal and a vertical project surface) is used for visualization of the VE. When the user selects an object by the ray-casting technique, the object moves and attaches to the pencil-like manipulator and then follows the user's movement. In the system, an assembly process involves three phases: transport to target position, coarse positioning and fine positioning. Three artificial support mechanisms - *guiding sleeves*, *sensitive polygons*, and *virtual magnetism and snap in* – are developed to support the three phases of the assembly process respectively. Guiding sleeves makes use of priori knowledge about possible target positions and orientations of objects. It supports the user during the transport phase of an assembly task by means of wireframe animation of the assembly path. In coarse positioning of an assembly task, the sensitive polygons can be used to constrain the degrees of freedom for the selected objects. For instance, a sensitive polygon positioned at the port of a hole can restrict the motion of a pin to the axial direction of the hole and thus considerably facilitate the assembly task. In the final phase of an assembly task, it is often necessary to position objects exactly, i.e., parallel to each other at arbitrary locations, without leaving any space between them. Virtual magnetism and snap-in are used for precisely positioning the selected object to its final position in an assembly. During interaction, the physically-based behaviour of virtual objects is simulated. This includes automatic calculation of the objects' inherent mechanical characteristics. In addition, the force feedback is integrated into the interaction with virtual objects.

Two-handed Assembly – University of Hong Kong

Sun & Hujun at the Chinese University of Hong Kong [Sun & Hujun 2002] have presented a two-handed assembly with immersive task planning in a VE. In the two-handed assembly system, two 3D input sensors (3D stylus and 3D Polhemus) are assigned to the right (dominant) hand and left (non-dominant hand) respectively. The manipulation functions can be selected from the menu. The selected function can be interactively performed jointly by two hands. The *Zoom in/out* function can be applied to one or all objects in the assembly environment. If the left hand intersects one object, the motion of the right hand controls the zoom in/out for that object so the user can inspect the object in detail. If the left hand selects no object, the right hand will zoom in/out for the whole assembly scene. In an assembly process, the mating pairs among the mechanical components can be interactively selected with two hands. The user picks one object by either hand (left or right), the other objects that can be mated with the selected one will flash. The user can then select one of the flashing objects using the other hand. All the possible mating paths (the relevant spatial-temporal information between the mating pairs prior to assembly) can be inspected and optimal paths between them planned upon the two-handed input. Once confirmed, the user can move either object or both of the mating objects with two hands. The mating path will guide the user's hand moving towards each other while avoiding any possible collision with the other objects. For manipulation of an assembly, the left hand sets the reference frame for the two mating parts. When the left hand moves, both the mating parts move accordingly so the relative location between them is the same. The right hand is assigned for the mating of two parts guided by the mating constraints.

VLEGO – Nara Institute

The VLEGO system [Kiyokawa et al 1996, 1997, 2000] at Nara Institute of Science and Technology in Japan, allows the user to design 3D virtual objects (i.e. virtual blocks) by using a set of two-handed operations such as assembly, decomposition and coloring objects. In the system, a user views a virtual workspace stereoscopically through a head mounted display or a projector with head-tracking facility. The user holds a pair of 3D input devices. Each device has a 3D magnetic tracker 3SPACE (Polhemus) and four feather touch switches on it. These devices are used for manipulating two 3D cursors that manipulate virtual objects. An object is selected when a tip of a 3D cursor is positioned in it. And then the selected object follows the user's movement. For assembly, two virtual objects are picked by left and right hands. 6DOF is mapped to firstly picked block while 4DOF with constraints (4DOFC) is mapped to the secondly picked object. Being bound to 4DOFC, the object can be located on discrete positions at intervals of 1cm and its orientation is restricted at 0, 90, 180 and 270 degrees of horizontal rotation. When the two picked objects are close enough to each other, the relative position and orientation of these objects are discretely aligned. If the upper or lower faces of these objects contact each other after a collision avoidance process, these are combined into a new object when one of these objects is released.

Assembly Using Two "Frogs" – Delft University

Gribnau & Hennessey [Gribnau & Hennessey 1998] at Delft University of Technology describe an interface for 3D object assembly that can be operated with two-hands as shown in Figure 2-11. The input device developed for the interface is called the "Frog". The frog is designed to be held with the fingers, intentionally avoiding the whole-hand for reasons of comfort and efficiency [Zhai et al 1996]. Inside the frog is a 6DOF, magnetic tracker that measures the Frog's location and orientation. Two buttons on the Frog are used to select objects and to clutch. The frog held with the non-dominant hand is used to position and orient objects not being dragged by the dominant hand. The non-dominant hand can assist the selection process by bringing the object close to the cursor. In case an object is being dragged to be placed upon a target object, the non-dominant hand can move and orient the target object, such that it facilitates the placement.

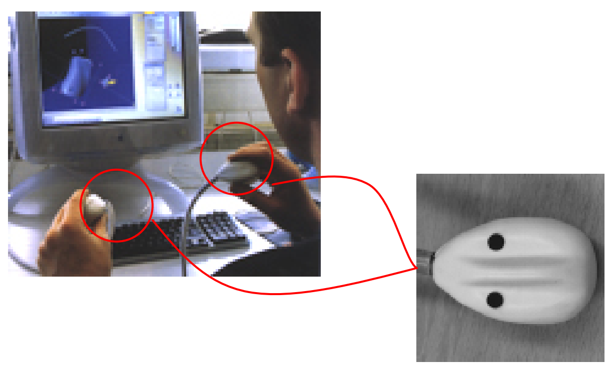


Figure 2-11 Two-handed interface using "Frog"

Virtual Assembly Planning System – Herot-Watt Univeristy

In the Virtual Assembly Planning system developed at Herot-Watt University [Dewar et al 1997, Ritchie et al 1999], a HMD is used with a 3D mouse and a Polhemus magnetic tracking system. To attach two components within the VE, two tools, called *Proximity Snapping* and *Collision Snapping*, are employed. In Collision Snapping, the user picks up a component, and moves it towards a component to which it is to be mated. As soon as a collision is detected between the two objects, the user is asked, via a toolbox, if the two components are to be joined. If the two are to be joined then the method of joining (e.g.

screwed, glued, inserted etc.) can be chosen from another toolbox. After the joining method is selected, the collision snapping algorithm repositions and re-orientates the selected object, so that its location related to the other one is the same as in the final assembly state. Proximity Snapping offers a more realistic approach to assembly as the user is not asked for a joining method input until the selected component is sufficiently close to its final position relative to one or more of its neighbours. However, it's a computationally expensive approach. During assembly interaction, the assembly sequence and method of joining is stored and an assembly plan is produced automatically.

Other examples using the snapping mechanisms for assembly

These snapping mechanisms for interactive assembly are also employed in some other VEs. For example, a constraint-based VE [Fernando et al 1998, 2001] has been developed at University of Salford to support the assessment of assembly and maintenance tasks within an immersive CAVE environment. The user moves around in the CAVE space with the hand and head positions are tracked. In the system, a mating condition is recognized between geometric features when the assembly parts are coming together. The CODY Virtual Constructor [Jung et al 1997, 1998] has been developed at University of Bielefeld, to enable an interactive assembly of 3D visualized mechanical parts to complex aggregates. The system allows the direct manipulation of parts using space-mouse, data-glove or similar input devices. In assembly mode, if the moved objects are brought in a position where one of their connection ports is close enough to the connection port of another object, a snapping mechanism will complete the fitting process. The system also supports natural language instructions. Audio feedback is provided during interaction. The PROSSEIA_VR has been developed at Center of Computer Graphics in Portugal for training of industrial assembly process in VE [Grave et al 2001, Silva et al 2000]. The system cover the training of all the steps associated with two elementary operations involved at the assembly lines: inserting pieces into the assembly panel and connecting these pieces with wires. The system uses a HMD for enabling a full immersive system. The head and hand of the user are tracked. The user uses a glove device for interaction with the VE. To grab an object, the user touches the object with the thumb and the index at the same time. The object is released when one of these fingers ends the contact with the object. Connecting a wire to one piece is done by releasing the wire while colliding with the piece. A zooming process is performed every time a user introduces a wire into a small hole of the piece. When it is finished, the piece returns to its original size.

2.3 Classification of Spatial Interaction in Engineering Assembly

The previous section reviewed a number of engineering assembly systems using advanced VE technologies. It shows that the dominant form of interaction strategies in engineering assembly is through spatial interaction devices involving the pointing devices (e.g. stylus) and glove devices. A variety of spatial interaction techniques taking advantage of these devices have been reviewed. They can be classified in terms of the assembly tasks they support: selection, positioning and attachment. These tasks are identified in Chapter 1.

2.3.1 Selection

Classic selection techniques such as ray casting and grab gesture are commonly used in engineering assembly environments. A 3D input device is used to shoot a ray into the scene [Zachmann et al 1998, Ritchie et al 1999, Gribnau & Hennessey 1998]. An object can be selected when the ray insects the object. To confirm the selection, the user performs a 'grab' action (usually by pressing a button). With a glove-based device, the grab gesture technique is often used. The virtual hand grasps virtual parts just like the real hand would grasp their real counterparts. Some types of grasping involve the whole hand in particular the palm [Zachmann & Rettig 2001, Jayaram et al 1999] while some types involve the fingers [Grave et al 2001].

2.3.2 Positioning

By using the spatial input devices, the virtual components or the entire scene follows the user's hand movement and is directly positioned in 3D space. However, the direct 6DOF manipulation of virtual object is limited to coarse positioning tasks [Mine et al 1997]. This is because the user's real hand always moves in free space, there are no mechanical points of reference other than his body, and there are no rests or supports for the user's hand [Zachmann & Rettig 2001]. Further, the biomechanical constraints of the hands and arms prevent translations from being independent of rotations, so rotation will be accompanied by inadvertent translation, and vice versa [Hinckley et al 1994a].

In assembly applications, like in other CAD systems, objects must often be positioned precisely. In the Fraunhofer system [Zachmann & Rettig 2001], precise positioning of components is made possible by constraining interactive object motion and by abstract positioning via command interfaces. The VADE system also uses constrained motion to simulate realistic interaction to assist the user in guiding the parts into position [Jayaram et al 1999]. The VLEGO system employs discrete placement constraints, which restrict the position and orientation of 3D objects discretely to make it easy to arrange [Kiyokawa et al 1997]. Constrained object manipulation for precise positioning is also commonly used in the other CAD applications such as the CHIMP system developed at University of North Carolina at Chapel Hill [Mine 1997]. By using the hand-held widgets, selected objects can be translated along a line or in a plane, or translated (3D) without rotation, or rotated (1D) about any vector, or rotated (3D) without translation. It was found that hand-held widgets are easier and more efficient to use than co-located widgets. They can take advantage of proprioception (a person's sense of the position and orientation of his body and limbs) when using the widget. In addition, the constrained manipulation is valid and useful even when force-feedback is available in the MAESTRO system [Steffan & Kuhlen 2001].

When objects are very small or at a distance, the scale adjustment is often required during assembly. The PROSSEIA_VR employs a manipulation tool to perform a zoom process every time a user introduces a wire into a small hole of the piece [Grave et al 2001]. Ritchie et al [Ritchie et al 2000] also uses the similar method. It allows the user to enlarge or shrink the virtual prototype to enable human-scale ergonomic access to either fine geometry details or large-scale geometric features within the virtual environment. In a CAD system, Chu et al [Chu et al 1998] use a button on a pointing device for zoom-in and a second button for zoom-out. When the zoom-in / zoom-out button is clicked down, the viewpoint continuously zooms-in/zooms-out in the pointing direction of the pointing device until the user releases the button. The evaluation results showed that this method is more preferable for *zoom-in to a feature* test, compared with some other methods such as using hand action and motion, or using voice command. In the CHIMP system [Mine 1997], the *head-butt zoom* has been developed as a way for head motion to be used in a zoom process. The user frames the chosen detailed subset of his current view using a screen-aligned rectangle in front of his face. The corners of the rectangle are set up by the position of two hands. The user leans forward to get a close up and detailed view; leans back to return to the normal view.

2.3.3 Attachment

Attachment of two components requires the exact placement of a component relative to the other. The snapping mechanisms have therefore been developed to support efficient attachment tasks. They are used in most of the engineering assembly systems including the IVPS. The intelligent techniques built into the snapping mechanisms include constraint identification, constraint creation and satisfaction [Thompson et al 1998, Fernando et al 1998, Ritchie et al 1999]. Before two components are snapped together, the user needs to specify a constraint between them. This can be achieved by a number of approaches through positioning and selection operations. For example, a constraint can be specified by the user or detected by the system when two components are manipulated to collide with each other [Grave et al 2001,Ritchie et al 1999], or two components are positioned to close to each other [Gomes and Zachmann 1999, Ritchie et al 1999, Jayaram et al 1999, Fernando et al 1998]. Alternatively, a constraint can also be specified through selecting the geometric features from the two components [Chu et al 1997]. Once the constraint is specified, the snapping algorithm repositions and re-orientates one component related to the other one. Normally the kinematic behaviours of the assembly will be simulated depending on the satisfied constraints [Jayaram et al 1999, Fernando et al 1998]. It is evident that selection and positioning operations are largely used for attachment tasks. It is, therefore, believed that selection and positioning techniques play a crucial role in assembly tasks.

2.4 Evaluation studies for Engineering Assembly within a VE

A number of evaluation studies have been conducted to assess the usability of engineering assembly within a VE. These include efficiency, ease of use, learnability, intuitive interaction, training of workers, multimodal-input/multi-sensory, and ergonomics of VE hardware.

To investigate the relationship between real world and virtual world for industrial assembly, a number of evaluations were undertaken at Heriot-Watt University [Dewar et al 1997, Ritchie et al 1999]. The results showed that the assembly tasks within a VE take considerably longer than their real equivalents. The results also showed that the virtual assembly system can produce feasible, useful assembly plans when utilized by assembly planning experts and, in a general sense, there is a strong correlation between assemblies built in the real and virtual worlds. Boud et al at the University of Birmingham [Boud et al 2000] also investigated whether the VE technology can be used for the training of human assembly operators. The investigation concluded that the VE would enable an operator both to practice and to train for an assembly task before the physical prototype has been built. This would reduce assembly-completion time when the task is subsequently undertaken on real components. The investigation highlighted the limitation of the lack of haptic feedback provided by current input devices for VEs. To address this, an investigation of haptic feedback issues for assembly were reported in [Boud et al 2000]. An instrumented object (IO) was employed that enabled the user to pick up and manipulate the IO as the representation of a component from a product to be assembled (Figure 2-12). It provides an encompassing method of haptic feedback to aid operators conducting assembly tasks in VEs. The reported findings indicated that object manipulation times are superior when IOs are employed. This supports Hand's statement that "*providing feedback by manipulating physical input devices which closely correspond to virtual objects is an important step towards bridging the gap between knowing what we want to do and knowing how to do it*" [Hand 1997].

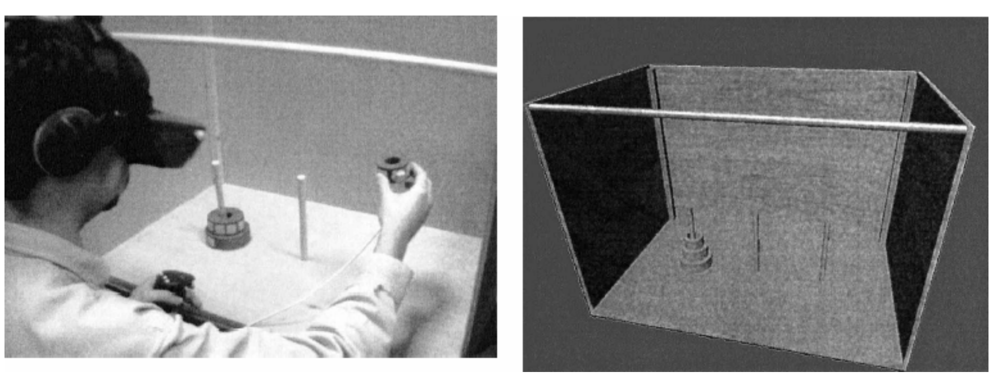
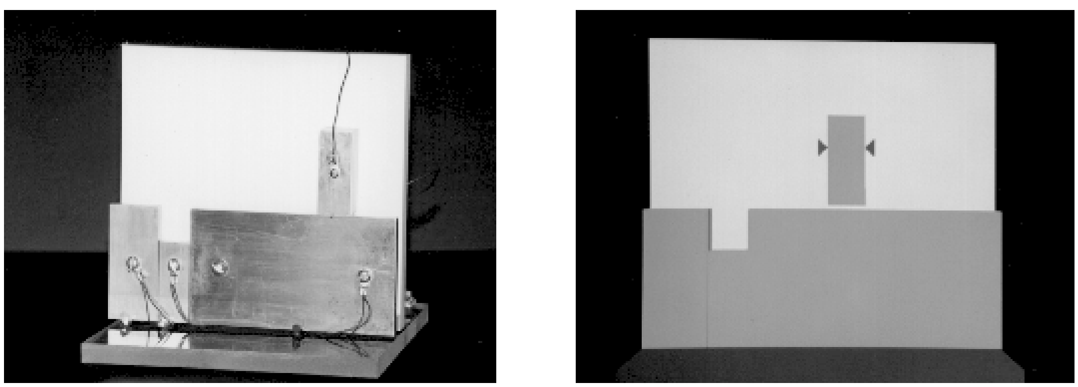


Figure 2-12 Object manipulating using the real instrumented objects (IOs) in VEs [Boud et al 2000]

Gupta et al [Gupta et al 1997] described an investigation of the efficiency of Multimodal VEs for assembly tasks such as part handling and part insertion. In a Multimodal VE, the human operator senses the synthetic environment through visual, auditory and haptic displays and then controls it through a haptic interface. The experiments used 2D peg-in-hole apparatus (Figure 2-13a) and a VE simulation of the same apparatus (Figure 2-13b). The experiments showed that the Multimodal VE is able to replicate experimental results in which increased task completion times correlated with increasing task difficulty (measured as increased friction, increased handling distance combined with decreased peg-hole clearance). However, the Multimodal VE task completion times are approximately twice the physical apparatus completion time. The results show that the time for assembly completion increases by a factor of 1.3 in the absence of force feedback. It was observed that stereo viewing capabilities can produce models that communicate volume and depth more effectively than conventional 2D or 3D models. However, subjects did not feel that 2D line task was more difficult than the 3D stereoscopic task. The limitations of current force feedback device were reported. They include spatial discrepancy between visual and haptic images, not being able to model the rolling of the fingers, and inaccurate finger-object contact.



a) in the real world b) in the multimodal VE

Figure 2-13 Peg-in-hole assembly task [Gupta et al 1997]

Several assembly evaluations were conducted to test and verify the performance and capabilities of the VADE system at Washington State University. Two of them were reported in [Jayaram et al 1999]. In these experiments, fingertip twirling of parts and haptic feedback were disabled, since the parts tended to slip from the user’s hands too easily. Total time to perform the assembly, total “pure” assembly time for all the parts (the time between the moment users grab the part and the moment they place that part on the based part) and gripping time (the time users spend on reaching and trying to grab the parts) were recorded and analyzed. The results showed that pure assembly time in a VE is lower than actual assembly time. This can be attributed to the lack of fastening operations in the VE. The results indicated that the difficulty in handling the parts increase with the size of the parts. As the assembly models become larger, users need to walk some distance to grab the part, find better viewing positions to look at the model, align the parts, and so on. The results also showed that an HMD-based implementation of VADE doesn't suit assemblies with a large number of parts since it often tires the users. The "sluggishness" of VR systems, created by tracking frequency, tracking latency, frame rates and graphics latency, doesn't seem to affect gross motor movements (moving a part into place and aligning it). However, it significantly affects fine-motor movements such as finger and wrist movements.

Gomes and Zachmann at Fraunhofer Institute reported a user survey at BMW to evaluate the acceptance and feasibility of virtual prototyping for the assembly process [Gomes & Zachmann 1999]. To interact with the assembly application, the user preferred the combination of voice input and data glove, instead of the combination of 3D menu and glove or selection by someone else. The possibility to move in 3D space without having to deal with 3D coordinates of points and vectors was an impressive experience for the users. Most users were missing precision movements of the viewpoint and exact positioning of parts in the VE. The tactile feedback provided by the CyberTouch™ was evaluated as significantly less helpful than the acoustic feedback and visual feedback. The limitation of current VR input/output devices were also discussed such as the weight of the HMD, vibration of the tracker data and too many cables for input / output devices. The results indicated that the use of VEs for assembly will play an important role in the near future in automotive industries.

To compare different input/output methods, Iowa State University conducted a study [Evans et al 1999] to compare a VR interface (a PINCH glove and stereo display) to a desktop-based interface (a 2D mouse and monitor) using a spherical mechanism design task. The results of this evaluation were reported in terms of interaction device preferences and visualization interface preferences. Using a 2D mouse interacting with computer data is preferred as opposed to a PINCH glove when performing interaction tasks for spherical mechanism design. The results also indicated the preference of the stereo glasses interface over the computer monitor interface as the stereographic visual effects can provide ideal spatial quality for visualizing complex 3D objects such as spherical mechanisms.

An experiment reported in [Ye et al 1999] investigated the potential benefits of VR (Virtual Reality) environments in supporting assembly planning by comparing three different environments: a traditional engineering environment (TE), a non-immersive desktop VR (DVR) environment, and an immersive CAVE VR environment (CVR). The experiment was based on a between-subjects design. There were five subjects for each experimental environment. The results show that the subjects' performance time in the TE was significantly longer than that in the DVR and that in the CVR, whereas the difference in performance time between the DVR and the CVR was not significant. The total number of problematic assembly steps in the TE condition was significantly greater than that in the CVR. Hence, the results revealed the advantages of the two VR environments over the traditional engineering environment in improving the subjects' overall assembly planning performance and in minimizing the handling difficulty, excessive reorientation, and dissimilarity of assembly operations.

An evaluation of the MAESTRO (Multimodal Interaction Techniques for Assembly Simulation in Virtual Environments) has been presented in [Steffan & Kuhlen 2001]. The MAESTRO comprises physically-based modeling, haptic feedback and artificial support mechanisms. The experimental results showed that all three features – haptics, physics, and artificial support – considerably improve user performance and user acceptance during the completion of assembly tasks in a virtual environment. However, the MAESTRO can only handle virtual scenes of rather low complexity due to the algorithms employed in the system. Furthermore, the MAESTRO makes use of a force feedback device (the PHANToM™) that merely produces a force vector. However, for many manipulation tasks it is desirable to adequately present torques or even to stimulate the whole hand-arm system.

Summary

The evaluation studies have shown the advantages and limitations of the VE software and hardware. 3D input / output is natural and intuitive to the user. However, the weight of an HMD tires the user. “Sluggishness” caused by the tracking system latency significantly affects fine-motor movements such as finger and wrist movements. Current force feedback interfaces are not yet practical or available for complex engineering assemblies. In addition, fine and precise interaction is still difficult. As Gomes and Zachmann reported, most users missed precision movements of the viewpoint and exact positioning of parts in the VE [Gomes and Zachmann 1999]. The difficulty in selecting and positioning the parts is also highlighted due to the size of the parts [Jayaram et al 1999]. Although there is the weakness of current VE interfaces, the reviewed evaluation studies indicate the use of VE for assembly will play an important role in the near future in industries.

2.5 Conclusion

This chapter describes the existing interaction techniques for engineering assembly using the desktop-based IVPS. The state-of-the-art interactive engineering assembly systems are reviewed. Most systems use spatial interaction to support assembly tasks including selection, positioning and attachment. These spatial interaction techniques are classified in terms of these tasks. It is evident that selection and positioning operations are largely used for attachment tasks. It is, therefore, believed that selection and positioning techniques play a crucial role in assembly tasks. A number of evaluations have been undertaken to evaluate the usability of the VEs for engineering assembly. The results show that 3D input is natural and intuitive to the users. However, precise interaction is found difficult due to the limitations in the VE hardware and software.

Chapter 3
Usability Evaluation of the existing IVPS

Although the IVPS has proved functioning to be successful, the user interface is limited to mouse and keyboard. This chapter undertakes a usability evaluation using the desktop-based interface. The evaluation shows how people perform the engineering assembly tasks including selection, positioning, attachment and disassembly both in the real world and within the VE. The evaluation results show the limitations in the use of 2D input for tasks involving 3D selection and positioning operations during assembly process. The major drawbacks are the lack of correlation between 2D manipulation and 3D motion, and lack of a spatial reference to indicate the positioning functions associated with the mouse buttons. Further, 2D interaction within a 3D environment is not intuitive enough to the users when performing engineering assembly tasks which require users to specify complex spatial information. A set of implications have been generalized to develop a more efficient and intuitive spatial interface in the next chapters.

3.1 Introduction

To improve an existing product, there is a need to capture the usability defects in the product [Lindgaard 1994]. Without knowing where in the system users run into problems or what kinds of problems they are likely encounter in the existing system, one has little hope of improving anything. Further, if improvements result, one has little hope of understanding and demonstrating why the new system turned out to be better. This is based on the understanding of the users' goals and tasks, and how the system affecting the users and their performance [Hartson 1998].

Therefore, the purpose of the evaluation in this chapter is to better understand the limitations of the existing IVPS and identify the areas for further research. The following two questions are to be answered:

1) How do people perform an assembly task in the real world and in the IVPS?
2) What are the strengths or weakness of the existing interaction techniques?

3.2 Usability Evaluation

3.2.1 An assembly task

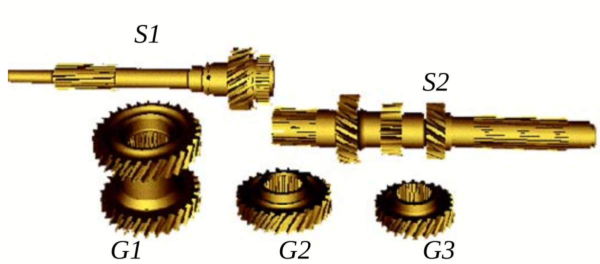


Figure 3-1 Gearing mechanism components

Table 3-1 Part Description

Part No.	***Description***	***Subassembly Group***
S1	Input drive shaft	Input drive stage
S2	Lower drive shaft	Output drive stage
G1	Lower drive shaft drive gear	Input drive stage
G2	$1^{st}/3^{rd}$ ratio output selection gear	Output drive stage
G3	$2^{nd}/4^{th}$ ratio output selection gear	Output drive stage

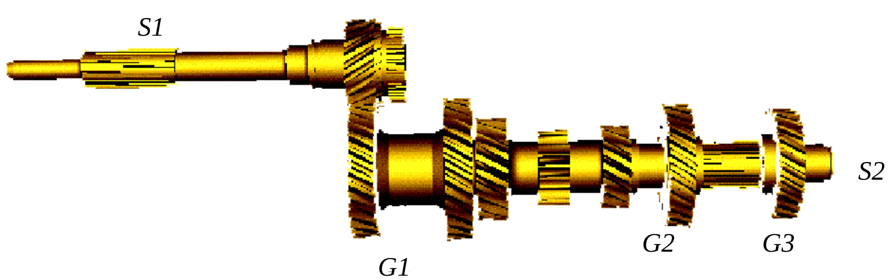


Figure 3-2 Final assembly of gearing mechanism

The task in the evaluation required a subject to assemble 5 components (Figure 3-1) to build up a simple gearing mechanism (Figure 3-2). This is a simplified 6-speed automotive gearbox. Table 3-1 provides a more detailed description of each of the components. The assembly includes two types of mating condition: a gear fit mating condition between Part G1 and Part S1, and concentric fit mating condition between Part G1 and Part S2, Part G2 and S2, and Part G3 and Part S2. These mating conditions determine the accurate position of each component.

3.2.2 Evaluation design

The evaluation was conducted within two types of environment. Environment 1 included real physical models on a table. Subjects were required to complete the experimental task with both hands (Figure 3-3) while sitting at the table. Environment 2 was the desktop-based IVPS described in Chapter 2. Subjects were required to complete the same experimental task by interacting with the virtual models within the VE system using a keyboard and a 2D mouse on a SGI Octane machine. The assembly sequences in both environments were not restricted because the experiment was to separate the assembly subtasks from any possible assembly process.

Figure 3-3 Assembling the real physical models

Although the evaluation involved two environments: the real world and VE, it didn't focus on the quantification of the difference between them in terms of assembly time like in [Gupta et al 1997], or the investigation of correlation (i.e. knowledge transfer) between them like in [Ritchie et al 1999]. Instead, studying the people's behaviour in the real world in this study would provide a better understanding of the user's tasks and the constraints in the VE.

As described in Chapter 1, observation, interviews and post-questionnaire were used in the evaluation. The post-questionnaires are presented in Appendix B.1.

3.2.3 Subjects

Six subjects were used for this evaluation. All of them were post-graduate students from the School of Computing and ranged in age from 20 to 40. The subjects varied in terms of their background knowledge of the gearing mechanism. None of the subjects had used the IVPS system.

3.2.4 Procedure

- Subjects were asked to complete a pre-experiment questionnaire.
  The purpose of this was to gather as much information as possible about them such as age, prior experience with CAD software and gearing mechanisms etc.
- Evaluator introduced the assembled gearing mechanism using the real model.
- Evaluator disassembled the physical gearing mechanism and put each part on the table.
- Subjects executed the experimental task in Environment 1.
- Subjects completed a post-questionnaire for Environment 1.
- Evaluator introduced the IVPS system and taught subjects to use it within the Environment 2.
- Subjects executed the experimental task within the Environment 2.
- Subjects completed a post-questionnaire for Environment 2.

3.3 Results and Discussion

Feedback from the observation of each subject performing the task and their opinions on the use of the system were collected (see Appendix B.2).

3.3.1 Constructing an Assembly in the Real World

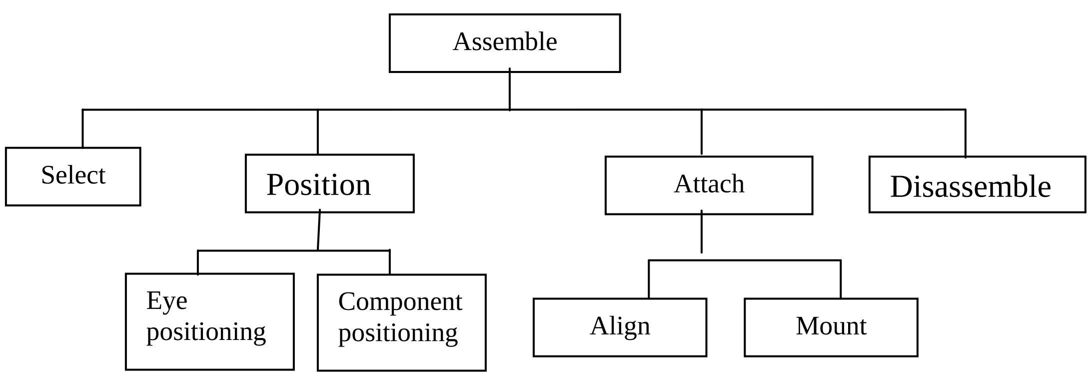


Figure 3-4 Constructing an assembly in the real world

In this experiment, all the subjects thought the simple physical gearing mechanism assembly task was very easy to complete by using both hands. The required mental effort and physical effort were generally found to be low during the whole process.

Although the procedure for completing this gearing mechanism assembly was variable due to the different assembly sequences performed by each subject, a general assembly task model emerged shown in Figure 3-4.

In the real world, ***selecting*** a component involved the subjects extending their hands to pick the component on the table. A component can then be ***positioned*** in the hands or on the table with the position or orientation changed. ***Attaching*** two components was decomposed into two subtasks in terms of the operation process: 1) ***Aligning*** a component involved moving the component to the start point of the attachment, such as insertion point. 2) ***Mounting*** involved moving the component to the final position of the attachment. During the process, the subjects often ***positioned*** their eyes in order to view the physical models from different viewpoint. If a wrong component is attached, they might need to ***disassemble*** it first, and reassemble it in the correct position and orientation.

3.3.2 Constructing an Assembly within the IVPS

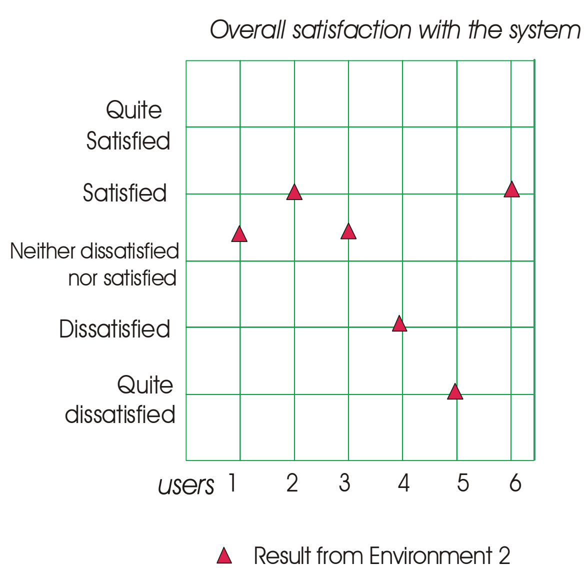


Figure 3-5 Overall satisfaction with the system

Of the tested subjects, five completed the assembly tasks. However one didn't. The reason is discussed later. From the overall view, subjects noted the difficulties with the system. Figure 3-5 presents the overall satisfaction of the subjects with the system. Only two of them were satisfied with the system.

The architecture of the IVPS interaction model is repeated in Figure 3-6. It illustrates how the users construct an assembly within the VE. The assembly tasks within the IVPS are the same as in the real world: **selection**, **positioning**, **attachment** and **disassembly**. However, it was seen that the VE system changed the way in which the task was performed. Interacting with the IVPS needed different cognitive requirements and capacities. This is considered below.

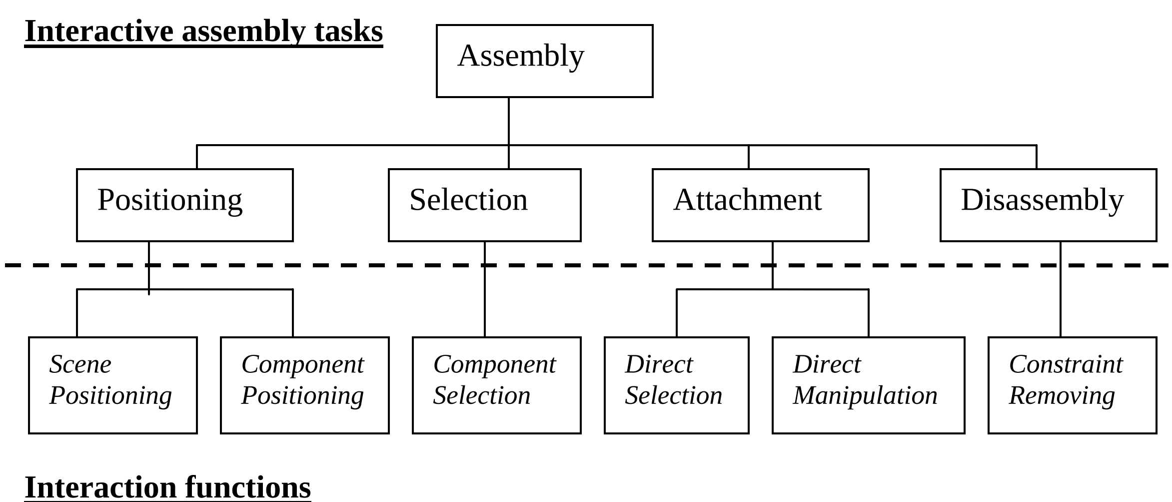


Figure 3-6 Architecture of the IVPS interaction model

- ***Selection***

None of the subjects thought picking a component in the IVPS was difficult. *Component Selection* technique provides a clear visual feedback indicating the component is going to be selected or has been selected.

- ***Positioning***

Most of the subjects thought translation and zoom functions were easy using the mouse. However, rotating 3D objects using 2D mouse movement was quite difficult due to the mismatch between 2D movement of the physical device and the requirements of 3D rotation. Subjects often confused the association of rotation, zoom and translation functions to each of the mouse buttons due to two reasons. Firstly, no spatial reference was associated with the mouse to indicate the relationship between the button and its assigned positioning function. Secondly, no visual cue was provided to indicate which function was active. *Scene Positioning* and *Component Positioning* were frequently performed during the assembly process. But the subjects had to press a key to switch from *Component Selection* to *Scene Positioning* mode; or press another key to switch from *Scene Positioning* to *Component Selection*. This was found very inconvenient. Manipulation of a constrained component in an assembly was thought to be a natural and accurate manipulation in the IVPS system as the system can simulate the kinematic behaviour of the assembly by maintaining any previously formed constraints. Two of the subjects thought this was the best thing in the system.

- ***Attachment***

The performance of an attachment task within the IVPS (Figure 3-6) is totally different from the real world (Figure 3-4). In the IVPS, performing this task can be achieved either by *Direct Selection* or by *Direct Manipulation*. The detailed process of using both is discussed in Chapter 2. The intelligence built into these techniques such as automatic constraint detection, creation and satisfaction enhanced the subjects' performance. Further, it was found that attachment of two components is impossible without them. For example, it was very easy to create certain types of constraint such as a gear fit constraint between Part G1 and Part S1 using *Direct Selection*. One subject said it was amazing to see two components automatically put together once selecting two geometric features. However, some weaknesses and unexpected performance results were exposed. Some subjects tried to use the hole surfaces in Part G1, G2 and G3. They found it was difficult to select them. They had to rotate them until a proper orientation of the holes was viewed. Further, rotation using a 2D mouse was found very difficult. When using *Direct Manipulation*, the subjects needed to manipulate one component close to the other one that was to be mated. However it was found difficult for the subjects to perceive the related position between two components due to the lack of 3D perceptual feedback of the 2D screen. Moreover, a required constraint can only be created when the related position of the two components satisfies certain conditions determined by the constraint. This means there is the requirement for *related precision*. The observation was that it often took time for the subjects to manipulate two components using the mouse and ensure their position to satisfy the related precision before they are snapped together.

This is the problem of related precision. In this study, one of the subjects didn't complete the task due to this problem. The subject spent a lot of time in using *Direct Manipulation* to attach two components. As the subject didn't manipulate the selected component precisely enough related to the other one, the manipulated component was finally constrained but positioned in a wrong place in an assembly. The subject got so frustrated when seeing the caused errors several times that he finally gave it up.

- ***Disassembly***

The subjects reported the need to break a constraint on any component they wanted. However, the undo action can only sequentially break constrains, one by one in the reverse order to which they were applied. If the subjects broke a constraint by accident, there was no way to re-apply it except assembling it again.

3.4 Generalised Implications

Assembly in both the real world and the VE system include selection, positioning, attachment and disassembly tasks. In the real world, people use natural constraints to guide components into their desired position and orientation. However, the natural constraints cannot be currently represented completely and accurately in the VE [Zachmann & Rettig 2001]. It is seen that the VE system changes the way in which the task is performed in terms of the provided interaction functions. It has been shown that interaction with the VE needs different cognitive requirements and capacities. The intelligent techniques which are built into *Direct Selection* and *Direction Manipulation* enhanced the subjects' performance. It was found that attachment of two components is impossible without them. However, the results also indicate the limitations of the existing interaction techniques using the desktop-based interface. The major drawbacks are the lack of correlation between manipulation and effect, lack of a spatial reference associated with the mouse to indicate the relationship between the mouse buttons and positioning functions, as well as frequent mode switch by pressing keys. The inadequacy of the desktop metaphor becomes particularly evident when performing the attachment tasks which demand higher precision. Further, 2D interaction with a 3D environment is not intuitive enough to the users. There is a need to develop more efficient and intuitive spatial interfaces for engineering assemblies within a VE.

The results of the study can be used to formulate the implications for the design of a spatial interaction model for engineering assembly:

1) Match 3D manipulation with spatial input. This provides the cognitive correlation between users and the models they are manipulating [Conner et al 1992, Gobbetti & Balaguer 1995].

2) Minimise interference in the interaction process. For example, pressing keys to switch between interaction modes distracts the user from the task. This means that the action sequences should be structured logically and consistently.

3) Spatial reference, visual feedback and visual cues are important for 3D graphical interaction. A spatial reference can provide the user's perceptual system with something to refer to [Hinckley et al 1994b]. Colour has been suggested as a useful and powerful method for attracting attention and assisting recognition in this experiment. Visual cues should be designed to indicate the state of translation and rotation, the direction of translation and the orientation of rotation of a selected component.

4) Finally, there is a need to add a flexible Undo process during the interaction procedure. For example, the user should be able to break a constraint on any component.

3.5 Conclusion

This chapter reports a usability evaluation of the IVPS using the existing desk-top based interface. The study describes how people perform an assembly task by studying people's behaviour both in the real world and in the IVPS. The ways in which the VE system affects people are analysed by studying their interaction within the IVPS. The strength and weakness of the existing interaction functions within the desktop-based IVPS system are evaluated. The results suggest there is a need to know if more expressive spatial input/output devices are valid for developing a more direct and intuitive VE environment. A set of implications are concluded for the design of a spatial interface for engineering assembly within the VE. The next chapter will evaluate a one-handed spatial interaction model using spatial tracked input devices such as Stylus and CyberGlove™ for assembly tasks.

Chapter 4
Evaluation of a One-handed Spatial Interaction Model for Engineering Assembly

In chapter 3, the results of the usability evaluation strongly suggested that there is a need to undertake further study into whether the use of more expressive spatial interaction devices, with up to 6DOF (Degrees of Freedom), could improve a user's task-performance within the IVPS.

This chapter describes a one-handed spatial interaction model for engineering assembly using the IVPS. By taking advantage of two 3D interaction devices: the stylus and CyberGlove™, one-handed stylus and one-handed glove interfaces are implemented. This chapter reports a study to evaluate the impact of the one-handed spatial interfaces on the task-performance for engineering assembly within the VE. The results show that the stylus interface is generally found to be a more precise and easier to use interface, enabling the user to exercise greater control over selection and positioning operations. A number of reasons will be discussed. Further, the evaluation identifies a number of problems of *precision* in spatial selection and positioning using the 6DOF spatial input. These include the problems of *scale, slide, related precision,* and *global precision.* This chapter finally indicates there is a need to develop a more efficient and intuitive spatial interface to overcome these problems in spatial selection and positioning.

4.1 A One-handed Spatial Interaction Model

The architecture of a one-handed spatial interaction model for engineering assembly within the IVPS is shown in Figure 4-1. In the one-handed spatial interaction, the positioning, selection, attachment and disassembly tasks are performed using the provided interaction functions (described in Chapter 1). These functions are supported by the continuous 6DOF input control by the dominant hand. For *Component Selection* and *Direct Selection*, the *ray-casting* technique [Bowman & Hodges 1997] is used to select a component, or a geometric feature. *Component Positioning* employs a classic *object-centred manipulation* [Mine et al 1997]. The movement and orientation of the 3D input device is directly mapped to the movement of the selected component. The centre of rotation is the centre of the bounding box of the selected component. *Scene Positioning* uses the *scene-in-hand* technique [Dai et al 1996]. The movement and orientation of the 3D input device is directly mapped to the movement of the entire scene. The centre of rotation is the centre of the scene. The feedback from the usability evaluation in Chapter 3 suggested that there is a need to add a flexible Undo process during the interaction process. Therefore, a *Constraint Removing* function has been added to allow the users to remove a constraint on any component they want. The users only need to select a component using *Component Selection*, and the constraints associated with the selected component can be removed, one by one in the reverse order to which they were applied.

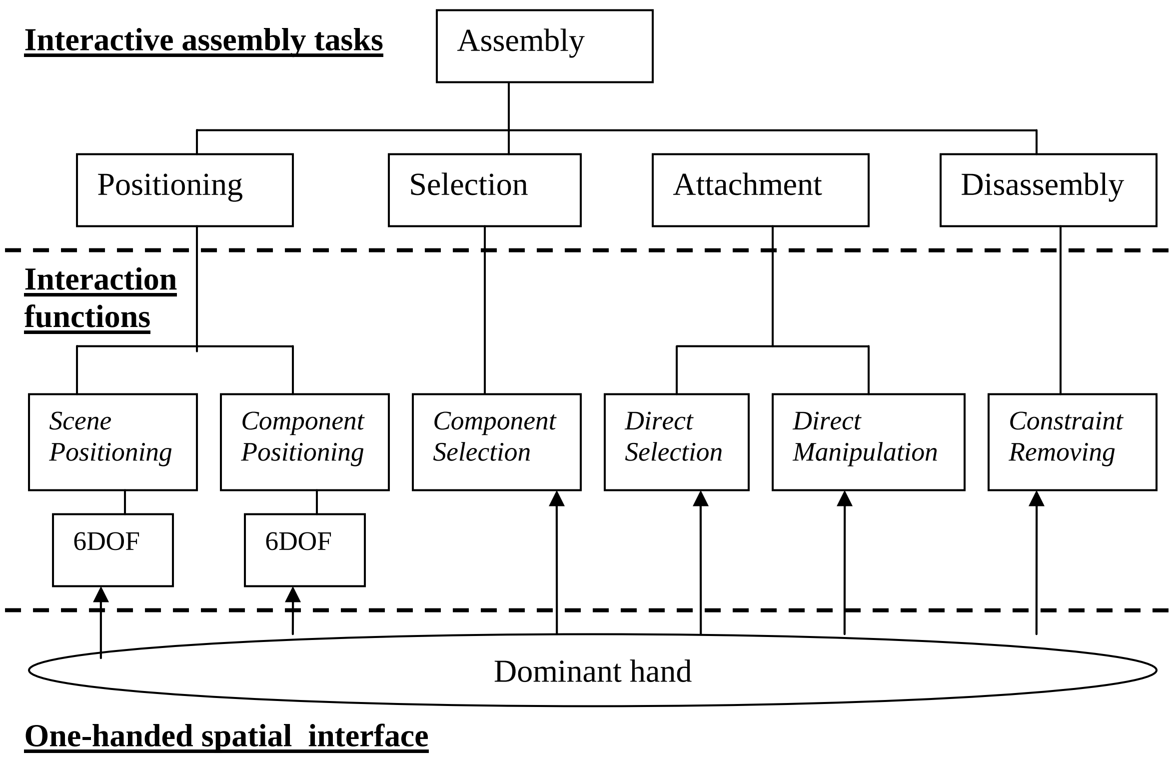


Figure 4-1 Architecture of the one-handed spatial interaction model

The one-handed spatial interaction model supports two spatial input devices: the stylus and CyberGlove™. The implementation structure of the one-handed spatial interaction model is shown in Figure 4-2. The user provides input to the system through the input devices. At the lowest level of the system, this input is received and processed by the device drivers to create input events. For the glove device this includes gesture recognition, while the stylus device driver identifies the status of the buttons. Both devices also have their position and orientation tracked in 3D. These recognised events are then mapped onto specific interaction functions or modes within the IVPS using an event-mapping table. Any impact on the assemblies is processed by the constraint engine and the entire scene is rendered on output devices such as a large stereo display.

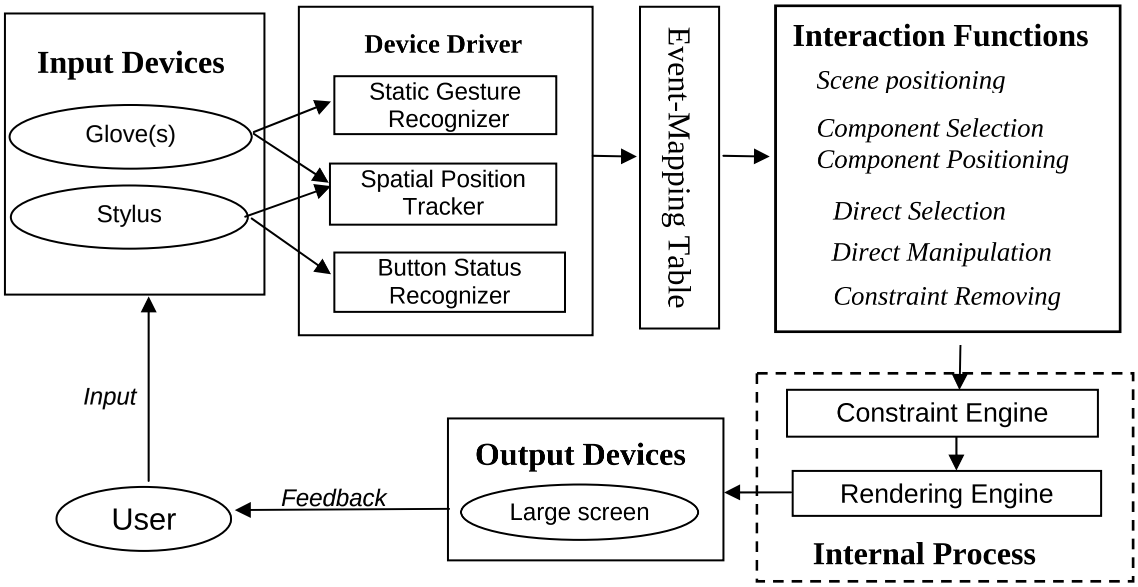
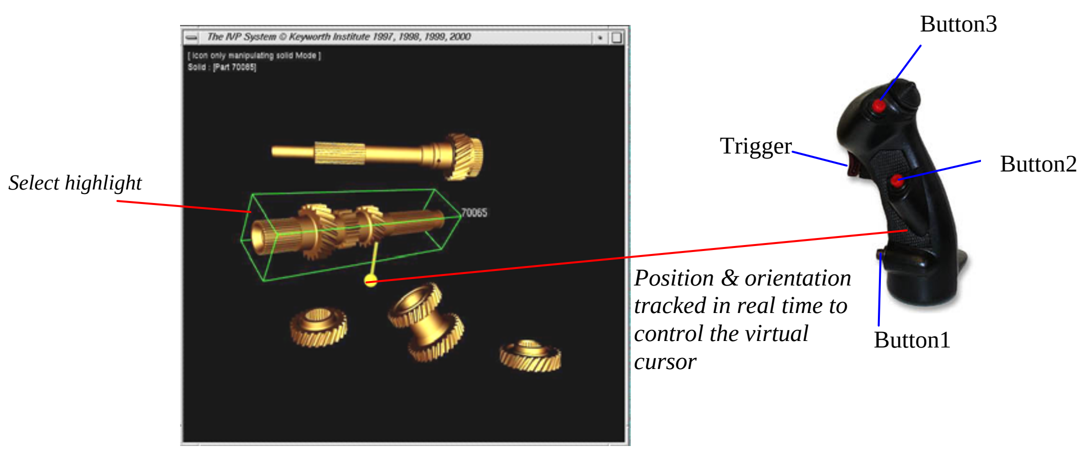


Figure 4-2 Implementation structure of the one-handed spatial interaction model within the IVPS

The following sections descibe the two configurations of the one-handed spatial interaction model based on the different spatial input devices: one-handed stylus interface and one-handed glove interface.

4.1.1 A one-handed stylus interface



(The green box indicates the current component is picked by pressing the trigger)

Figure 4-3 The one-handed stylus interface

The stylus interface is shown in Figure 4-3. The stylus is a flight-stick or joystick without the base, but containing a sensor so that its position and orientation can be tracked using an Ascension Flock of Birds system. It has a number of buttons. The stylus is represented within the virtual environment by a virtual cursor that follows the movement of the physical device. Pressing buttons, or combinations of buttons, on the stylus will trigger button events. These events are mapped onto interaction functions in accordance with Table 4-1. Colour has been suggested as a useful and powerful method for attracting attention and assisting recognition in Chapter 3. Therefore, when the mode is changed, the colour of the virtual cursor is also changed in order to provide visual confirmation of the mode change to the user.

Table 4-1 Button event mapping

Pressed buttons	Operations
Trigger	Selecting and manipulating a component in *Component Selection* mode, or confirm a selection in *Direct Selection* mode
Button3	Positioning the entire scene
Button1	Switch to *Direct Selection* mode
Button2	Switch to *Direct Manipulation* mode
Button2+Button3	Switch to *Component Selection* mode and reset the virtual cursor
Button1+Button3	Switch to *Constraint Removing* mode

Positioning the entire scene involves pressing Button3 and moving the stylus around. While this button is held down, the position and orientation of the stylus is mapped directly on the entire scene. To ***select*** a component the user must manipulate the virtual cursor to point at the required component and then presses the front trigger button to select it. The component remains selected and can be directly ***manipulated*** until the trigger is released. The trigger is frequently used for these operations as it is very easy to touch and press by the user's index finger while the user holding the stylus. Visual cues are presented to the user during the selection process. While the user is selecting a component, a red bounding box is used to indicate which component the user is currently pointing to. When a component is actually picked the box changes to green as shown in Figure 4-3.

To attach two components using ***Direct Selection*** mode, the user must point to and select the features from the two components using the trigger. The system provides visual cues throughout this process by highlighting the selected features either in red to indicate that they cannot be mated , or green to indicate that they can (Figure 4-4). To form a constraint using ***Direct Manipulation*** mode the user first selects and manipulates a component in the usual way by pointing and pressing the trigger button. While the component is manipulated the system predicts and highlights possible constraints that exist between the selected component and its nearest component or collided component (Figure 4-5). Once the required constraint is recognised the user releases the trigger button to deselect the component. The system then automatically satisfies the constraint and the two components are "snapped" together. Once a component is selected in *Constraint Removing* mode, the latest added constraint on it will be removed. And then the component will then transform back to its previous position.

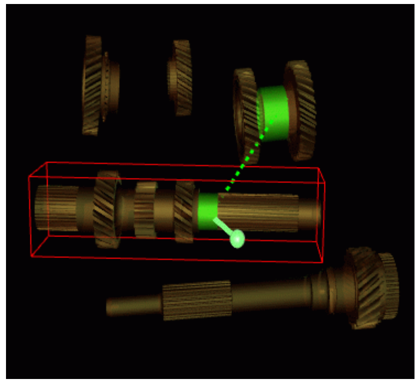


Figure 4-4 Attaching two components by *Direct Selection* (The user selects two cylindrical features to form a concentric constraint)

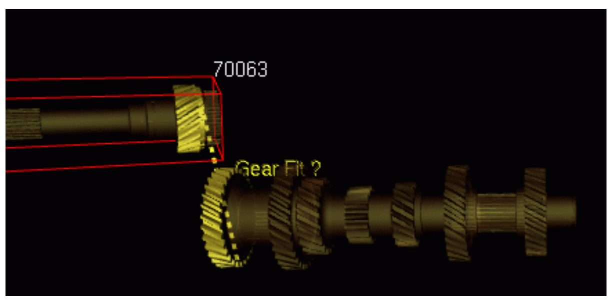
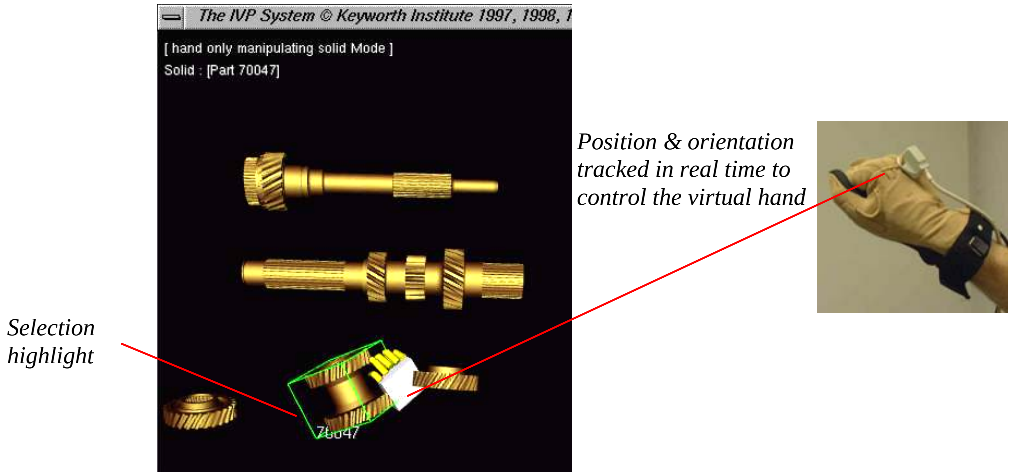


Figure 4-5 Attaching two components by *Direct Manipulation* (A gear fit constraint is detected when two components are close to each other)

4.1.2 A one-handed glove interface

The CyberGlove™ used for this interface contains 22-sensors (three flexion sensors per finger, four abduction sensors, a palm-arch sensor, and further sensors to measure flexion and abduction) to capture hand and finger motions. A tracking sensor is also attached to the CyberGlove™ so that its position and orientation can be tracked. The user's hand is represented within the virtual environment by a 3D graphical hand that moves and flexes to mimic the movement of the user's real hand, as illustrated in Figure 4-6.



(The green box indicates the current component is picked by making a fist)

Figure 4-6 The one-handed glove interface

The static gesture recogniser within the glove device driver can recognise up to eight different hand gestures. Once a gesture is recognised a particular input event is raised and mapped on to a particular interaction function as shown in Table 4-2. The reason for choosing these specific gestures is that they are distinctly separate and therefore they are less likely to be confused by the recogniser. To identify a gesture the recogniser first inspects the status of each finger, which can be stretched (S) or bent (B). By identifying specific combinations of stretched and bent fingers, it is possible to recognise which gesture is currently being formed by the user. For example, if the status of the index finger is stretched and the others are bent, the gesture can be identified as the one finger gesture. If all the fingers are stretched or bent, the gestures are the flat hand or fist respectively. The method to calculate the status of each finger (X) is described as the following:

If

$$X >= 0.5 * (S_{max} - B_{min}),$$

then

$$X = S;$$

otherwise

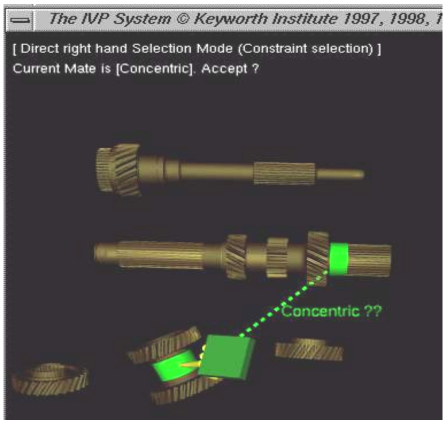
$$X = B.$$

The maximum of the stretched data (S_{max}) and the minimum of the bent data (B_{min}) can be obtained when the user is calibrating the glove device. As with the stylus cursor, the colour of the virtual hand is changed when the interaction mode changes, in order to provide the user with a visual confirmation.

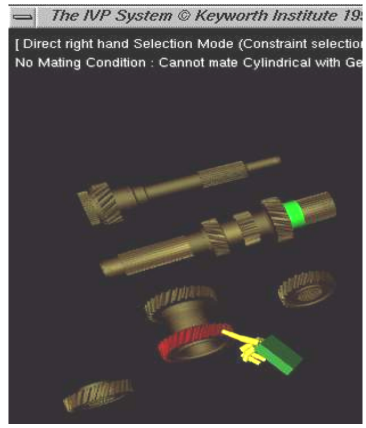
Table 4-2 Gesture mapping

Hand Gesture	**Operations**	**Hand Gesture**	**Operations**
 THUMB UP	Positioning the entire scene	 OK	Switch to *Component Selection* mode
 FLAT HAND	Select a component	 FIST	Grab and manipulate a component
 ONE FINGER	Switch to *Direct Selection* mode and select a feature	 TRIGGER	Pick the geometric feature which is under selection
 TWO FINGERS	Switch to *Direct Manipulation* mode.	 THREE FINGERS	Switch to *Constraint Removing* mode

To ***position*** the entire scene the user must make the thumb up gesture. While this gesture is held, the tracked position and orientation of the users hand is mapped directly onto the translation and rotation of the scene. To ***select*** a component the user holds their hand flat and moves it until the virtual representation intersects with the required component [Zachmann & Rettig 2001]. The component is then selected by making a fist and can then be directly ***manipulated*** while the fist gesture is maintained. The flat hand and fist gestures were employed in order to mimic the process of reaching and grabbing objects in the real world. To form a constraint using ***Direct Selection*** the user must point to the features they wish to put together, using the one finger gesture. This gesture also mimics the gesture we often use to point an object in the real world. As shown in figure 4-7, the system highlights the selected features in green or red depending on whether they can or cannot be mated successfully. To confirm a selection the user makes a trigger gesture and the system automatically satisfies the constraint. To form a constraint using ***Direct Manipulation*** method the user first makes the two-finger gesture to signal that they wish to enter *Direct Manipulation* mode. A component can then be selected and manipulated in the normal manner using the flat hand and fist gestures. As the component is manipulated the system will predict and highlight possible constraints between this component and its nearest component or collided component. When the user releases the component, the system automatically snaps the components together. To remove a constraint, the user needs to switch to *constraint removing* mode using a three finger gesture, and then point to the related component just like pointing to the feature in the *Direct Selection* mode.



a) The user selects two cylindrical features and is asked whether they wish to form a concentric constraint.



b) The user selects two features that cannot be mated.

Figure 4-7 Attaching two components by *Direct Selection*

4.2 Evaluation

The purpose of the study was to evaluate the impact of the one-handed spatial interaction model on the task-performance for engineering assembly. This was to determine what are the advantages and weaknesses of the one-handed spatial interfaces in terms of the use of different devices: stylus and glove.

4.2.1 Task

In order to get a better correlation with the previous results, the assembly task presented in this evaluation was the same as in Chapter 3. This was to assemble 5 car gearbox components (Figure 3-1) to build up a simple gearing mechanism (Figure 3-2).

4.2.2 Environment

The software platform for the evaluation was the IVPS with the one-handed stylus interface and one-handed glove interface as described in the previous sections. A large (1.5m x 1m) vertical rear-projected cabinet was employed to display the virtual environment in stereo, using active LCD shutter glasses. The glasses enable a viewer to see line-interlace stereoscopic image. The glasses alternately “shutter”, (i.e. block), the viewer’s left, then right, eyes from seeing an image. The stereoscopic image is alternatively shown in sequence left-image, then right-image in sympathy with the shuttering of the glasses.

4.2.3 Subjects and methods

The experiments involved a total of twelve test subjects. They were chosen from a variety of backgrounds (including geography, mechanical engineering, electronic engineering, language, business, computing and chemical engineering). All of them used a computer daily, but with little or no previous experience with VE systems. None of them were colour-blind or left-handed.

As described in Chapter1, observation, interviews and post-questionnaire were used in this study. The task completion time were recorded by computer. The questionnaire (see Appendix C.1) was prepared to gather qualitative feedback on the subject’s perception of task difficulty, mental effort, physical effort, satisfaction, stress, fatigue and learnability. The rating scale of these subjective measures was described in Chapter 1.

The study used a within-subjects design [Zhai 1995]. In within-subjects design, the same group of subjects is assigned to all experimental conditions; that is, each and every subject performs all experimental conditions. In within-subjects experiments, subjects may carry over some effects, such as skills or fatigue, from earlier conditions to later conditions. In order to overcome this possible transfer effect, the sequencing of the experimental conditions in within-subject design is usually balanced. The subjects are assigned to the conditions in such a way that all experimental conditions have an equal number of times of being first, second, etc.

The twelve subjects were asked to perform the assembly task with one of the input devices and then repeat the task with the other one. Half of them were asked to use the glove interface first, while the other half were asked to use the stylus first. The assembly sequences were restricted for a better correlation of the results using each interface. For each subject the evaluation involved the following steps:

1) A pre-questionnaire to gather the subjects' background and experience;

2) Basic training with IVPS using the first interface;

3) Practice to familiarize themselves with the assembly task, interaction techniques and the first interface;

4) Close observation of the actual assembly task being performed once in the first interface;

5) A post-questionnaire and interview for the first interface

6) Basic training using the second interface;

7) Practice to familiarize themselves with the second interface;

8) Close observation of the actual assembly task being performed once in the second interface;

9) A post-experiment questionnaire and interview for the second interface;

Video footage of the each subject performing the tasks during step 4 and 8 was also captured for later study and correlation with their feedback.

4.3 Results

After the experiment, user feedback (Appendix C.2) for the assembly tasks using each interaction function was collected. The verbal comments from the users were also recorded.

4.3.1 General feedback on the one-handed stylus and glove interface

Table 4-3 presents a summary of the feedback for all subjects after performing the task using both the glove and the stylus interfaces.

Table 4-3 General feedback on the one-handed stylus and glove interface

Device	Task time (min)	Task Difficulty *1 hard* *5 easy*	Mental effort *1 low* *5 high*	Physical effort *1 low* *5 high*	Stress *1 low* *5 high*	Fatigue *1 low* *5 high*	Self-satisfaction *1 not satisfied* *5 satisfied*	Learnability *1 difficult* *5 easy*
Stylus	4.9	3.9	2.4	1.7	1.6	1.7	4.1	4.2
Glove	6	3.4	2.6	3.1	2.1	2.7	3.9	4.4
Difference	1.1	0.5	0.2	1.4	0.5	1.0	0.2	0.2

All the subjects enjoyed using both spatial interfaces in the experiment. They said they felt more fun when using the stylus or glove than the mouse. The general feedback indicates that a majority of the subjects felt the stylus was easier to use for the assembly task than the glove. The task completion time in the stylus interface was faster than glove interface (with a difference of 1.1 min.). The subjects felt that the glove interface required slightly greater mental effort (a difference of 0.2) resulting in a higher level of stress (with a difference of 0.5), it demanded much greater physical effort (a difference of 1.4) and resulting in higher levels of fatigue (with a difference of 1.0). During interviews, subjects stated that the main reason for the difference was that the glove required them to form specific gestures, which they perceived as a more difficult task than having to press particular buttons on the stylus. From the observation, the subjects shift their attention from the screen to the control devices more frequently using the glove when they were changing the gestures. Ten of the twelve subjects reported that they felt the stylus was the easiest to use when performing the actual task. However almost half of subjects found that learning to use the gesture-based interface was easier than learning the button-based interface. They reported that this was because they found hand gestures easier to remember and more natural than a set of unmarked button. Therefore seven subjects chose the glove as their favourite device to use for this task (including three of the ten that chose the stylus as the easiest). The main reason given for choosing the glove was that they perceived this as a more natural and fun interaction device to use than the stylus even though it was often more difficult to use. The subjects were also asked to comment on the use of the stereoscopic display and shutter glasses during the experiment. All of the subjects, except one, were able to perceive the depth within the image. Most of subjects felt that depth perception assisted them in performing the required tasks. However, one of the subjects reported that the shutter glasses were uncomfortable as they produced unacceptable levels of eye fatigue.

As selection and positioning operations are frequently involved in assembly tasks, the following sections describe the user feedback in terms of selection and positioning.

4.3.2 User feedback on selection

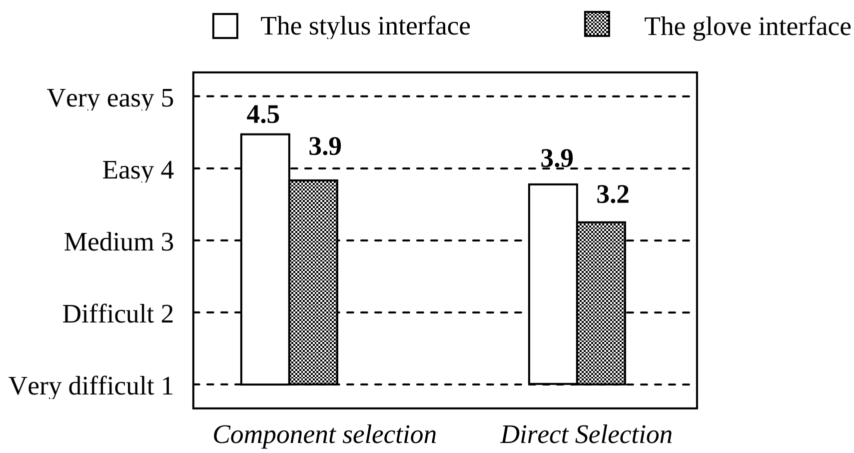


Figure 4-8 Feedback on selection in terms of task difficulty

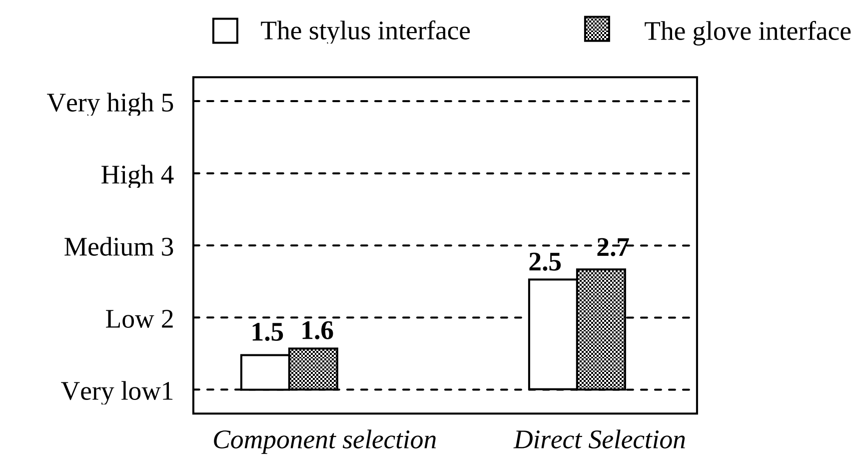


Figure 4-9 Feedback on selection in terms of mental effort

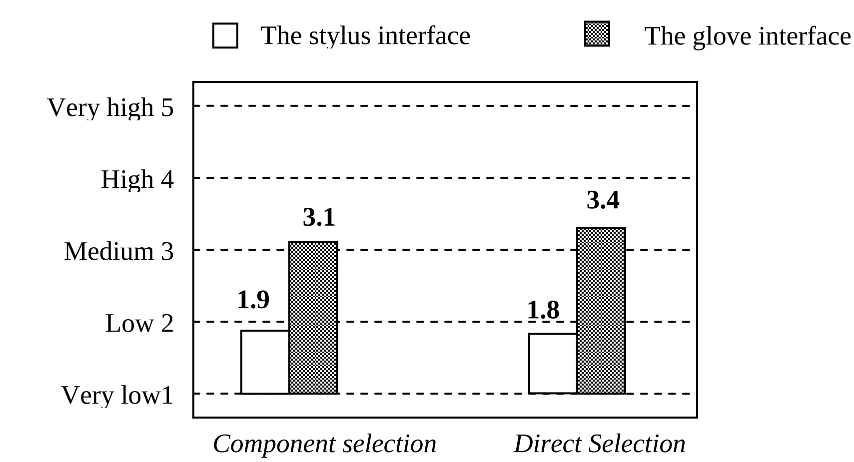


Figure 4-10 Feedback on selection in terms of physical effort

Figure 4-8, Figure 4-9 and Figure 4-10 present the feedback from the subjects for *component selection* and *Direct Selection*, in terms of task difficulty, mental effort and physical effort respectively.

For selecting a component, Figure 4-8 shows the stylus was easier than the glove (with a difference of 0.6). The required mental effort for this task was almost the same in Figure 4-9. However using glove required much higher physical effort (with a difference of 1.2) in Figure 4-10.

For selecting geometric features in *Direct Selection,* Figure 4-8 shows the subjects felt the glove was more difficult to use than the stylus (with a difference of 0.7). The results also indicate that they felt the mental effort required for this task in each case was very similar (only with a difference of 0.2) in Figure 4-9. The subjects also felt that the glove required considerably more physical effort (a difference of 1.6) than the stylus when performing the same task (Figure 4-10). When using the glove interface some subjects also reported difficultly making the required gesture to confirm the selection, while maintaining the same surface selection. In some case their hand would move slightly while changing gestures, resulting in the selection of different features. The problem of displacement of user's hand has also been observed in [Seay et al 2000] when performing selection or release.

The results in Figure 4-8 indicate that selecting geometric features in *Direct Selection* using either device was more challenging or difficult task than *Component Selection*. The subjects felt selecting a feature was harder than selecting a component, particularly when the feature was small in the scene such as the collar on each of three gear components. This is the problem of *scale*. The small size of target demands greater precision and requires the user to exercise more control of the position of the target component or the virtual cursor (or virtual hand) in both interfaces. For example, it was observed that the subject had to spend a lot of time in performing a sequence of "select-pull-release" steps to manipulate the component or the entire scene to the required position. When manipulating the virtual cursor or virtual hand to point at the feature, the subjects had to keep the dominant-hand very stable. Otherwise, the virtual cursor or virtual hand would jump around and miss the target due to the minor electromagnetic interference within the environment. Thus the subjects had difficulty in selecting the intended feature and found the task frustrating with both the glove and stylus interfaces. The problems of the tracking devices which result in the difficulty of fine manipulation have also been highlighted in [Jayaram et al 1999, Gomes & Zachmann 1999]. Further investigation also revealed that problems with precision during picking and selection operations were due, at least in part, to the choice of virtual representation of the 3D device. The stylus was represented within the virtual environment by a pointer. In this case, to pick and select a feature (or component) the subjects were able to concentrate on manipulating the pointer to establish a single clear point of contact between the pointer and the target. On the other hand, the glove was represented by a virtual hand, which could flex and move in response to the user's hand. In this case, subjects sometimes had difficulty determining which part of the hand needed to make contact with the target feature or component in order to select it.

4.3.3 User feedback on positioning

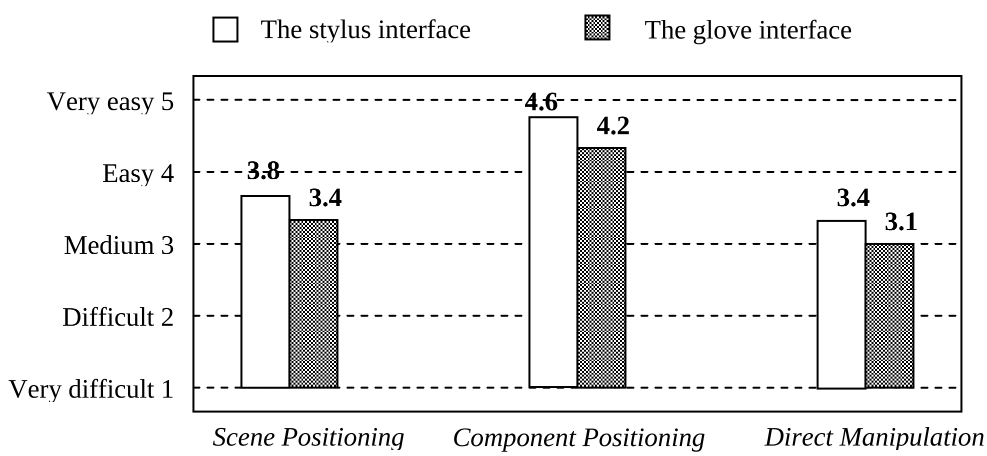


Figure 4-11 Feedback on positioning in terms of task difficulty

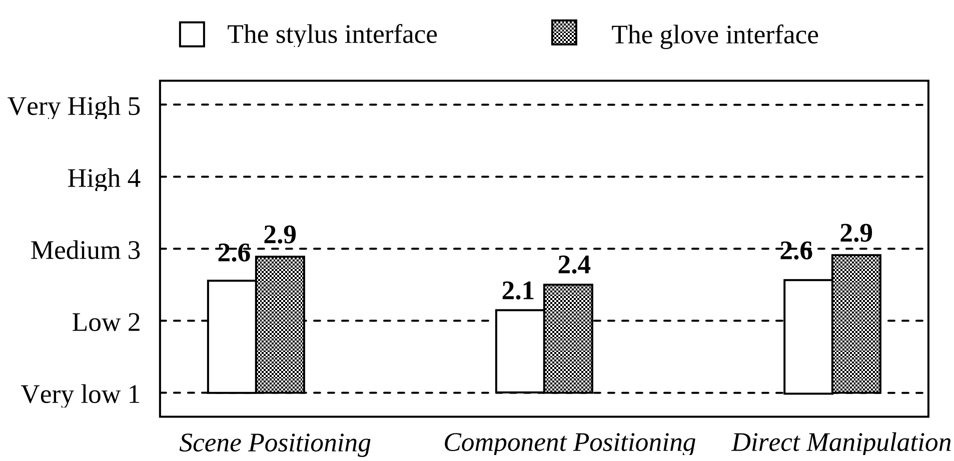


Figure 4-12 Feedback on positioning in terms of mental effort

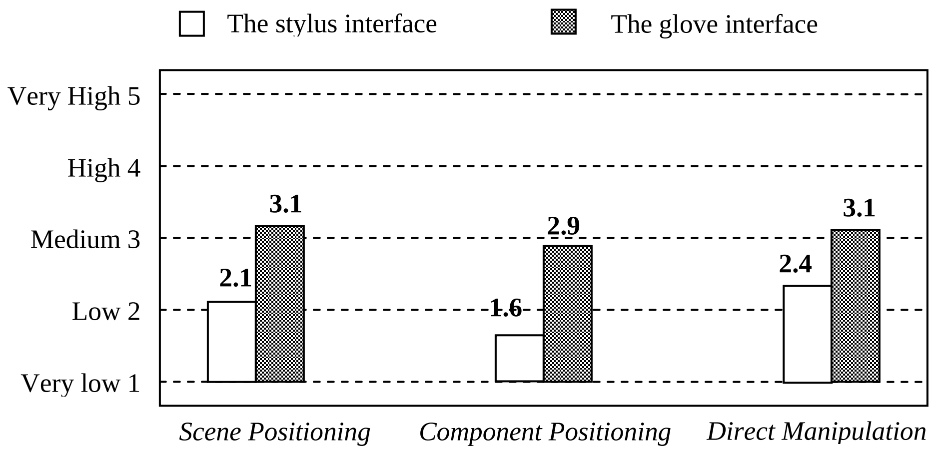


Figure 4-13 Feedback on positioning in terms of physical effort

Figure 4-11, Figure 4-12 and Figure 4-13 present the feedback from the subjects on three tasks involved positioning operations: *Scene Positioning*, *Component Positioning* and *Direct Manipulation*, in terms of task difficulty, mental effort and physical effort respectively.

Figure 4-11 shows that the subjects felt the stylus was easier to use than the glove for positioning the entire scene (with a difference of 0.6). The results in Figure 4-12 indicate that they felt the mental effort required for this task in each interface was similar (with a difference of 0.3). The results also indicate that this task demanded greatly higher physical effort (a difference of 1.0) when using the glove in Figure 4-13.

Once again, Figure 4-11 shows that the subjects felt the stylus was easier to use than the glove for positioning the selected component (with a difference of 0.4). The results in Figure 4-12 also indicate that the difference they felt the mental effort required for this task in each case was not great (with a difference of 0.3). The results also indicate that this task demanded considerably greater physical effort (a difference of 1.3) for the glove in Figure 4-13. Two subjects reported that using the stylus they felt more comfortable and in more control of the component when holding something physical during manipulation. It gave them a reference for the motion of the component. The subjects commented on the need for a source of reference for manipulation when using the glove. With the glove, when the subjects picked an object by making a fist gesture, they were not actually holding anything and thus could not perceive a natural centre or orientation for the manipulation. One of the subjects also reported that the scaling of physical hand movement to the movement of the virtual component did not feel natural when wearing the glove. In both the stylus and glove interfaces, subjects also reported the problem of *slide* when manipulating a constrained component in an assembly. The selected component easily slid out of its desired position when the constraints associated with the component were not fully specified during assembly process. The subjects had to spend time on putting the component back to the correct position.

In the similar way, Figure 4-11 shows that the subjects felt the stylus was easier to use than the glove for *Direct Manipulation* (with a difference of 0.6). The results in Figure 4-12 indicate that they felt the mental effort required for this task in each case was also similar (with a difference of 0.3). The results also indicate that this task demanded greater physical effort (a difference of 0.7) when using the glove in Figure 4-13. Additionally, when using the glove, the visual feedback provided by the system to indicate which constraint had been detected would sometimes be obscured by the virtual representation of the user's hand. In such cases the subjects often did not realize that a constraint had been detected and would either release the component, resulting in a formation of an unintentional constraint, or would continue moving the component and miss the constraint altogether.

Among *Scene Positioning*, *Component Positioning* and *Direct Manipulation*, the subjects perceived that *Direct manipulation* was the most difficult for both interfaces due to the highest precision demanded (Figure 4-11). This is because the selected component is required to be positioned related to its mated component. The problem of *related precision* was also reported in Chapter 3. During interviews the subjects reported that they could not fine adjust the orientation of the manipulated component easily since all rotation occurs at the wrist and thus found the task harder to perform using both devices. The subjects also felt that *Scene Positioning* was more difficult than *Component Positioning* using both interfaces. They said it was not easy to put some components in the position which they wanted on the screen by controlling the entire scene. The subjects also reported that *Scene Positioning* required greater concentration and spatial awareness than *Component Positioning*. This is the problem of *global precision*. Therefore, *Direct Manipulation* and *Scene Positioning* required higher mental effort (Figure 4-12) and physical effort (Figure 4-13) than *Component Positioning* due to the problems of related precision and global precision respectively.

4.4 Discussion

The results have shown that the spatial input was intuitive to the users. The one-handed spatial interfaces were relatively easy to understand and use. The results have suggested that the task-performance is strongly affected by the physical features of the input devices and the way they are mapped onto the tasks. Aside from physical problems, such as electromagnetic interference resulting in tracking precision problems, the stylus interface was generally found to be a more precise and easier to use interface, enabling the user to exercise greater control over selection and positioning operations. The reasons include:

1) The choice of virtual representation for the 3D device.

For the virtual cursor chosen for the stylus, the users could perceive the intersection between the cursor and the picking target more clearly than the virtual hand used for the glove interface. Moreover, when using the glove interface the virtual hand would often occlude important visual feedback.

2) The choice of gestures for the sequential operations.

The users experienced some difficulty in executing specific sequences of operations using some gestures. For example, one finger then trigger gesture for selecting geometric feature, while maintaining the same feature selection.

3) Physical reference of manipulation

When the user grasps the stylus, they are physically holding something within the palm of their hand. Thus the manipulation of components is perceived as more natural and consequently easier. However, with the glove, when the users select an object by making a fist gesture, they are not actually holding anything and thus cannot perceive a natural centre or orientation for the manipulation.

Based on the feedback, there are a number of problems of *precision* have been highlighted in spatial selection and positioning using both the one-handed stylus and glove interfaces. They include:

1) the problem of *scale*

When a geometric feature is very small such as the collar on the gear component, the user needs to exercise more control of the position of the target component and the tracked device. For example, the user often needs repeated "select-pull-release" steps to manipulate the component or the entire scene to the required position where the target feature can be properly viewed or easily selected. Further more, the user needs more careful control of the virtual cursor or virtual hand due to the limitations of the tracked devices such as the unstable sensor data. Otherwise, slight movement of the user's hand would miss the target as illustrated in Figure 4-14.

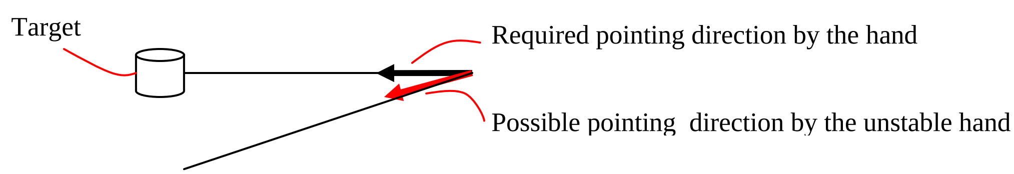


Figure 4-14 Slight rotation of the hand would miss the target

2) the problem of *slide*

Manipulation of a constrained component in an assembly is thought as a natural and accurate manipulation in the IVPS as the system can simulate the kinematic behaviour of the assembly by maintaining any previously formed constraints. However, the constrained component easily slides out of its proper position when the mating conditions associated with the component are not fully specified during assembly process. Therefore the user cannot maintain the current precise position of the constrained component due to the problem of slide. For example in Figure 4-15, Part G3 is constrained with Part S2 by a concentric mating condition. This means Part G3 would move along the axis of Part S2. However, it might slide out of its proper position and move far away from Part S2 along its axis. Once this happened, the subjects would spend time on dragging Part G3 back to the correct position on Part S2.

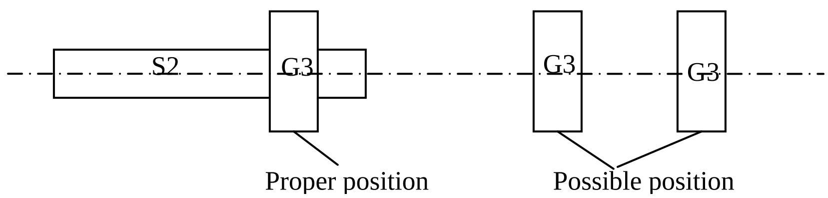


Figure 4-15 Possible position of Part G3 related to Part S2 during manipulation due to the problem of slide

3) the problem of *global precision*

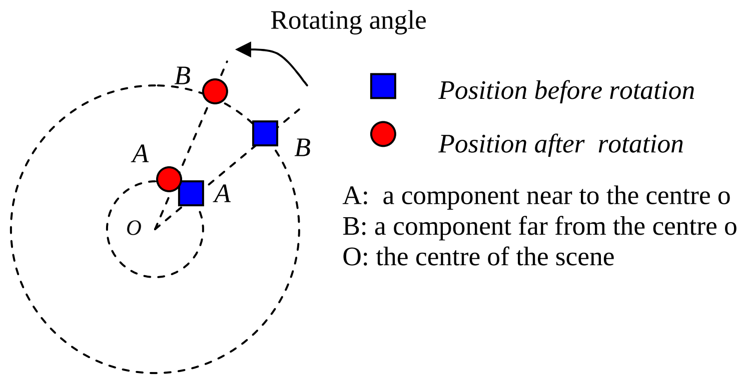


Figure 4-16 Position of two components before & after rotation of the entire scene

It is desirable to position the entire scene because this avoids having to switch models or select a component. However, precisely translating the entire scene can be problematic. It is natural that the user's hand would twist slightly when moving due to the biomechanical constraints of the hands and arms [Hinkley et al 1994b]. The slight twist would slightly rotate the entire scene. However, an object that is far form the centre of rotation would have a much greater angle of rotation (Figure 4-16). This makes it difficult to accurately position the object when translating the entire scene. In Figure 4-16, when rotating the entire scene with a small angle, Component B (far away from the scene center O) moves longer distance than Component A (close to the scene center O). Therefore, fine adjustment of the position of Component B would be much more difficult than Component A.

4) the problem of *related precision*

In an assembly, a component is often required to be positioned precisely related to another one. For example, to attach two components by *Direct Manipulation,* a particular mating condition between them can only be detected when the related position of the two components satisfy the requirements determined by the mating condition. This is found to be a difficult task using 6DOF spatial input.

4.5 Conclusion

This chapter presents a one-handed spatial interaction model for engineering assembly within the IVPS. By taking advantage of two spatial input devices: the stylus and CyberGlove^{TM}, a one-handed stylus and a one-handed glove interface are implemented.

This chapter reports an evaluation conducted to investigate the impact of the spatial interfaces on the assembly task-performance. The results suggest that the spatial input is intuitive to the users. The task-performance is strongly affected by the physical features of the input devices and the way they are mapped for the tasks. The stylus interface is generally found to be a more precise and easier to use interface, enabling the user to exercise greater control over selection and positioning operations. A number of reasons are discussed. Further, a number of problems of precision have arisen from the evaluation in spatial selection and positioning using a 6DOF spatial input. They include the problems of scale, slide, related precision, and global precision. To improve task-performance for engineering assembly, there is a need to develop a more efficient and intuitive spatial interface to overcome these problems in spatial selection and positioning. This is addressed in the next two chapters.

Chapter 5

Two-handed Spatial Interfaces within a VE

Based on the feedback in Chapter 4, it was difficult for the users to perform spatial selection and positioning operations for assembly using the 6DOF input, due to a number of problems of precision. This chapter is concerned with the design of a two-handed spatial interaction model to overcome these problems. This model assigns to the non-dominant hand tasks such as positioning that can be performed by a sequence of 1DOF sub-tasks. This leaves the dominant hand to perform 6DOF tasks such as selection, positioning and attachment. Section 5.2 reviews two-handed spatial interfaces, and section 5.3 describes two-handed theory and experiments. A table-based two-handed interface is presented in section 5.4. The initial user feedback in section 5.5 indicates that this interface has not the potential to significantly improve the task-performance for engineering assembly. A number of reasons are discussed in section 5.6. This section also makes a number of implications for the design of a new two-handed spatial interface in the next chapter.

5.1 Motivation for Two-handed Spatial Interfaces

In the physical world people often use both hands to cooperatively perform many tasks such as dealing cards, playing a stringed musical instrument, threading a needle, striking a match, etc. Threading a needle is an interesting example. One usually holds the needle in the non-dominant hand and the thread in the dominant hand. The dominant hand guides the thread through the eye of the needle, while the non-dominant hand coordinates its action with the requirements of the dominant hand. Even writing on a piece of paper with a pen, which has sometimes been mistakenly classified as a one-handed behavior, is demonstrably two-handed by Guiard [Guiard 1987]. Guiard has shown that the handwriting speed of adults is reduced by about 20% when the non-dominant hand cannot help to manipulate the page. Therefore, a fundamental observation provided by Guiard is that, in the set of human manipulative tasks, purely one-handed acts are by far in the minority, while two-handed acts are commonplace. Guiard's theory on *bimanual action* (cooperative action of the two hands working together) is further described in section 5.3.

A few user interface researchers have explored the possibility of using both hands in computer interfaces. The early studies in [Buxton & Myers 1986] have shown that a two-handed input is superior to a one-handed input for the 2D positioning and selection tasks. The two principal advantages for two-handed interfaces were discussed in these studies. Firstly, the division of labour across two hands means that each hand can more effectively operate in "home position". Secondly, subtasks can be assigned to each hand allowing for the possibility of temporal overlap thus reducing the time to complete the task. Kabbash et al [Kabbash et al 1994] came to a similar conclusion, however, they also showed that two hands could be worse than one if an inappropriate interaction technique is employed.

As spatial positioning presents tasks with many degrees-of-freedom, using both hands can potentially allow users to control these in a way that seems natural and takes advantage of existing motor skills [Hinckley 1996]. Building partly on the empirical work [Buxton & Myers 1986], some 3D interface researchers have demonstrated systems with compelling two-handed interfaces for spatial positioning within a VE [Frohlich & Plate 2000, Hinckley et al 1994a]. These also include some engineering assembly applications which have been described in Chapter 2 [Gribnau & Hennessey 1998, Sun & Hujun 2002].

This chapter is therefore concerned with the design of a two-handed spatial interface for improving the task performance of spatial positioning and selecting engineering assemblies within a VE. The goal is to overcome the problems of precision identified in Chapter 4.

5.2 Two-handed Spatial Interfaces within a VE

There has been a growing interest in two-handed interfaces for spatial positioning within a VE. This section provides the samples of two-handed spatial positioning techniques within a VE. The two-handed spatial interfaces for assembly applications are not included in this section since they have been described in Chapter 2.

In the conventional two-handed interaction, the non-dominant hand often uses a 6DOF tracker for spatial positioning and orienting [Shaw & Green 1997] [Forsberg et al 1998] [Cutler et al 1997] [Grossman et al 2001]. For example, in [Shaw & Green 1997], the non-dominant hand can be used for free manipulation of the entire scene. For the same task in [Grossman et al 2001], the non-dominant hand is used for tumbling and panning, while the dominant hand is for zooming operations.

Figure 5-1 The Cubic Mouse

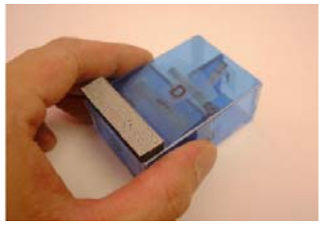


Figure 5-2 The ToolStone

Figure 5-3 The "pop-through-button" device

To overcome the limitations of using 6DOF spatial input by the non-dominant hand and improve the efficiency of spatial positioning and orienting, a few researchers have explored the potential of using special 3D input devices for the non-dominant hand. For example, the Cubic Mouse (Figure 5-1), reported in [Frohlich & Plate 2000], consists of a tracked cube-shaped box with three perpendicular rods passing through its center. It represents a reference model. Users hold the device in their non-dominant hand to position and orient the reference model, while their dominant hand operates the rods and the control buttons. However, by just twisting the wrist of the non-dominant hand, it is impossible to achieve larger rotation without the help of the dominant hand. All of its applications deal with manipulation of a single virtual model (the reference model). The ToolStone (Figure 5-2) [Rekimoto & Sciammarella 2000] is a cordless, multiple DOF input device that senses physical manipulation of itself, such as rotating, flipping and tilting. For 3D rotation of an object, the horizontal and vertical motions of the ToolStone control the direction of the rotation axis, and its rotation controls the angle of object rotation. The "pop through button" devices (Figure 5-3) [Zeleznik et al 2002] have been developed for VE navigation and interaction by pressing a button lightly and firmly. For example, the "pop through button" allows a user to perform translation by pressing a button lightly and orbital translation with firm pressure. This has been incorporated into a two-handed painting system in a VE. The users hold the pop through buttons by the non-dominant hand to assist the dominant hand to perform the painting tasks.

Another way leading to intuitive and precise interaction techniques is to use passive real world props augmenting interaction through tactile feedback. The advantages of the prop-based approach has been demonstrated in [Hinckley et al 1994a] for a neurosurgical planning application (Figure 5-4). A small doll head held in the non-dominant hand controls the viewpoint and scale of the displayed information, a small plate held in the dominant hand controls the current cross-sectioning plane. It supports previous work [Badler et al 1986] which has shown the advantage of interaction relative to a real object. Grossman et al [Grossman et al 2003] have presented an interface for creating and manipulating curves using a high degree-of-freedom curve input device (Figure 5-5). This device allows the user to directly control the shape and position of a virtual curve widget. The feedback from expert users indicates that they liked manipulating the tape using both hands simultaneously. However, it is noted that there was amount of physical work that could be required to manipulate the tape. It indicates the challenge of providing simple, easily understood physical artifacts to control virtual elements without increasing the work required of the user.

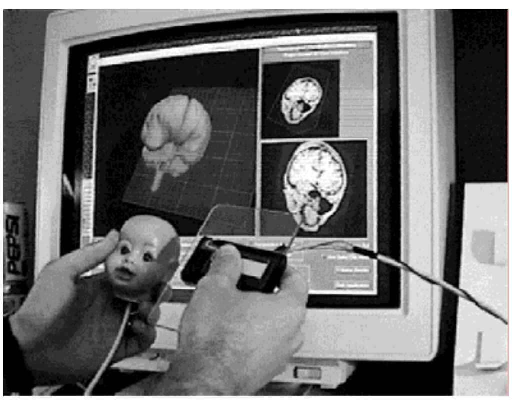


Figure 5-4 The two-handed prop-based interface [Hinckley et al 1994a]

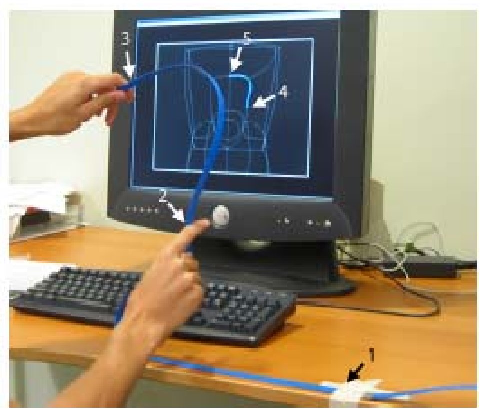


Figure 5-5 The curve input device [Grossman et al 2003]

"Pen-and-pad" is the recently most studied prop-based interfaces (Figure 5-6) [Coquillart & Wesche 1999] [Bimber et al 2000] [Stoev & Schmalstieg 2002] [Haan et al 2002] [Schmalstieg et al 1998]. The user usually holds a tracked palette or clipboard in the non-dominant hand and a stylus in the dominant hand. The palette provides a reference for asymmetric two-handed interaction and passive haptic feedback. One example of its applications is the use of World-In-Miniature (WIM) technique in the "Pen-and-pad" interfaces. The WIM concept (Figure 5-7) has been firstly presented in [Stoakley et al 1995]. The WIM provides the user with a miniature copy of the virtual environment. It can be attached to a tracked clipboard in the non-dominant hand [Mine 1996]. By moving the clipboard the user changes the position and orientation of the WIM, allowing him to view it from different direction. The dominant hand can perform large scale manipulations of remote objects simply by manipulating the corresponding miniature copy in the WIM. However, it was found in [Mine 1996] that fine-grained manipulations in the WIM are difficult, particularly if the user is forced to hold a copy of the entire environment in his hand. As the environment has been scaled down to WIM size, individual scene elements may be quite small, and thus difficult to see, select, and manipulate. Inspired from the WIM, Through-The-Lens metaphor [Stoav & Schmalstieg 2002] enables simultaneous exploration of a virtual world from two different viewpoints (one called primary world and the other called secondary world). A set of through-the-lens techniques proposed for positioning can allow reaching through the window and manipulating the objects seen through it. Haan et al used a tracked transparent Plexipad as the *direct data slicer* [Haan et al 2002] for the exploration of scientific data. It serves as an excellent feedback for constrained probing when the user is selecting a point of interest on the Plexipad.

Figure 5-6 The pen-and-pad interface on the Virtual Table in [Schmalstieg & Encarnacao 1998]

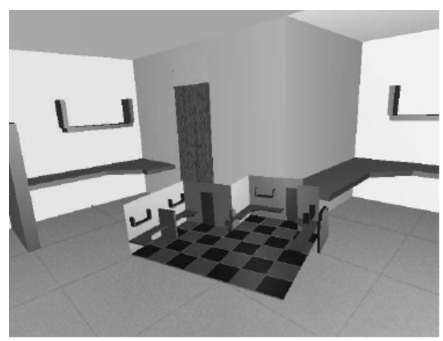
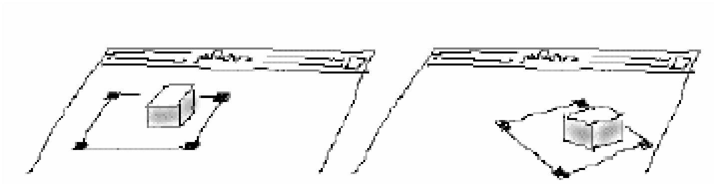
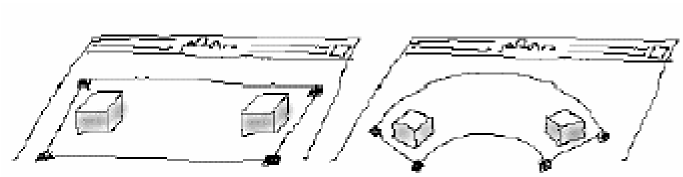


Figure 5-7 The World-In-Miniature (WIM) viewed against a life-size virtual environment [Stoakley et al 1995]

The *graspable* user interface in [Fitzmaurice et al 1995] further demonstrates the advantages of interacting with computer applications using physical props, called *bricks*. Users, for example, move and rotate a virtual object by manipulating a physical brick placed on top of it (Figure 5-8 a). With multiple bricks users can perform more complex operations such as simultaneously positioning and sizing a virtual object (using a brick held in each hand) (Figure 5-8b). Experimental evaluations of the graspable interface have been presented in [Fitzmaurice & Buxton 1997]. The evaluations compared the *space-multiplexed* graspable interface with a conventional *time-multiplexed* interface. In a space-multiplexed interface, multiple physical devices can be attached to different functions. In a time-multiplexed interface, a single input device such as a mouse controls different functions at different points in time. The results show that the space-multiplexed graspable interface outperforms a conventional time-multiplexed interface for a variety of reasons, including the persistence of attachment between the physical device and the logical controller.



a) Move and rotate virtual object by manipulating a physical brick, which acts as a handle.



b) Moving and rotating both bricks at the same time causes the electronic object to be transformed.

Figure 5-8 The *graspable* interface [Fitzmaurice et al 1995]

Inspired from the brick-based interaction, a planning tool BUILD-IT based on computer vision technology has been developed with capacity for complex planning and composition tasks [Rauterberg et al 1997]. In BUILD-IT, brick-based camera control has been explored using two bricks [Fjeld et al 1999a, 1999b]. For example, one brick offers shift and rotation, a second brick adds zoom. Distance between them sets zoom (Figure 5-9). An evaluation has been conducted to compare the brick-based interface with three alternative tools for single-user problem solving [Fjeld et al 2002]. These three alternative tools are a 3D physical, a 2D cardboard, and a mathematical tool. The results show that the 3D physical tool performs best, followed by the brick-based interface, the 2D cardboard and the mathematical tool.

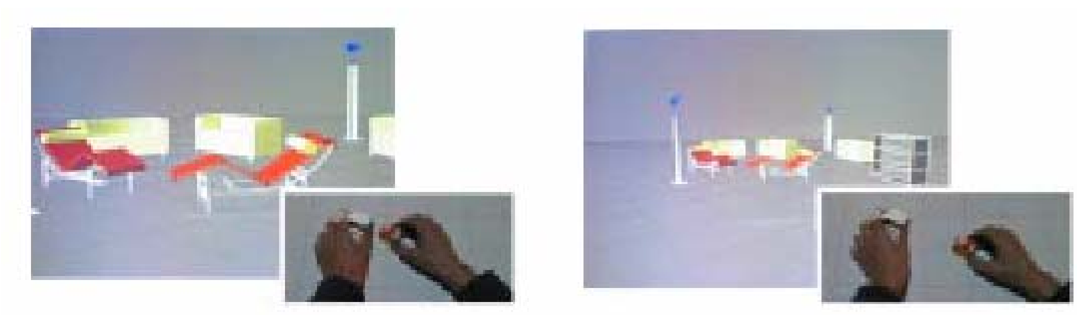


Figure 5-9 Camera handling in BUILD-IT: Zooming in (left) and out (right) [Fjeld et al 1999b]

There are some other examples of using physical objects for 3D positioning control. The computational building blocks [Anderson et al 2000] enable 3D design using Lego-like blocks. However, these blocks are assembled and constructed off-line, and then digitally sampled in a relatively slow process. To overcome this problem, a user interface called *ActiveCube* has been presented in [Kitamura et al 2000]. It can in real time update each connect or disconnect event by using actual physical cubes. With this interface, the user can easily construct various 3-D structures in a VE by simply combining the cubes (Figure 5-10). Each ActiveCube is equipped with both input and output devices, which makes the interface intuitive and helps to clarify the causal relationship between the input of the user's operational intention and the output of simulated results. An experimental evaluation confirms the sensitivity and reliability of the use of ActiveCube [Sharlin et al 2002].

Figure 5-10 Interaction with the ActiveCube

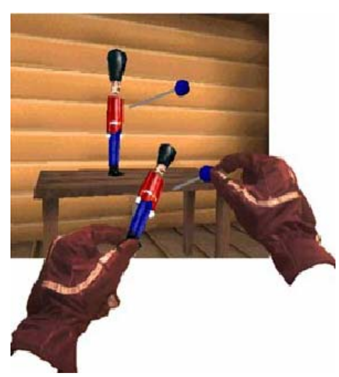


Figure 5-11 The Voodoo Dolls interface

The Voodoo Dolls technique [Pierce et al 1999] has been developed to interact with objects at a distance in a VE (Figure 5-11). With this technique, the user dynamically creates dolls: transient, hand held copies of objects whose effects on the objects they represent are determined by the hand holding them. When a right-handed user holds a doll in his right hand and moves it relative to a doll in his left hand, the object represented by the doll in his right hand moves to the same position and orientation relative to the object represented by the doll in his left hand. It allows users to both position and orient objects more accurately than the HOMER technique [Pierce & Pausch 2002]. The HOMER technique [Bowman & Hodges 1997] uses ray casting to select the object and then moves the user's virtual hand to the position of the object for manipulation.

Summary

The review of the two-handed spatial interfaces has shown that there is a growing interest in using two-handed interfaces for spatial positioning. However, these interfaces have a number of limitations with respect to the problems of precision in spatial positioning. Most of the two-handed approaches have limited the non-dominant hand in coarse 6DOF positioning. Moreover, the non-dominant hand positioning is often limited by the design of the device [Gribnau et al 1998] and the biomechanical constraints of the hand [Frohlich & plate 2000]. Therefore there is a need to design an efficient two-handed interface for spatial positioning to address the problems of precision.

5.3 Theory and Experiments for Two Hands

5.3.1 Guiard's Kinematic Chain model

Guiard has proposed the *Kinematic Chain* as a general model of skilled asymmetric bimanual action, where a kinematic chain is a serial linkage of abstract motors [Guiard 1987]. The Kinematic Chain model hypothesizes that the dominant hand and non-dominant hands make up a functional kinematic chain: for right-handers, the distal right hand moves relative to the output of the proximal left hand. Based on this theory and observation of people performing manual tasks, Guiard proposes three high-order principles governing the asymmetry of human bimanual gestures, which can be summarized as follows:

1) *Dominant to non-dominant reference*: The motion of the dominant hand typically finds its spatial references in the results of motion of the non-dominant hand;
2) *Asymmetric scales*: The non-dominant hand and the dominant hand are involved in different motions. When compared to the motions of the dominant hand, the motions of the non-dominant hand tend to be of lower frequency and higher spatial amplitude;
3) *Non-dominant precedence*: The movement of the non-dominant hand precedes the dominant hand.

5.3.2 Experiments for 2D tasks

A classic study in [Buxton & Myers 1986] (Figure 5-12) demonstrated that two-handed input can yield significant performance gains for two 2D tasks. Two experiments were conducted. The first one involved the performance of a compound task: positioning / scaling a graphical object. The two sub-tasks were performed by different hands using separate transducers. Without prompting, novice subjects adopted strategies that involved performing the two sub-tasks simultaneously. The results also showed that the speed of performing the task was strongly correlated to the degree of parallelism employed. The second experiment involved the performance of a compound task navigation / selection. It compared a one-handed versus two-handed method for finding and selecting words in a document. The results showed that the two-handed methods resulted in improved performance for both experts and novices. Further, the first order benefit cannot be attributed to the two hands being used at once. Rather, the improvement is interpreted as being due to the increased efficiency of hand motion in the two-handed technique. In the one-handed approach, significant time is consumed in moving the pointer between the document’s text and the navigational tools. In the two-handed version, the hands are always in home position for each of the two tasks, so no such time is consumed. It is therefore expected that there would be the greatest improvement in performance in transitions where there is the greatest distance between the target and the navigational tools.

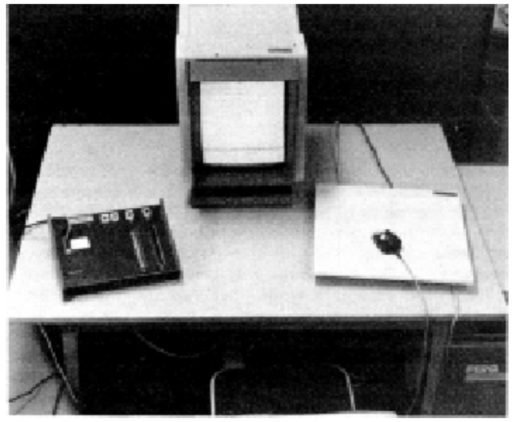


Figure 5-12 Buxton's experimental environment [Buxton & Myers 1986]

Pointing and dragging tasks were compared using the dominant hand versus the non-dominant hand in [Kabbash et al 1993]. For small targets and small distances, the dominant hand exhibited superior performance, but for larger targets and larger distances, there was no significant difference in performance. It was concluded that *"the hands are complementary, each having its own strength and weakness"*. A second experiment in [Kabbash et al 1994] studied compound drawing and color selection in a "connect the dots" task (Figure 5-13). The experiment evaluated the two-handed ToolGlass technique [Bier et al 1993]. The ToolGlass consists of a semi-transparent menu which can be superimposed on a target using a trackball in the non-dominant hand. The dominant hand can then move the mouse cursor to the target and *click through* the menu to apply an operation to the target. This integrates the initiation of drawing and color selection into a single action. The results showed that the ToolGlass technique gave rise to the best overall performance. It suggested that if two-handed techniques can be designed such that they take into account skills that are already in place, two hands for interaction can be very much superior to one. It was also demonstrated that, if designed incorrectly, two-handed input techniques can yield worse performance that one-handed techniques. In particular, it was argued that techniques which require each hand to execute an independent sub-task can result in increased cognitive load, and hypothesized that consistency with Guiard's principles [Guiard 1987] is a good initial measure of the "naturalness" of a proposed two-handed interaction.

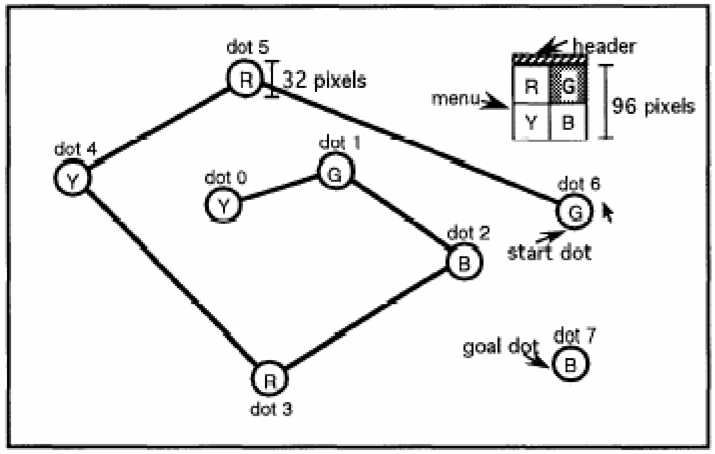


Figure 5-13 Kabbash et al's connect the dots experiment [Kabbash et al 1994]

The manual and cognitive benefits of two-handed input has been further explored in an experiment study using an "area sweeping" task [Leganchuk et al 1999]. The experiment compared the conventional one-handed GUI approach with two bimanual techniques including the ToolGlass [Bier et al 1993] and the two-handed "stretchy" technique [Krueger 1983]. The results showed that the bimanual techniques resulted in significantly faster performance than the *status quo* one-handed technique, and these benefits increased with the difficulty of mentally visualizing the task. There was no significant difference between the two bimanual techniques. The results supported the hypothesis that bimanual manipulation may bring two types of advantage to human-computer interaction: manual and cognitive. Manual benefits come from increased time-motion efficiency. Cognitive benefits arise as a result of reducing the load of mentally composing and visualizing the task at an unnaturally low level which is imposed by traditional one-handed techniques.

5.3.3 Experiments for 3D tasks

A set of experiments have been conducted to study two hands performing 3D tasks at University of Virginia. One experiment has been presented on cooperative bimanual action in [Hinckley et al 1997b]. Right-handed subjects manipulated a pair of physical objects, a *tool* and a *target object*, so that the tool would touch a target on the object (Figure 5-14). For this task there is a marked specialization of the hands. Performance is best when the left hand orients the target object and the right hand manipulates the tool. It is significantly reduced when these roles are reversed. This suggests that the right hand operates relative to the frame-of-reference of the left hand. Furthermore, when physical constraints guide the tool placement, this fundamentally changes the type of motor control required. The task is tremendously simplified for both hands, and reversing roles of the hands is no longer an important factor. This indicates that specialization of the roles of the hands is significant only for precise manipulation. Another two-handed experiment has been presented in [Hinckey et al 1997a] using a 3D manipulation task to align two virtual objects (Figure 5-15). The two-handed interaction used the prop-based interface (Figure 5-4). The results suggested that the two hands together provide sufficient perceptual cues to form a frame of reference which is independent of visual feedback. The same is not true for one hand moving in empty space. It is interpreted that users may not have to constantly maintain virtual attention when both hands can be involved in a manipulation. The results also suggested that using two hands can potentially impact performance at the cognitive level by changing how users think about a task.

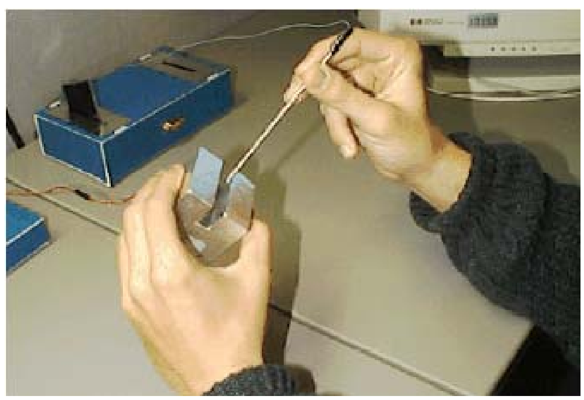


Figure 5-14 The *tool* and *target object* experiment [Hinckey et al 1997b]

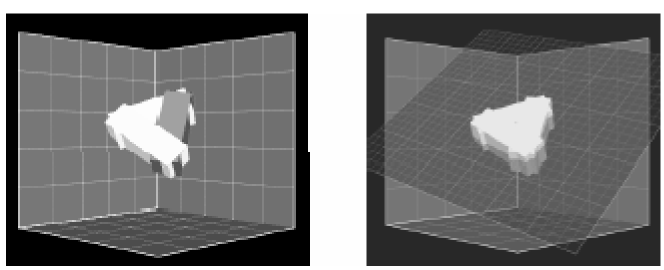


Figure 5-15 Stimuli for the alignment task [Hinckley et al 1997a]

Two experiments have been presented in [Balakrishnan & Kurtenbach 1999] to study bimanual camera control and object manipulation in 3D graphics interfaces. Both compared the two-handed interaction with the status-quo one-handed interaction. In the first experiment, the two-handed users used the non-dominant hand for camera control and the dominant hand for a target selection. The results showed that using the bimanual technique was 20% faster. Experiment 2 compared performance in a more complicated object docking task. However, performance advantages were shown only after practice. Both experiments showed that the users strongly preferred the bimanual technique.

A study has been presented to investigate the differential levels of effectiveness of various interactions on a simple rotation and translation task on the virtual workbench [Seay et al 1999, 2000]. The study involved four configurations of spatial interfaces in terms of the number of hands (one or two hands) and different interaction devices (pinch gloves and a 6DOF stick). They were: one-handed glove, one-handed stick, two-handed glove, and two-handed stick. The task involved placing a rod into the open side of a five sided cube or box (Figure 5-16). The results suggested that the sticks may be a more precise and efficient interaction device than pinch-gloves in object manipulation tasks requiring a degree of precision. One reason was that the user had to break down the stereo effect by interposing his/her hand between the eyes and the object presented on the display using pinch-glove during interaction on the virtual workbench. Another reason was that using pinch-glove, the tracker placement caused difficulty in precisely placing objects when forming the gesture for releasing the virtual object. Regarding to one-handed versus two-handed interaction, the obtained results indicated the number of hands had on effect on performance of the task. Hence the availability of the second interaction device did little to enhance performance when compared to the one-handed configuration. These results seemed to suggest that there may be classes of tasks for which two hands are not better than one. It is speculated that one such class of interactions would be those requiring relatively precise movement by the dominant hand operating within a static or environmentally maintained spatial frame of reference.

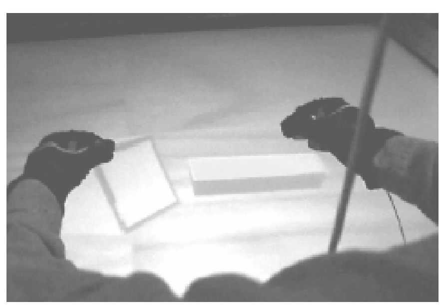


Figure 5-16 The box and rod task performed in the two-handed glove interface [Seay et al 1999]

5.3.4 Summary

The reviewed experimental results suggest that modeling two-handed interaction is less straightforward than one-handed interaction: the various ways in which two hands are integrated have implications for both motor and cognitive aspects of the task. In this respect, Guiard's theory [Guard 1987] offers a helpful framework for designing two-handed input techniques, particularly on the asymmetrical division of labor of the two hands. However, two hands can be worse than one, if the technique is designed inappropriately. The two-handed studies have shown that if two-handed techniques can be designed such that they take into account skills that are already in place, two hands for interaction can be very much superior to one [Kabbash et al 1994, Hinckey et al 1997a]. The challenge for the designer is to understand the nature of these skills and recognize how they can be applied in interacting with complex system [Kabbash et al 1994].

5.4 Design of a Table-based Two-handed Spatial Interface

The following reports a new two-handed spatial interaction model which has been designed to improve the task-performance of spatial positioning and selection operations in engineering assembly systems. This model is to address the problems of precision in spatial selection and positioning.

The design of the two-handed interaction model follows the Guiard's principles [Guiard 1987]. The non-dominant hand is assigned to positioning the target object, while the dominant hand manipulates the tool to select the target [Hinckley et al 1997b, Buxton & Myers 1986, Kabbash et al 1994, Balakrishnan & Kurtenbach 1999]. This means that: 1) positioning an object sets the frame of reference for the virtual cursor to select the target; 2) positioning demands lower precision than selection; and 3) the object movement is preceded by selection.

The design is also based on the observation that some tasks such as positioning are often best performed by a series of 1DOF steps [Shaw & Green 1997]. These tasks are assigned to the non-dominant hand. This leaves the dominant-hand to perform the 6DOF tasks such as manipulation of assemblies, selections and attachment. The structure of the two-handed interaction model using the IVPS is illustrated in Figure 5-17.

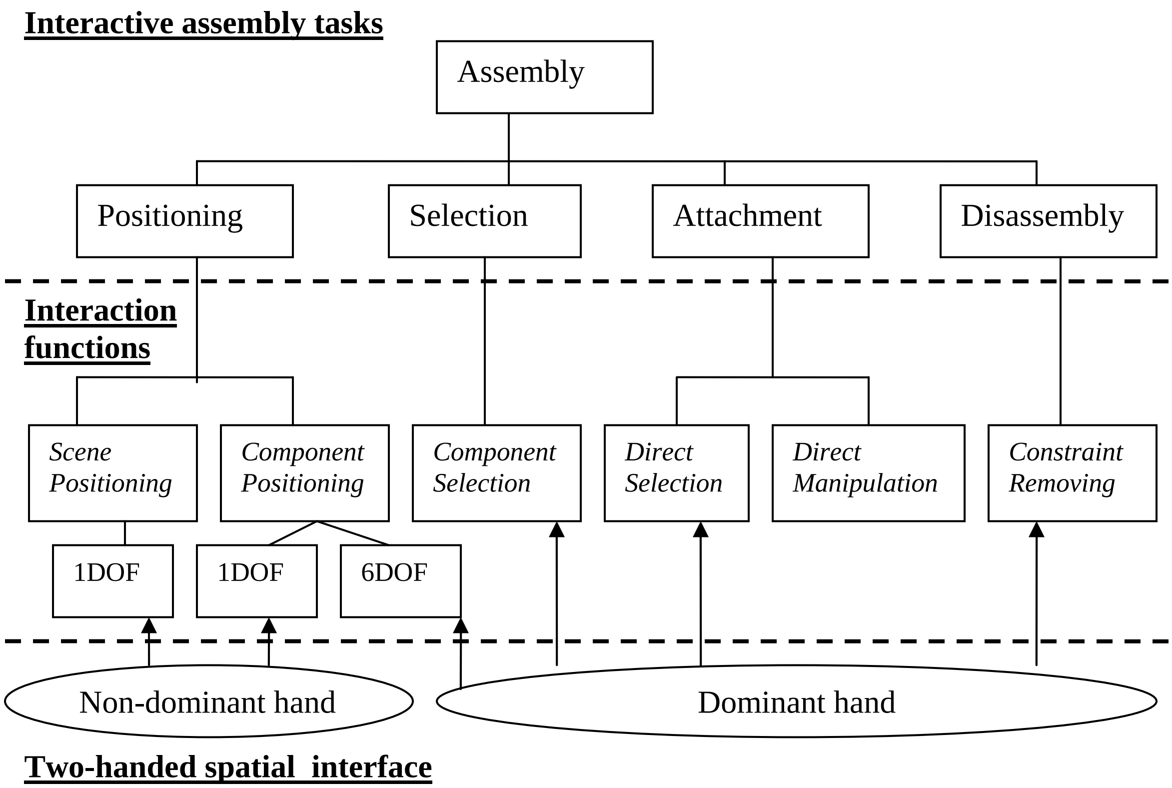


Figure 5-17 Architecture of the two-handed spatial interaction model

For attachment tasks, the two-handed spatial interaction in this chapter is only concerned with using *Direct Selection*, which has the problem of scale in spatial selection. The next chapter will discuss Direct Manipulation which has the problem of related precision in spatial positioning.

A table-based two-handed spatial interface has been designed as shown in Figure 5-18. It takes full advantage of the TAN Holobench at University of Leeds. The Holobench is an L-shaped 3D projection table with two orthogonal projection surfaces. Each projection area is around 180cm x 110 cm. The vertical plane is used for the 3D visual display and the horizontal plane is used to support the table-based interface and provide the control for the non-dominant hand.

The table-based interface as shown in Figure 5-18 provides a number of 1DOF positioning functions including the *zoom-in*, *zoom-out* and *rotation.* They are laid out on the horizontal plane within reach of the non-dominant hand. The *rotation* is to the left of the *zoom-in* while the *zoom-out* is in front of the *zoom-in*. An experimental input device for the non-dominant hand has been built to enable the user to activate the positioning functions. It is a 6DOF magnetic *tracker* with a *button* attached on one side and is tracked by the Ascension Flock of Birds system. The dominant hand uses the stylus as described in Chapter 4.

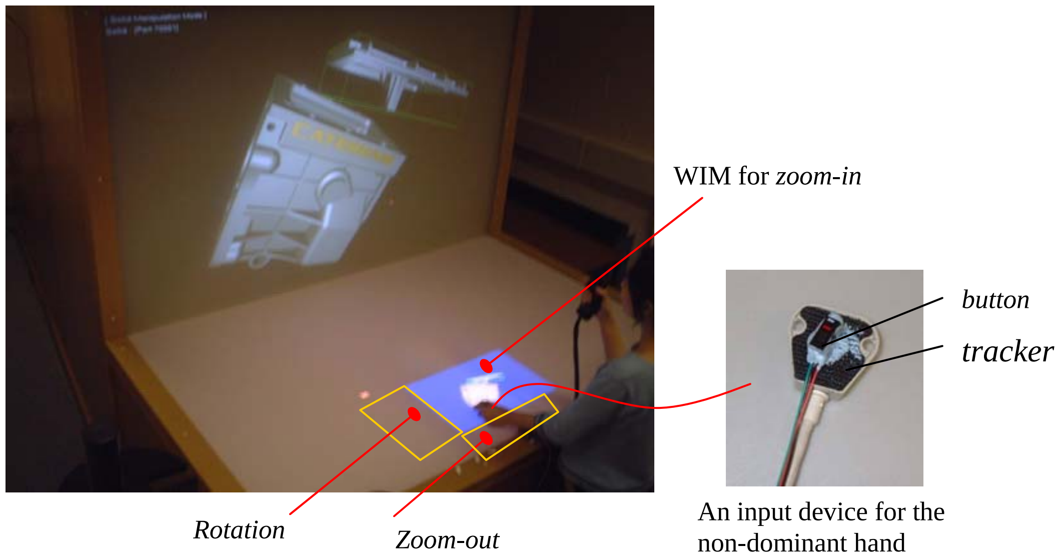


Figure 5-18 The table-based two-handed spatial interface

The *zoom-in* function is used to magnify a target area based on the WIM concept [Stoakley et al 1995] . A mini window is opened on the table. The size of the window can be set by the user. Its default size is around 45cm x 28 cm. The mini window provides the user with a miniature copy of the entire scene, no matter where the current viewpoint is on the vertical plane. Since precise manipulation of an object in the WIM is difficult [Mine 1996], the WIM is mainly used to specify a target area that needs to be magnified. To specify the area, the user simply moves the tracker to touch the area on the table. Once the user presses the button on the tracker, the target area moves forward at a constant speed until the user releases the button. The speed is adjusted according to the current distance between the scene centre and the user. As a result of *zoom-in*, the target area is magnified and displayed in the center of the vertical screen but the miniature keeps still. Thus the WIM can always provide an overview (or map) of the virtual environment. This helps the user to specify any area even not being displayed on the vertical screen. The virtual cursor also moves to the target area after the zoom-in. The *zoom-out* is used to move the entire scene backwards. When the user places the tracker in the *zoom-out* space on the table and presses the button, the entire scene moves backward at the same speed as in the *zoom-in* until the button is released

The *rotation* function is to rotate a selected component about the X, Y, Z axes. At first, the user moves the tracker in the *rotation* space on or above the table while the button is pressed. The path and distance of the hand's movement will be accordingly mapped to the rotating axis and the rotating speed as illustrated in Figure 5-19. To specify the +X / -X axis, the user's hand slides rightwards / leftwards respectively on the table; To specify the +Y /- Y axis, the user's hand moves upwards / downwards; To specify the +Z /- Z axis, the user's hand moves forwards / backwards. The highlighted component by the stylus then keeps rotating around the specified axis at the specified speed until the button is released.

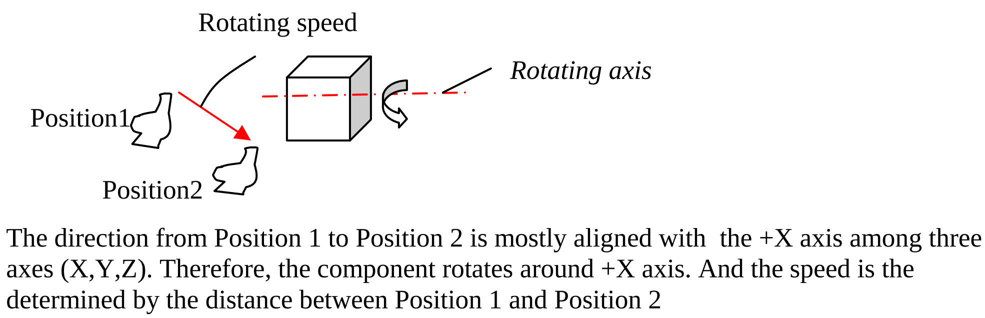


Figure 5-19 Specify a rotating axis and speed

Incorporating the table-based interface with the one-handed stylus interface described in Chapter 4, the table-based two-handed spatial interface for engineering assembly has been implemented within the IVPS.

5.5 Initial User Feedback

It is important to get some early feedback from the users at the design stage. Two users were invited to use the table-based two-handed interface within the IVPS. One of them was very experienced in using various 3D graphics software, and the other was experienced in human computer interaction within a VE. It was felt that at this stage it would be more valuable to obtain feedback from expert users of other VE systems rather than rely on novices who would be unlikely to understand all the 3D interactions involved in complex engineering assembly tasks. After training and practicing, the users were asked to use the system to perform a simple assembly task and then a difficult one. Each was repeated three times. The simple one involved two components with three mating conditions between them. And the difficult one involved four components with three mating conditions between each two of them. In total, nine mating conditions were involved. The two users became familiar enough with system to get the overall feel of the various functions, and were able to give us valuable feedback, leading to the following observations:

- They like using both hands as they felt comfortable and found it fun. One said *"it is nice to see my left hand can actually do something"*.

- They preferred the *zoom-in* to the *rotation* by the non-dominant hand. They found it was helpful to positioning and selecting a small feature. One said "*it is very useful to manipulate the viewpoint*". The other said "*It is very easy to use as you only need to touch the table and press a button*". However, they also reported that what they got sometimes was not they wanted using the *zoom-in*. The reason was observed that there was a mismatch between the point the user specified on the table and the point the system recognized on the vertical screen due to imprecise data from the tracker. It was also observed that the user had to move his eyes away from the vertical screen and look down to the mini window for a while to find a point in the mini window in the use of *zoom-in.* The users reported difficulty in the use of the *rotation* tool. The virtual objects started to rotate only after the movement of the non-dominant hand. The *post-facto update* forced the users to think ahead about the rotation axis and direction when using the *rotation*. And also there was a mismatch between the rotation the users wanted and the rotation the virtual objects actually did due to imprecise movement control by the non-dominant hand. Switching between the *zoom-in* and the *rotation* function was found to be difficult due to the different motor skill and cognitive load involved. It was observed that the users rarely used the *rotation*.

- Further it was observed that the involvement of the left hand didn't increase with increasing task difficulty. The button clicks by the left hand were almost the same in both tasks. It was found positioning was still largely performed by the right hand.

5.6 Discussion and Implications

The user feedback has shown that the *zoom-in* function is useful to address the problem of scale and ease of use. It only required the users pressing the button by the non-dominant hand. However, the *zoom-in* didn't allow eye-off interaction since the user had to find a point in the mini window. This distracted the user's attention from the focus of the current task. The precision of the specified point in the mini window was still problematic, due to the noisy sensor data and the difficulty in precisely mapping the physical position of the tracker to its virtual position in the VE. In addition, the *zoom-in* could only save manipulation time in the Z (in/out) direction. Once the target area was magnified, fine rotation of the component was always required. However, the *rotation* function was hard to use. It was not only due to the imprecise movement controlled by the non-dominant hand, but also due to the lack of a spatial cue or reference so that the user couldn't understand and predict how to control 3D rotation through the 2D input. When the *zoom-in* and the *rotation* functions were combined, switching between them was hard due to the different motor skill and cognitive load involved. It was hard for the users to master two different operations in two different spaces by the non-dominant hand. Therefore the user usually easily adapted to using the *zoom-in* and ignoring the *rotation*. The results indicate that the non-dominant hand was mainly used for magnifying a target (positioning along the depth dimension). The positioning tasks along the other dimensions were still mostly performed by the dominant hand. Therefore, it has not the potential to significantly improve task-performance for engineering assembly.

From the initial user feedback, a number of implications can be surmised for the design of a new two-handed spatial interface to improve the task performance for engineering assembly. These include

- 1 DOF input

It is found that precise placement of objects is easily controlled if they are controlling only one degree of freedom at a time. For example, the *zoom-in* increases the accuracy of the object position in the depth direction.

- Integrated input space

1DOF input often means separated translation and rotation operations. It may produce a better interface (than the table-based interface) if these operations are integrated into a single input space, and require the same motor skill. This can eliminate the switching between different input space, and skill transfer between different modes. For example, the users found it difficult to switch between *rotation* and *zoom-in* functions in the table-based interface due to different skills required for the two functions.

- Spatial references and visual cues

The difficulty in the use of *rotation* in the table-based interface was due to the lack of spatial references in the input spaces and visual cues in the VE. The user found the *rotation* control was not understandable and the rotation results were unpredictable. Therefore, if multiple functions for spatial manipulation are assigned to one input space, the input space should be firstly understandable. Secondly, the input state can be perceivable from spatial reference in the real world, and visual cues in the virtual world. This helps to determine the currently selected state without distracting a user's visual attention.

- Indirect control

The *zoom-in* function allows the user to control accurate object position along the depth direction by pressing the button on the tracker. This type of control is called *indirect control* [Bowman & Hodges 1997]. Indirect control of object position in one dimension, is a less natural technique than direct 6DOF input, and requires some training to be used well. However, once this technique is learned, it controls some accurate object position and orientation. Moreover, the technique does not exhibit the arm strain that can result from the use of direct 6DOF input [Bowman & Hodges 1997]. There are many examples of indirect control in desktop-based computer games. The movement of objects can be "continuously" varied by pressing a key on the keyboard. Some examples can also be found in spatial interaction in VEs [Zeleznik et al 2002, Bowman & Hodges 1997].

Chapter 6

Design and Evaluation of a

Cube-based Two-handed Spatial Interface

A novel cube-based two-handed spatial interface has been designed to improve the task performance of spatial positioning and selection operations in engineering assembly. It takes into account the design issues discussed in the last chapter. In addition, it overcomes the problems of precision identified in Chapter 4. This interface assigns to the non-dominant hand tasks such as positioning that can be performed by a sequence of 1DOF sub-tasks. This leaves the dominant hand to perform 6DOF tasks such as selection, positioning and attachment. A physical cube is used to provide the non-dominant hand with a spatial frame of reference. The evaluation results given in this chapter show that the new interface has the potential to reduce the performance time for assembly tasks by more than 25%, over the existing one-handed spatial interaction.

6.1 Design of a Cube-based Two-handed Spatial Interface

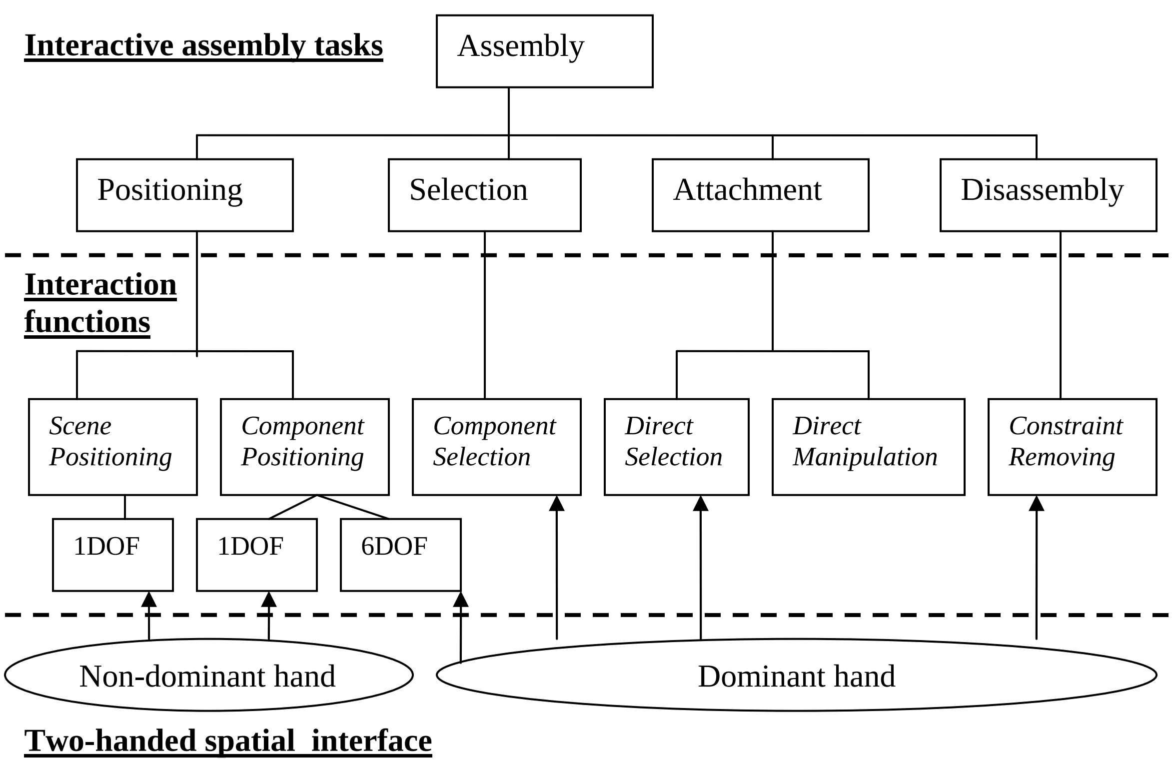
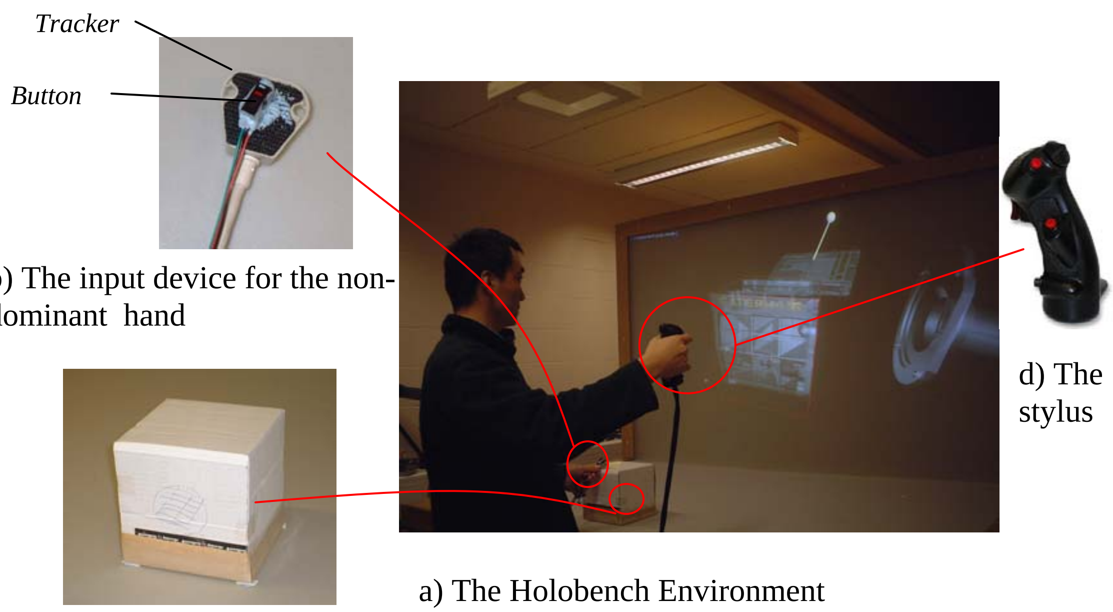


Figure 6-1 Architecture of the two-handed spatial interaction model

A cube-based two-handed interface has been designed to address the two-handed spatial interaction model presented in Chapter 5. This is repeated in Figure 6-1. The interface assigns to the non-dominant hand 1DOF positioning tasks. This leaves the dominant hand to perform 6DOF tasks such selection, positioning and attachment. However, the current design and implementation concerns attachment tasks only with *Direct Selection*, which has the problem of scale. The problem of related precision in *Direct Manipulation* is discussed in the next stage improvements in section 6.5.



b) The input device for the non-dominant hand

d) The stylus

a) The Holobench Environment

c) A physical cube

Figure 6-2 The cube-based two-handed spatial interface

The cube-based two-handed interface as shown in Figure 6-2 contains three interaction components: a physical *cube* (Figure 6-2c), the *tracker* and *button* device for the non-dominant hand (Figure 6-2b) and the *stylus* for the dominant hand (Figure 6-2d). The stylus, representing the virtual cursor, is used for component selection, 6DOF component positioning and attachment by *Direct Selection*. The functions mapped onto the stylus are described in section 6.1.2. The physical cube is placed on a table such as the horizontal plane on the TAN Holobench^{TM} (Figure 6-2a). It is a reference model of a *reference object*, which is a component (if there is a component selected by the virtual cursor) or entire scene (if there is no selected component). This means the coordinate system of the cube is identical to the local coordinate system of the reference object. The centre of the cube is identical to the centre of the reference object, i.e., the centre of the bounding box of the object. A number of 1DOF positioning functions for the reference object are assigned on the cube. These functions are fully described in the following section. The tracker and button device for the non-dominant hand is the same as in the table-based two-handed interface in Chapter 5. The tracker is used to specify these functions and the button is to run and cancel these functions.

6.1.1 Positioning by the non-dominant hand

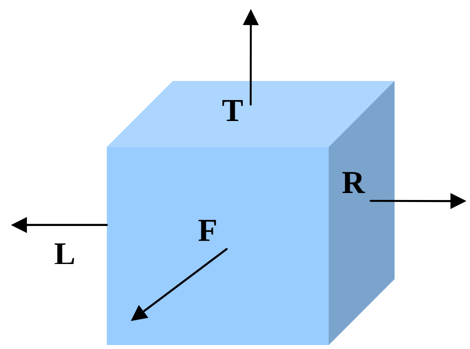


Figure 6-3 Four faces and their normal vectors on the cube

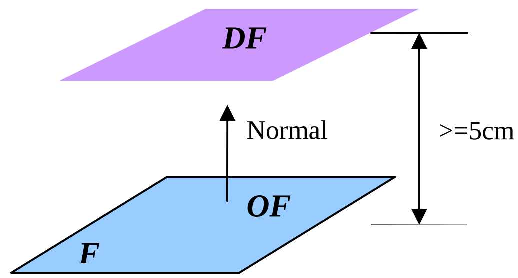


Figure 6-4 Surface *F* provides two tracker positions: OF and DF. The distance between them is more than 5cm.

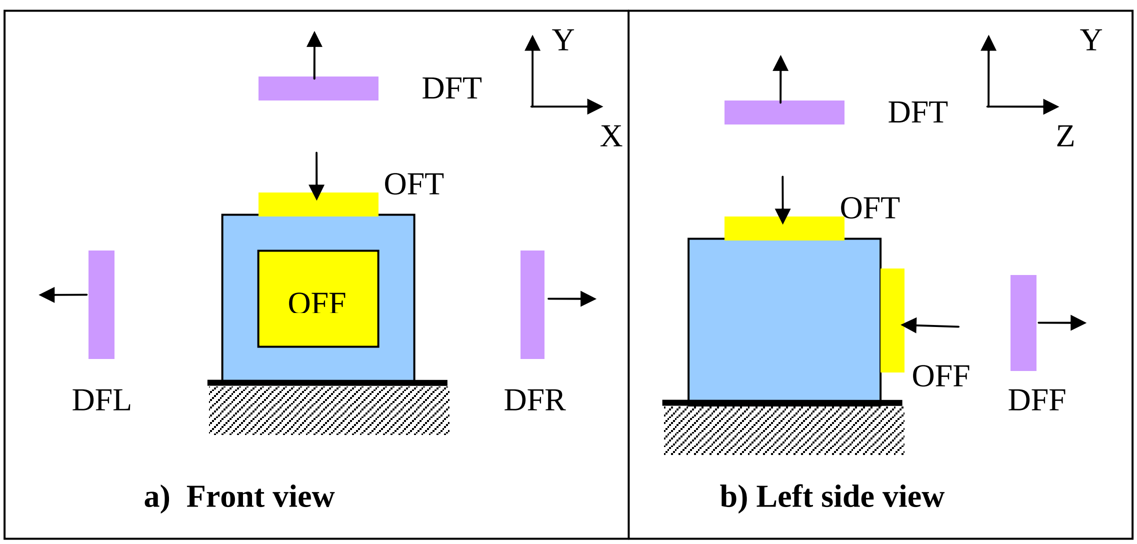


Figure 6-5 Available tracker positions related to the cube (The arrows related to the tracker positions represents the moving directions of the reference object)

On the cube, four faces including the left (L), right (R), top (T) and front (F) faces (Figure 6-3) are accessible to the non-dominant hand. Each face has its surface normal vector, which is perpendicular to the surface. The direction of the vector is towards outside of the cube. Each face provides two distinguishable positions for the tracker to place: on this face (OF), and at a distance (more than 5 cm) to this face in its normal direction (DF) (Figure 6-4). Thus the four faces determine eight tracker positions including four OF positions and four DF positions. Two types of 1DOF translation functions, *pushing* and *pulling*, are mapped onto OF and DF positions of each face respectively. The pushing function is to move the reference object opposite the surface normal direction, while the pulling function is to move the reference object in the surface normal direction. This mimics the actions people take to push and pull an object in the real world. For example, to pull an object in the real world, they might firstly put their hands on the object and then push it away from us. To pull an object, they might firstly tie this object with a rope and then pull the rope. In this case, there is a distance between them and the object. In the interface, if all eight positions of four faces are used for function mapping, some of the functions would be repeatedly used. For example, if the tracker is in the OF position of the left face, the reference object moves to the right. The object has the same movement when the tracker is placed in the DF position of the right face. To avoid this, only six positions are available for the tracker placement (Figure 6-5). They are the DF position of left face (DFL), right face (DFR), front face (DFF) and top face (DFT), and OF position of front face (OFF) and top face (OFT). The mapping between the tracker positions and translation functions is shown in table 6-1. When any

Table 6-1 The mappings between translation functions and tracker positions

Tracker position	Translation functions
DFL	Pulling the reference object leftwards, i.e., in the (-1,0,0) direction
DFR	Pulling the reference object rightwards, i.e., in the (1,0,0) direction
DFF	Pulling the reference object forwards, i.e., in the (0,0,1) direction. Or the *magnifier* when there is specified point to be magnified.
DFT	Pulling the reference object upwards, i.e., in the (0,1,0) direction.
OFF	Pushing the reference object backwards, i.e., in the (0,0,-1) direction.
OFT	Pushing the reference object downwards, i.e., in the (0,-1,0) direction.

one of these functions is specified by the tracker, the visual cues are displayed on the screen to indicate the selected function. Once the button on the tracker is pressed, the reference object moves in the specified direction at a constant speed. The speed is adjusted according to the current distance between the scene centre and the user. The object can keep moving at this speed until the button is released. Figure 6-6 shows the user pulls a component to the left when the tracker is in the DFL position. In particular, when the tracker is in DFF position and the stylus is pointing at a point on a component, the function for pulling forwards is now the *magnifier* function. The pointed point (i.e.

insertion point) is highlighted on the screen. Once the button is pressed, the point can be magnified and moves to the centre of the screen. Meanwhile, the virtual cursor automatically flies to this point. This attempts to avoid the cursor disappearing into the model when the reference object is moving close to the user. This function takes advantage of the *zoom-in* function used in the table-based two-handed interface. Figure 6-7 shows the user magnifies the point of interest when his hand is in the DFF position.

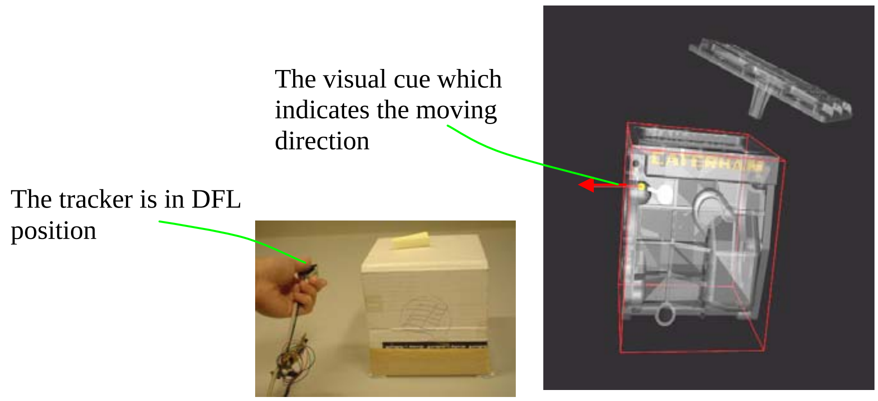


Figure 6-6 The user pulls a component leftwards

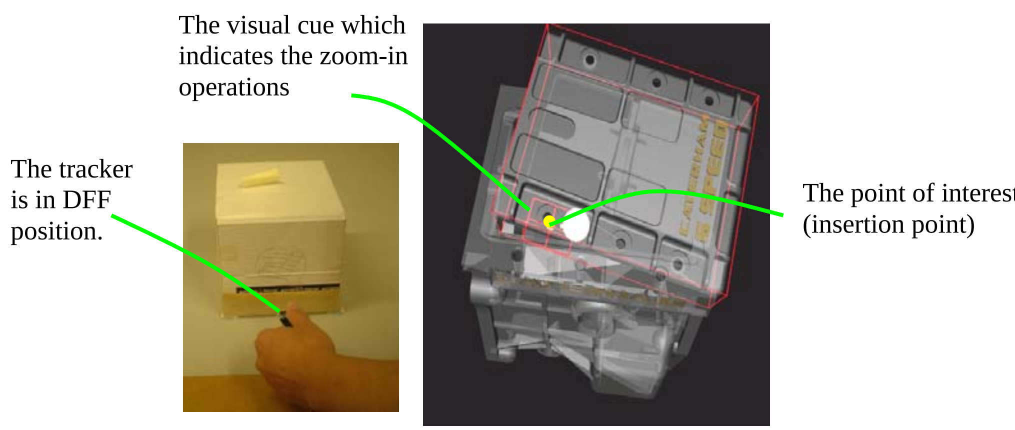


Figure 6-7 The user magnifies the point of interest using *magnifier*

In addition to the six translation functions, four 1DOF rotation functions for the reference object are mapped onto four edges on the front face of the cube. The four edges for the tracker to locate are the left (LE), right (RE), top (TE) and Bottom (BE) edge as shown in Figure 6-8. They are more easily accessible for the non-dominant hand than the other edges when a user is standing in front of the cube. Each edge represents the rotating axis and rotating direction. The mapping between the rotation functions and the edges is given in Table 6-2. The rotation functions satisfy the *right-handed coordinate system*. The specification of the rotation functions mimics the actions people take to roll a physical

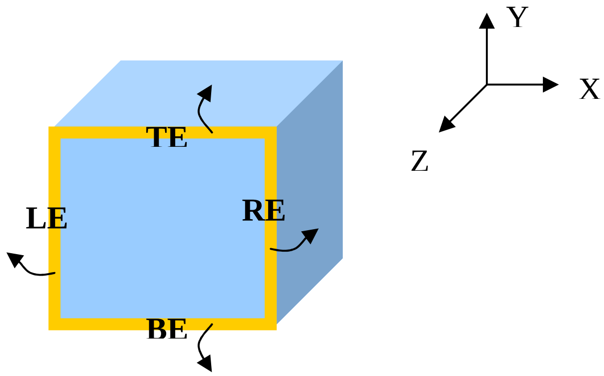


Figure 6-8 Four edges on the front face are used for rotation (the curved arrows represent the rotating directions)

Table 6-2 The mapping between the rotating functions and tracker position

Tracker position	Rotating functions
LE	Rotating around (0,-1,0) axis
RE	Rotating around (0,1,0) axis
TE	Rotating around (-1,0,0) axis
BE	Rotating around (1,0,0) axis

box in the real world. For example, they often apply forces on the edge of the box to roll a box on the ground. The rotating axis and directions of the box is determined by the hand's position. In this interface, when the tracker touches one of the edges, the visual cues are displayed to indicate the rotating axis and direction. Once the button on the tracker is pressed, the reference object rotates around the specified axis at a constant speed. As described above, the speed is adjusted according to the current distance between the scene centre and the user. The object can keep rotating at this speed until the button is released. The center of rotation is the center of the reference object. The indirect control of object manipulation by pressing / releasing the button to start / stop translation or rotation of the object means that, there is no limitation on the rotation angle caused by the mechanical design of the device [Gribnau et al 1998] or the twisting limitation of the wrist [Frohlich & plate 2000]. Figure 6-9 shows the user rotating the component when the tracker touches the left edge, i.e., in LE position.

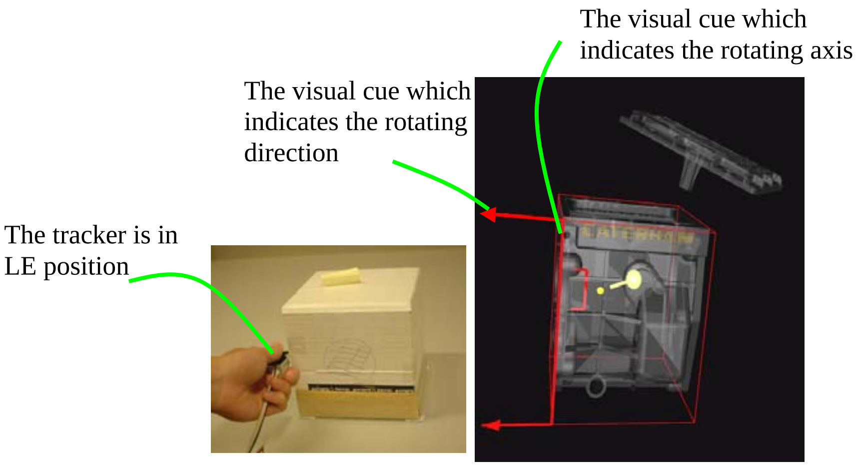


Figure 6-9 The user rolls a component

In particular, when the reference object is an assembly, the assembly is treated as a rigid body during positioning by the non-dominant hand. This means that one of the components in the assembly moves then the others will follow the same movement. This is to overcome the problem of slide identified in Chapter 4.

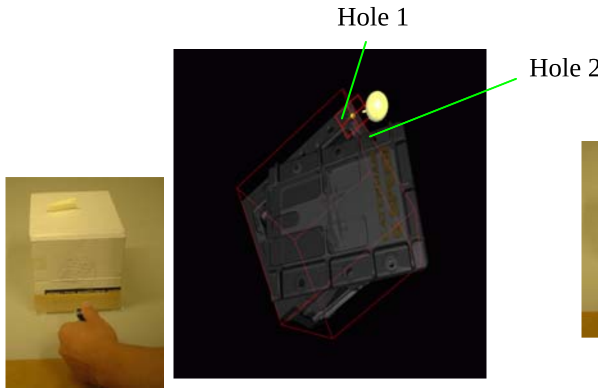
6.1.2 Interaction by the dominant hand

Component Selection, *Component Positioning*, *Direct Selection* and *Constraint Removing* by the dominant hand are the same as the one-handed stylus interface in Chapter 4. As *Direct Manipulation* is not considered in the current design, it is disabled on the stylus. Scene positioning is also disabled on the stylus since it can be completely performed by the non-dominant hand. These changes cause the slightly different button event mapping on the stylus from Chapter 4. It is shown in Table 6-3.

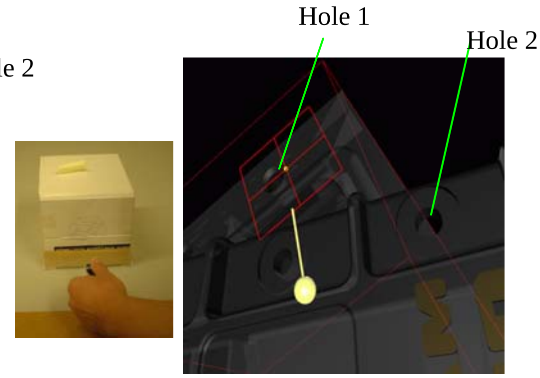
Table 6-3 Button event mapping on the stylus

Pressed buttons	Operations
Trigger	Selecting and manipulating a component
Button3	Switch to *Component Selection* mode
Button1	Switch to *Direct Selection* mode
Button2	Reset the virtual cursor
Button1+Button3	Switch to *Constraint Removing* mode

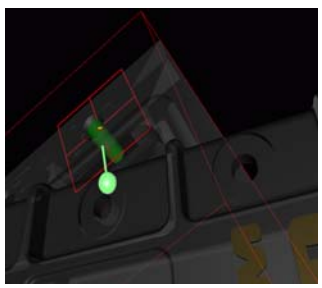
6.2 A scenario



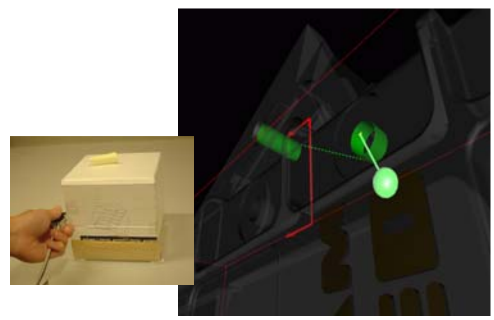
a) The two holes are so small that the user needs to magnify them. The dominant hand moves the yellow virtual cursor to point at the target area which is around the two holes. The non-dominant hand places the tracker in DFF position.



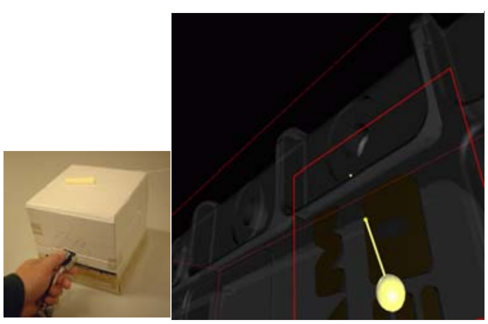
b) The non-dominant hand presses the button on the tracker, and the target area is magnified and the virtual cursor flies to this area.



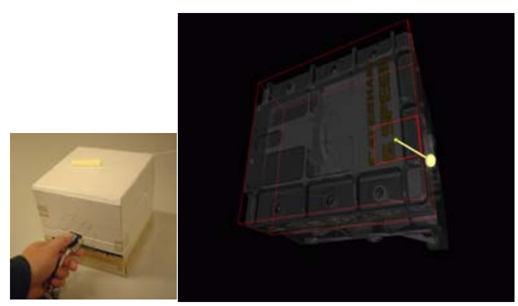
c) The dominant hand moves the cursor to select the first hole feature in *Direct Selection* mode. In this mode the virtual cursor is in green. The selected feature is highlighted in green.



d) To make the second hole feature more visible, the non-dominant hand rotates the component in a small angle by placing the tracker in LE position. The dominant hand selects the second hole. A valid concentric mating condition between the two holes is detected. Both features are highlighted in green and linked by a green dotted line.



e) The dominant hand presses the trigger on the stylus and two holes are snapped together. A concentric mating condition is therefore created and two holes are aligned with each other. To view the entire scene, the non-dominant hand pushes the scene backwards by placing the tracker in OFF position



f) The non-dominant hand presses the button on the tracker. The entire scene moves back to the current position.

Figure 6-10 An assembly scenario using the cube-based two-handed interface

This section demonstrates the use of the cube-based two-handed spatial interface in an assembly scenario. The scenario is to align two holes on two components by *Direct*

Selection. It requires the user to create a concentric mating condition between these two holes. This can be achieved by directly selecting two holes features. Figure 6-10 shows the sequence of the process. In addition, Video 5 in the attached CD can help the readers to further understand the use of the cube-based two-handed spatial interface.

6.3 Implementation

6.3.1 Calibrating the physical cube

The physical cube needs to be calibrated according to the position of its two corners P_1 and P_2 as illustrated in Figure 6-11.

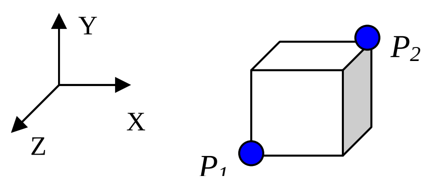


Figure 6-11 Calibration points on the physical cube

The tracker's position related to the cube can be easily identified by comparing its position (x,y,z) with P_1 (x_1,y_1,z_1) and P2 (x_2,y_2,z_2). For example, the tracker will be recognized on the front face of the cube if the following conditions are satisfied:

- $| z - z_1 | < e$,
- $x_1 < x < x_2$, and
- $y_1 < y < y_2$,

where, e is the tolerance value. In the same way, the tracker will be recognized on the left edge of the front face of the cube if the following conditions are satisfied:

- $| z - z_1 | < e$,
- $| x – x_1 | < e$, and
- $y_1 < y < y_2$.

Once again the tracker is at a small distance to the front face of the cube if the following conditions are satisfied:

- $z - z_1 > d$,
- $x_1 < x < x_2$, and
- $y_1 < y < y_2$.

Where d is the distance value.

6.3.2 Mapping the physical cube to the reference object

When using the cube-based two-handed interface, the physical cube needs to be mapped onto the bounding box of the reference object. When the tracker touches the front face on the physical cube, the front face of the bounding box should be highlighted. When the tracker touches the left edge on the physical cube, the left edge of the bounding box should be highlighted. To identify the directions of each face on the bounding box, the normal vector (**N**) of each face is firstly obtained from the geometric data stored in each solid node. Then, the vector **N** is compared with six directional vectors: (1,0,0), (-1,0,0), (0,1,0), (0,-1,0) and (0,0,1) to find out which vector the **N** is mostly aligned with. The direction of the face can therefore be identified. To identify the four edges on the front face, the four points on the face must be firstly obtained from the solid data structure. And then comparing the vectors formed by each two of them with the direction vectors (1,0,0) (-1,0,0) (0,1,0) and (0,-1,0). The direction of four edges can therefore be identified.

6.4 Evaluation

The cube-based two-handed spatial interface is designed to address the problems of precision (scale, slide and global precision) in spatial selection and positioning, which have been highlighted in the one-handed spatial interaction model. Therefore, there is a need to conduct an evaluation to determine the likely task performance of the cube-based two-handed interface, by a comparison with the one-handed spatial interaction model.

6.4.1 The one-handed stylus interface

The one-handed stylus interface used in this study is almost the same as in Chapter 4. As this study is not concerned with *Direct Manipulation*, it is disabled on the stylus. The button event mapping is therefore reorganized. As the main difference between two interfaces that are to be compared in this study is the added non-dominant hand interface, the dominant hand interface should be as the same as possible. Therefore, event mapping only slightly changes on Button2 and Button3 shown in Table 6-4. In addition to resetting the virtual cursor, Button2 is also used to switch to *component selection* mode. Button3 is used for scene positioning. The events mapped on the other buttons in this one-handed interface are exactly the same as in the cube-based two-handed interface.

Table 6-4 Button event mapping on the one-handed stylus interface

Pressed buttons	Operations
Trigger	Selecting and manipulating a component in *component selection* mode, and confirm a selection in *Direct Selection* mode
Button3	Positioning the entire scene
Button1	Switch to *Direct Selection* mode
Button2	Reset the virtual cursor and switch to *Component Selection* mode
Button1+Button3	Switch to *Removing Constraint* mode

6.4.2 User assembly task

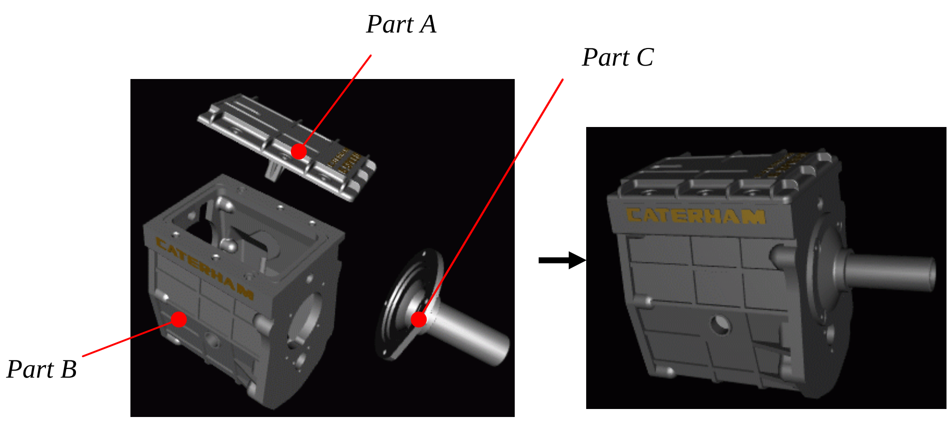


Figure 6-12 Gearbox casing assembly

Three components were involved in the assembly as shown in Figure 6-12. To start to assemble the three components, the flat base of Part A is attached to the top of Part B using an against mating condition. Part A is then located using concentric mating conditions between the holes on its base and the locator holes on Part B. To fix the components it is only necessary to mate two of the locator holes. Part C is then attached to Part B in much the same way.

The assembly task in this chapter is more complex than the one in Chapter 4 as the components contain a number of small holes. Selection of the hole features (on the inner side of the components) demands higher precision than selecting the surfaces on the outer side of the components in Chapter 4. This is a good example which presents the problems of precision in engineering assembly using spatial interfaces.

6.4.3 Subjects and methods

It would be more valuable to obtain feedback from potential users who had experience in the 3D modelling and assembly constraints. Therefore, twelve right-handed students from the mechanical engineering background were used in the evaluation. None of them are colour-blind. All of them had used the commercial desk-top CAD software such as I-DEAS.

As most operations and the device for the dominant hand were the same in both one- and two-handed interfaces, the skill transfer would be a serious problem if using within-subjects design in the evaluation [Poulton 1974]. Therefore, this study used the between-subjects design. The twelve subjects were randomly divided into two groups. Each group included six subjects. One group used the two-handed interface while the other used the one-handed interface. The between-subject design was also employed in a set of experiments in Zhai's experiments [Zhai 1995] to investigate human performance using different 6DOF input methods. However, one of the pitfalls of between-subjects designs is that individual differences may bias experimental results. It has been suggested in [Pitrella & Kruger 1983] that using matching tests for forming equal groups for experiments. However, choosing a suitable matching test is a very delicate task, since the test has to be sufficiently similar to the experimental conditions that measured. On the other hand, the test also requires equal amount of skill transferred from the matching test to each of the experimental conditions. It is often impossible to design such a test to fit all these requirements [Zhai 1993].

As described in Chapter 1, the evaluation methods include observation, post-questionnaire and interviews. All the users were given time for training and practice. After they felt comfortable and ready for the test, each group was tested to perform the task three times. Each time is referred to as a session. The test therefore involved three sessions. During the test, the time factors, including the *assembly time* (i.e., total task completion time), *selection time* (i.e. time for manipulating the virtual cursor for selecting a feature or component) and *positioning time* (i.e., time for positioning a component or entire scene), were recorded by the software. In addition to these objective measures, subject measures (as described in Chapter 1) were used including task difficulty, mental effort, physical effort, fatigue, stress, and learnability. After the test, subjects rated scale of each of the subjective factors through a post-questionnaire (Appendix D.1). The rating scale was described in Chapter 1.

6.4.4 Results

Table 6-5 Objective feedback from the two-handed users

Two-handed Users	Total time	Time of left hand positioning	Selection time	Time of right hand positioning
Rob	341	27	242	65
	275	37	205	17
	203	36	113	13
John	344	41	270	22
	332	33	266	23
	128	23	97	5
Oliver	350	41	283	16
	303	20	247	28
	200	19	161	14
Jule	250	26	191	27
	153	25	111	12
	84	15	57	9
Tom	227	24	181	18
	138	17	105	13
	193	19	157	11
Thomas	254	29	192	27
	288	36	209	36
	250	34	181	26

Table 6-6 Object feedback from the one-handed users

One-handed users	Total time	Selection time	Positioning time
Nic	280	212	59
	478	365	105
	618	515	94
Tom	313	227	76
	318	254	56
	346	266	70
Martin	473	403	58
	387	316	66
	307	234	69
Gareth	430	299	111
	436	320	99
	164	119	39
Ben	224	160	59
	200	137	53
	171	136	27
Matt	291	225	54
	555	450	91
	142	108	29

Between-subjects contrasts

Total assembly time, selection time and positioning time were measured. They are shown in Table 6-5 for the two-handed subjects and Table 6-6 for the one-handed subjects.

A comparison using the means between the two-handed interface and one-handed interface in each of the three test sessions is given in Figures 6-13, 6-14 and 6-15 respectively. In the first session (Figure 6-13), the results showed that the positioning time for the two-handed interface (60 sec.) was 14% shorter than one-handed interface (70 sec.). The selection time (227 sec.) was 11% less than one-handed interface (254 sec.). This only resulted in an overall reduction of 12% in the total assembly time. The times were 294 sec. and 335 sec. for the two- and one-handed interfaces respectively. In the second session (Figure 6-14), the results showed that the positioning time for the two-handed interface (52 sec.) was 33% shorter than one-handed interface (78 sec.). The selection time (191 sec.) was 38% less than one-handed interface (307 sec.). The reduced positioning and selection times resulted in a reduction of 37% in the total assembly time. The times were 248 sec. and 295 sec. for the two- and one-handed interfaces respectively. In the final session (Figure 6-15), the results showed that the positioning time for the two-handed interface (37 sec.) was 32% shorter than one-handed interface (55 sec.). The selection time (128 sec.) was 44 % less than one-handed interface (230 sec.). The reduced positioning and selection times resulted in a reduction of 39% in the total assembly time. The times were 176 sec. and 291 sec. for the two- and one-handed interfaces respectively. Finally, the mean-performance of these sessions is given in Figure 6-16 . The results showed that the positioning time for the two-handed interface (50 sec.) was 26% shorter than one-handed interface (68 sec.). The selection time (182 sec.) was 31 % less than one-handed interface (264 sec.). The reduced positioning and selection time resulted in a reduction of 29% in the total assembly time. The times were 239 sec. and 340 sec respectively.

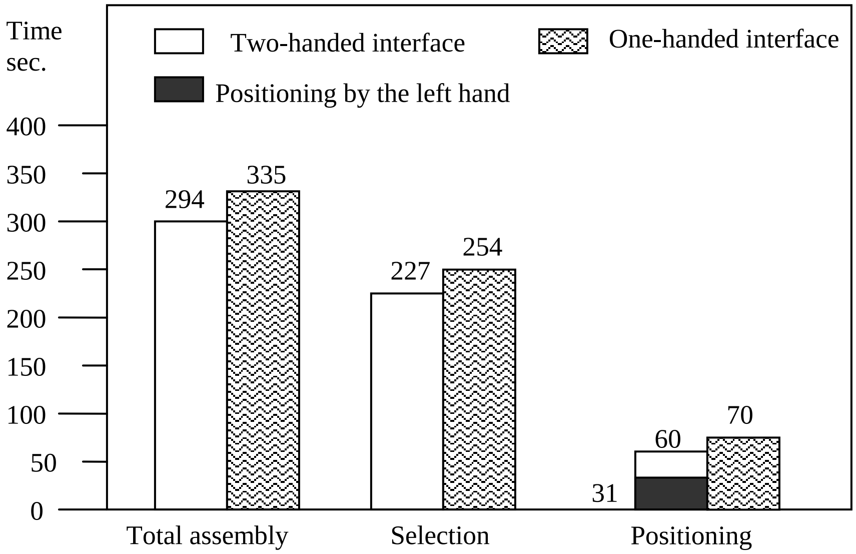


Figure 6-13 User's performance in both interfaces in Session 1

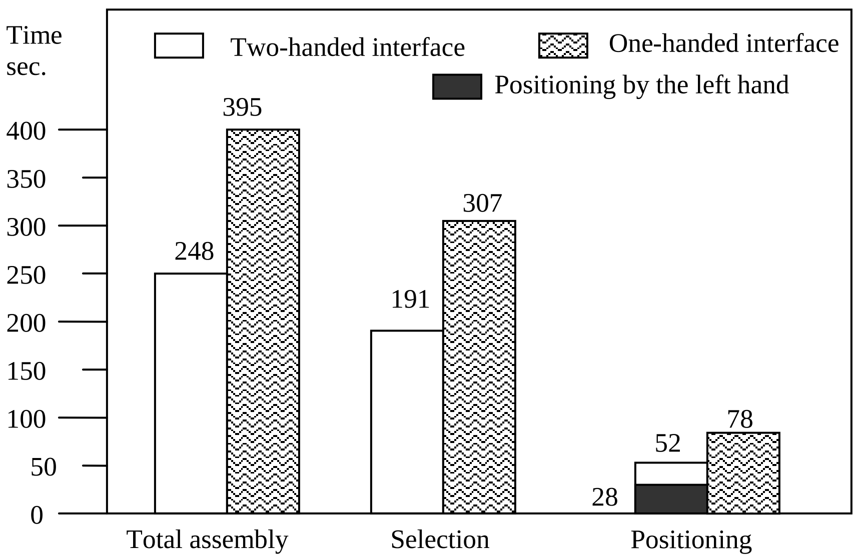


Figure 6-14 User's performance in both interfaces in Session 2

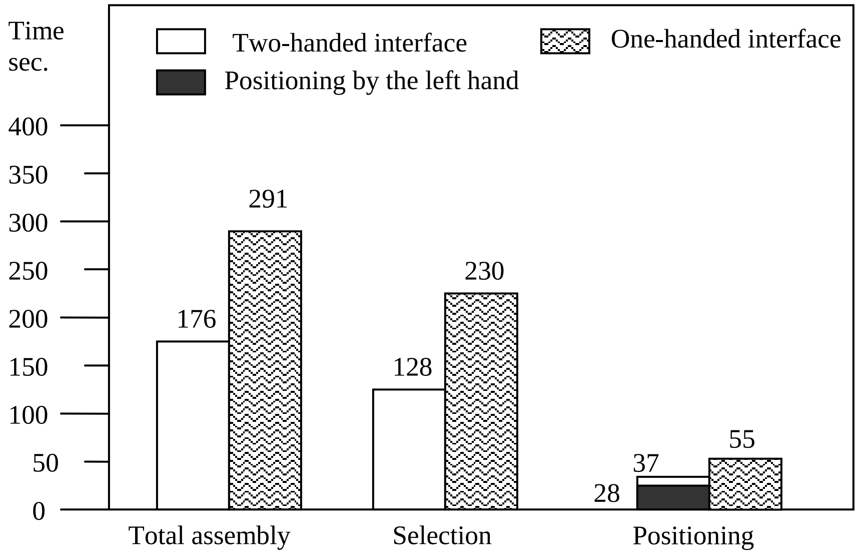


Figure 6-15 User's performance in both interfaces in Session 3

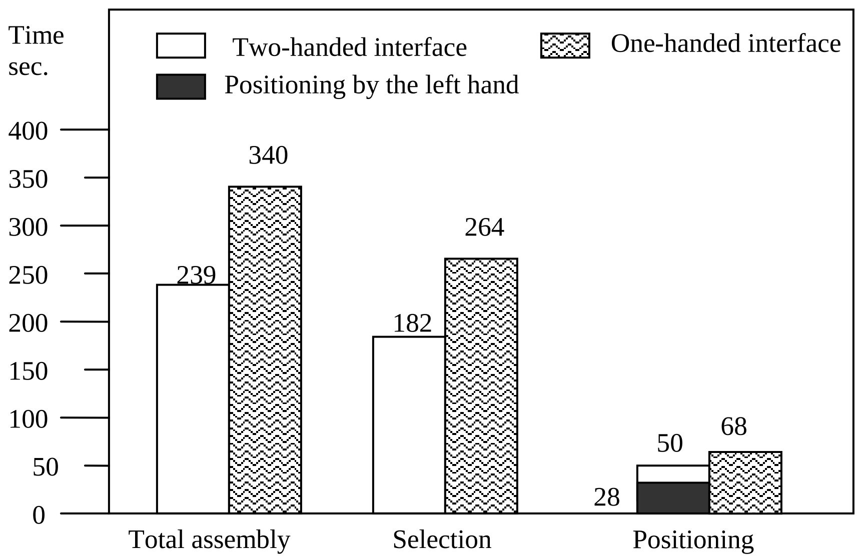


Figure 6-16 Mean-performance in both interfaces

An analysis of standard deviation of total assembly time was performed in the two-handed condition (M = 239sec., SD:80) and the one-handed condition (M=340sec., SD:137). The results show that the performance in the one-handed condition was dispersed from the average value more widely than the two-handed condition.

The experiment included between-subjects factors (two-handed vs. one-handed) and repeated measures (within-subjects) factors (session 1, 2 & 3). Repeated measures ANOVA (Analysis Of Variance) is an appropriate method for the mixed experimental design. It follows the logic of univariate ANOVA to a large extent. In univariate ANOVA the variance is partitioned into that caused by differences within groups and that caused by differences between groups, and then the ratio is compared. In repeated measures ANOVA, the individual variability of participants can be calculated as the same people take part in each condition. Thus more of error (or within condition) variance can be partitioned. The variance caused by differences between individuals is not helpful when deciding whether there is a difference between groups. In repeated measures ANOVA, it can be subtracted from the error variance. And then the ratio of error variance can be compared to that caused by differences between groups. This increases the power of the analysis and means that fewer participants are needed to have adequate power.

Therefore, an analysis of total assembly time with repeated measures (session 1, 2 & 3) was performed on the between-subjects factor of Condition (two-handed vs. one-handed). The results ($F(1,10)=6.11$, $p<.05$) show that Condition was a significant factor for task performance.

Within-subjects effects

In each session of the two-handed interface, it was found the assembly time greatly decreased with the increased practice. The second session (248 sec.) was 16% short than the first session (294 sec.); the last session (176 sec.) was 29% faster than the second session. Thus the last session was 40% faster than the first session. In the one-handed interface, however, the total assembly time in the second session (395 sec.) increased with 10% longer than the first session (355 sec.). Although the last session (291 sec.) was the fastest, it was only 9% shorter than the first session.

An analysis of total assembly time on the within-subjects factors (session 1, 2 & 3) was performed in the two-handed condition ($F(2,10)=7.81$, $p<.01$) and in the one-handed condition ($F(2,10)=.93$, $p<.5$). The results also indicate that the two-handed subjects could significantly improve task performance with more learning and practice. However, there was no significant learning effect on the one-handed subjects. The interpretation is that subjects learned a more effective task strategy and exercise easier input control in the two-handed condition.

Subjective feedback

The subjective feedback from each subject was collected in Appendix D.

The rating results of the subjective measures using the means is given in Figure 6-17. The mental effort perceived in both interfaces was low with the same amount of 2.1. Both interfaces were almost equally easy for the subjects to learn (with only a difference of 0.1). The subjects in both interfaces reported that the 3D system was much easier to learn than the commercial desktop software they had used. They felt it didn't take very long to understand the basics due to the simplicity of the system – just the pointer and components on the screen. The two-handed subjects felt much lower physical effort and task difficulty than the one handed users, both with a difference of 1.0. They also felt lower levels of fatigue (with a difference of 0.7) and extremely lower levels of stress (with a difference of 1.6) than the one-handed subjects. The two-handed subjects felt it much easier to use the stylus than the one-handed subjects (with a difference of 1.6). They didn't report arm strain which was often complained about by the one-handed users. The two-handed subjects also felt it was very easy to perform the task with the left hand. They felt very comfortable using two hands. One of them said *"I liked it that you had two things to use as a control, using both hands meant not everything was done with just one hand and lots of controls."* When the subjects were asked if there was anything distracting their attention, only one one-handed subject said finding buttons on the stylus distracted his attention at the beginning. The others in both interfaces said none. When the subjects were asked to make overall comments on the system from an engineering point of view, all of the two-handed subjects said the system was good. One said *" I really liked it. It was a lot easier and more fun than anything I had used before."* In the one-handed interface, four of six subjects said the system was good. But the other two felt the system was too hard and frustrating to be used on a daily basis. They reported difficulty in precisely controlling the direction of the virtual cursor for the selection of small features.

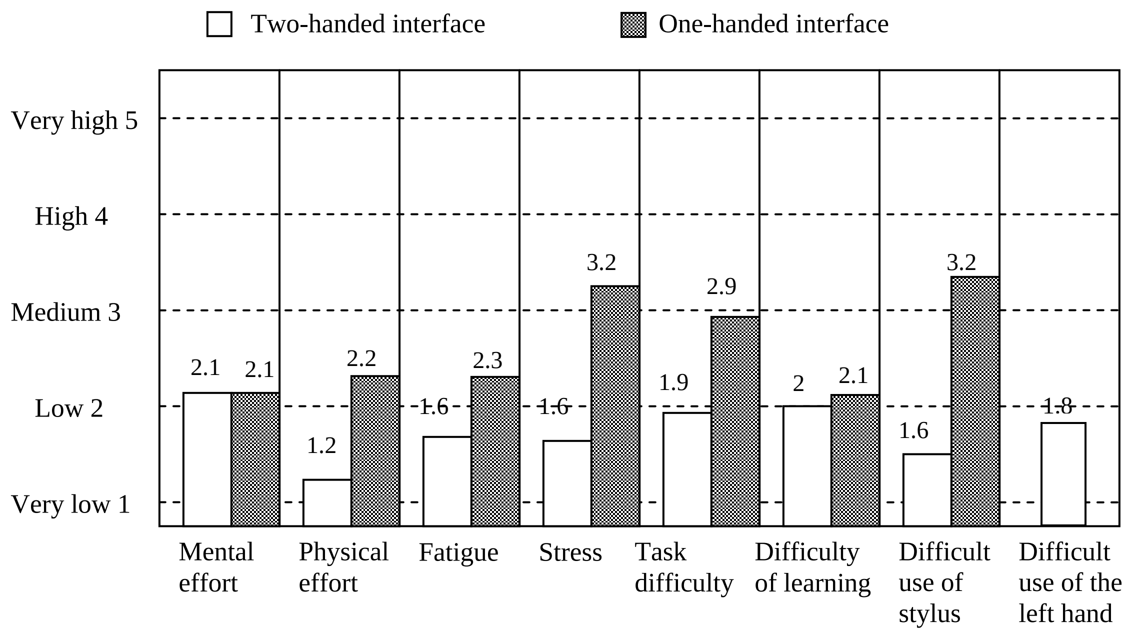


Figure 6-17 Subjective feedback

It was observed that a drawback in both interfaces was the cursor disappearing. It frustrated the users. In the two-handed interface, it occurred occasionally when the subjects used the *magnifier*. The user pointed at a point on a component with the dominant hand, and then magnified the component at the center of the pointed point by *magnifier*. As the component was magnified, the cursor sometimes disappeared. The reasons are discussed in the following section.

6.4.5 Discussion

The comparison with the one-handed spatial interface suggests that the cube-based two-handed spatial interface has the potential to improve task-performance by reducing the task completion time by more than 25% due to the improved positioning and selection. Furthermore the two-handed users perceived much less physical effort, fatigue, stress, and task difficulty in performing the task. The results further show that the subjects could quickly learn how to efficiently use the two-handed interface and therefore produced progressively improved performance. It is believed that the two-handed interface increases efficiency and precision due to:

- Simple and indirect 1DOF control by the non-dominant hand
- Spatial references provided by the cube
- Precise frame-of-reference set by the non-dominant hand in *magnifier*.

However, the main drawback in the cube-based two-handed interface is the cursor disappearing in the use of *magnifier*. This is caused by the unstable control by the dominant hand. When the user points at a point with the dominant hand, it is very possible for the cursor to move a bit due to the unstable hand or unstable sensor data sent to the stylus. This causes the pointed point to move. Therefore the user couldn't see the cursor in the expected position.

The results also reveal some other limitations in the two-handed interface due to:

- The inaccurate recognition for the tracker position

Sometimes the system can't precisely recognize the tracker position related to the cube due to the unstable data from the tracker sensor.

- The inaccuracy of the system response

When a reference component is in an ambiguous position where two of its six faces on the bounding box can be perceived as the front faces, the rotating direction would not be always consistent with the user's intention.

- The cable on the tracker

When the user shifts the tracker from one place to another place on the cube to switch functions, it is not very convenient due to the cable connected to the tracker.

6.5 Next Stage Improvements

Attaching two components can be achieved either by *Direct Selection* or *Direct Manipulation* within the IVPS. The cube-based two-handed spatial interface has shown the advantages in attachment of two components by *Direct Selection*. This splits positioning tasks into 1DOF control by the non-dominant hand and 6DOF control by the dominant hand. It would be interesting to explore the potential of the cube-based two-handed spatial interface for the attachment task using *Direct Manipulation*. The extended design of the interface is described in this section.

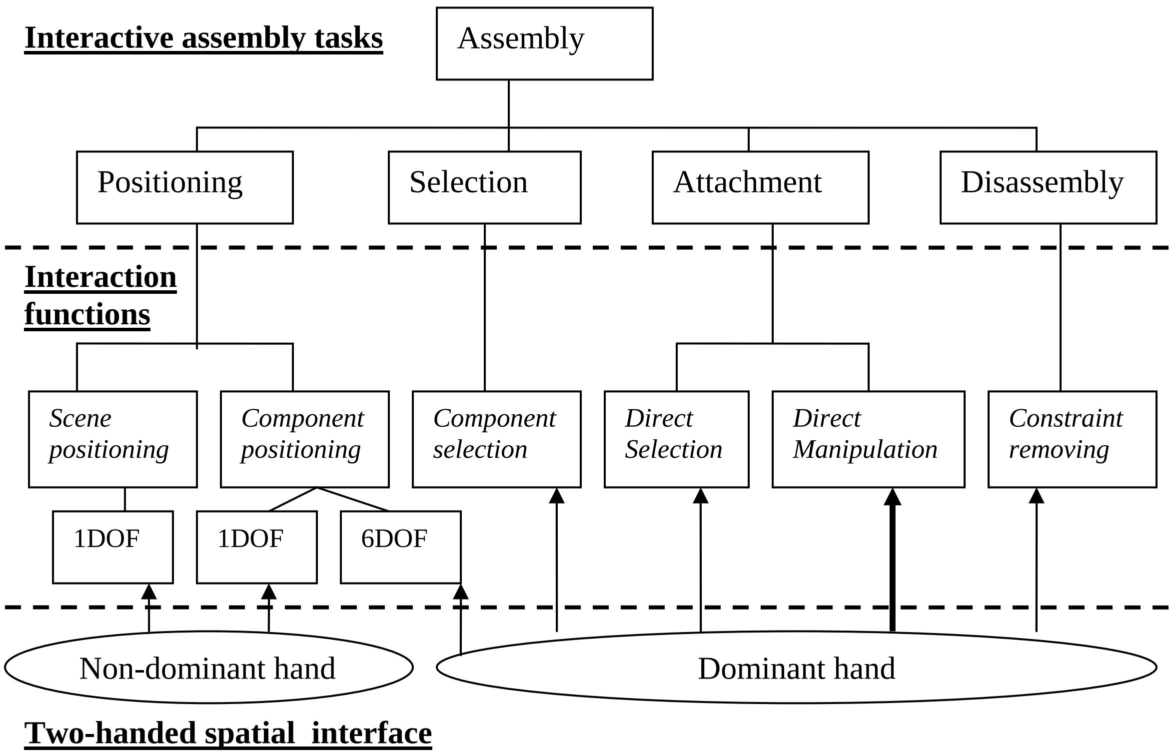
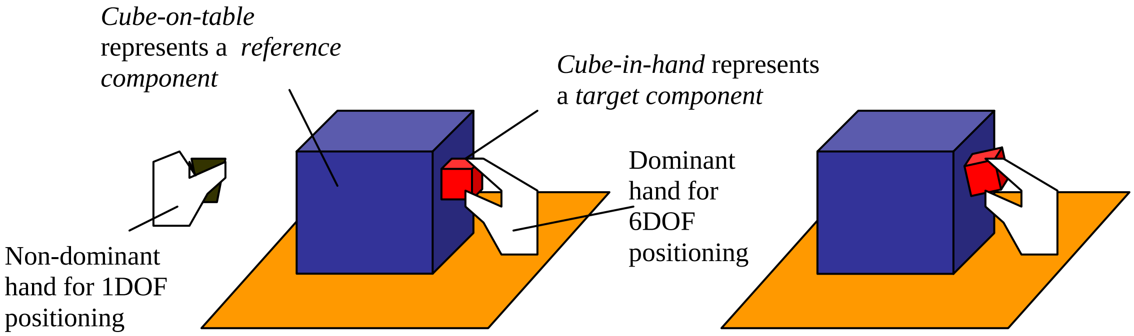


Figure 6-18 Architecture of the extended two-handed spatial interaction model

As described in Chapter 1, by *Direct Manipulation*, a constraint between two components can be detected when two components are positioned close to each other or in touch with each other. There is the problem of related precision. In addition, it is always required to position the entire scene to get a proper view of the components. There is the problem of global precision.

The two-handed interaction model in Figure 6-1 can be extended as shown in Figure 6-18, In order to address the problems of related precision and global precision. Based on Guiard's principles the non-dominant hand is assigned to position the entire scene for global control, while the dominant hand positions the component related to the one that is to be mated with. This means that: 1) positioning the entire scene by the non-dominant hand sets the frame of reference for the component positioning by the dominant hand; 2) Positioning the component to satisfy the related precision demands higher precision than positioning the entire scene (see Chapter 4); 3) positioning the entire scene is preceded by positioning the component. The two-handed interaction also takes advantage of the key observation that positioning is often best performed by a series of 1DOF steps using indirect input by the non-dominant hand. This leaves the dominant-hand to perform tasks such as 6DOF positioning and selection.



a) The left side of the *target component* touches the right side of the *reference component* when the dominant hand moves the *cube-in-hand* to touch the *cube-on-table*

b) Rotates the *target component* by rotating the *cube-in-hand* related to the *cube-on-table*.

Figure 6-19 Positioning in the extended cube-based two-handed interface

The extended cube-based two-handed interface is shown in Figure 6-19. The physical cube on a table (*cube-on-table*) is a reference model of the base component (*reference component*) of an assembly. The 1DOF positioning functions on the cube are the same as in section 6.1.1. They are used to position the entire scene by placing the tracker device related to the cube with the non-dominant hand. Instead of using a 6DOF pointing device like the stylus, the dominant hand holds a 6DOF cube-shaped device (*cube-in-hand*) which is a reference model of the *target component* of an assembly. The position and orientation of the cube-in-hand is directly mapped to the position and orientation of the target component. The related position of two cubes is directly mapped to the related position of the reference component and the target component. Figure 6-19 illustrates an example of positioning a target component related to a reference component. The user first moves the target component close to or to collide with the reference component (Figure 6-19a), and then finely adjusts the position and orientation of the target component related to the reference component (Figure 6-19b). This mimic the operations for attachment subtasks in the real world: *align* and *mount*, which were identified in Chapter 3. Aligning a component involves moving the component to the start point of the attachment. Mounting involves adjusting the component toward the final position of the attachment. Fine adjustment of the target component can be easily controlled when operating the cube-in-hand on the cube-on-table since the spatial reference and tactile feedback are provided [Hinckley et al 1994]. In addition, the match between the related physical position of two cubes and the related virtual position of two virtual components provides sufficient perceptual cues which might not only bring manual advantages but also cognitive advantages [Hinckley et al 1994, Legnachuk et al 1999].

Finally, different devices for the dominant hand: cube-in-hand and stylus, can be attached to different functions: *Direct Manipulation* and *Direct Selection* respectively. This type of interface is "space-multiplexed" [Fitzmaurice & Buxton 1997]. This affords the capability to take advantage of the shape, size and position of the physical controller to increase functionality and decrease complexity. It also means that the potential persistence of attachment of a device to a function can be increased.

Further work needs to be done to implement the extended design of the cube-based two-handed interface. An evaluation should be conducted to study the impact of the extended design on task-performance for engineering assembly within a VE.

6.9 Conclusion and Generalized Hypothesis

This Chapter presents a cube-based two-handed spatial interface for engineering assembly within a VE. This model addresses the problems of precision (identified in Chapter 4) in spatial selection and positioning. It assigns to the non-dominant hand tasks such as positioning that can be performed by a sequence of 1DOF sub-tasks. This leaves the dominant hand to perform 6DOF tasks such as selection, positioning and attachment. A physical cube is used to provide the spatial reference for the non-dominant hand. The evaluation results show that that the task performance is considerably faster than the one-handed spatial interface in terms of task completion, positioning and selection times. Furthermore the two-handed users felt that much less physical effort, fatigue, stress, and task difficulty in performing the assembly task. Finally, the design extension to the cube-based two-handed spatial interface is described as next stage improvement.

As indicated in Chapter 1, this research is intended to be hypothesis generation. A tentative hypothesis is put forward that summarises and offers opportunities for further research, as the following:

> **A two-handed spatial interface, which effectively integrates direct six degree-of-freedom input control by the dominant hand with indirect one degree-of-freedom input control by the non-dominant hand, while providing understandable spatial references, has the potential to improve task performance for engineering assembly by reducing the task completion times by more than 25%, over a one-handed spatial interface, which only provides direct six degree-of-freedom input control.**

But it is recognized that further evaluation studies will be needed before any definitive conclusion can be reached.

Chapter 7
Conclusion and Further Work

7.1 Thesis Summary

This thesis presents studies on the design of a novel two-handed spatial interface for engineering assembly, informed by a number of qualitative studies using a realistic assembly model within a fully working VE. The results show that the two-handed spatial interface has the potential to reduce task-performance times by more than 25%, over an existing spatial interface. The main contribution of this research is to demonstrate an improved understanding of task performance for engineering assembly. The experimental platform is the IVPS at University of Leeds.

Three phases are involved in the research. Phase one conducts a usability evaluation of the existing IVPS using a desktop-based interface. The study describes how people perform an assembly task including selection, positioning, attachment and disassembly, by studying people's behaviour both in the real world and in the IVPS. The ways in which the VE system affects people are analysed. The strengths and weakness of the existing interaction techniques using the desktop-based interface are evaluated. The results strongly suggest that there is need to know if more expressive spatial interaction devices could improve the task-performance within the VE environment.

The second phase of this research therefore assesses the usability of a one-handed spatial interaction model. This model allows the user to perform assembly tasks through a 6DOF spatial input. The user simultaneously controls the position of a virtual object in six dimensions. Two one-handed spatial interfaces are implemented using two spatial interaction devices: a stylus and CyberGlove™. An evaluation is conducted to study the impact of the two spatial interfaces on task performance for engineering assembly with the VE. The results suggest that the stylus interface is generally found to be a more precise and easier to use interface, enabling the user to exercise greater control over selection and positioning operations. Moreover, the results identify four problems of *precision* in the one-handed spatial selection and positioning. They are the problems of *scale* (such as selecting very small features in an engineering assembly), *slide* (such as manipulating constrained components in an assembly), *global precision* (such as manipulating the entire scene in which some components are long way from the centre of rotation) and related precision (such as manipulating the selected component related to the other components).

To overcome these problems of precision, the design and evaluation of a cube-based two-handed spatial interface is presented in the last phase of this research. This interface assigns to the non-dominant hand tasks such as positioning that can be performed by a sequence of 1DOF sub-tasks. This leaves the dominant-hand to perform the tasks such as 6DOF manipulation of assemblies, selection and attachment. A physical cube is used to provide the user with a spatial frame of reference. An evaluation study is conducted to study the impact of the new interface on assembly task performance. The evaluation results show that the new interface has the potential to reduce the task-performance times by more than 25%, over an existing one-handed spatial interface. The users felt that much less physical effort, fatigue, stress and task difficulty. Next stage improvements of the cube-based two-handed interface are described. Finally, this research generalizes a tentative hypothesis to be further tested and developed, as the following:

7.2 Further research

This section explores the further research based on the findings in this thesis.

7.2.1 Recommendations for the future spatial interfaces

The tentative hypothesis in Chapter 6 indicates that three issues, including degree-of-freedom control, the use of the second hand and spatial references, have large impact on task-performance for spatial interaction with engineering assemblies. Therefore, a number of recommendations are made in terms of these issues for the future design of spatial interfaces.

- *Indirect 1DOF input control increases efficiency and accuracy*

Indirect control of object position in one dimension, pressing buttons on input devices for example, is a less natural technique than direct 6DOF input, and requires some training to be used well. However, once this technique is learned, it controls more accurate object position and orientation, especially if there is the problem of scale and global precision. Moreover, the technique does not exhibit the arm strain that can result from the use of direct 6DOF input.

- *The non-dominant hand has the potential to perform precise positioning tasks*

The non-dominant hand is usually limited to coarse positioning. As indirect 1DOF control is very easy and simple, it is suitable for the non-dominant hand. This provides the potential for the non-dominant hand to perform precise positioning tasks.

- *Spatial references provided by physical objects increase efficiency and naturalness*

Spatial references provided by physical objects help the user to understand 3D space, and enable the user to perform natural and efficient control.

7.2.2 Further evaluations in engineering assembly

The hypothesis is generated based on the qualitative case studies. As mentioned in Chapter 1, the main weaknesses of case studies are their lack of representation of the population as a whole and the subjective biases of the observer. The rigor of the hypothesis might be argued. Therefore it is recognized that further evaluation studies will be needed before any definitive conclusion can be reached. These studies should involve large number of users and yield primarily quantitative results.

7.2.3 Extension to other problem domains

Although the cube-based two-handed spatial interface has been developed for engineering assemblies it is by no means restricted to this application. As mentioned in Chapter 1, transferability of the results depends on the degree of similarity between the original situation and the situation to which it is transferred. This section therefore explores some other domains where there are problems of precision in interaction.

Extension to Icona Aesthetica™

This interface has been demonstrated to the CAD designer in Icona Solutions Ltd. (www.iconasolutions.com). Icona has shown interest in extending the cube-based two-handed spatial interface model to the *Icona Aesthetica*™ product. Icona Aesthetica™ is an innovative new product for visualising the impact of production variations on the *aesthetic quality* of new vehicles early in the design process. Aesthetic quality [Maxfield et al 2002] has no precise definition. It is a customer perceived product attribute. It may be loosely defined as the 'look' of the product. Features such as the size and shape of gaps and the flushness between mating components are areas that need to be controlled in order to maintain the aesthetic quality of a product. For example, Figure 7-1 shows two views (from the rear) of an automobile body panel containing a fuel filler flap. The fuel filler flap on the car on the left products has unacceptable aesthetic quality whilst that on the right appears to be flush with the body panel and is probable acceptable to the customer.

Figure 7-1 Views of two cars of the same model

Aesthetic quality is inherently a visual attribute and thus design teams need help in visualizing the impact tolerance assignments have on gap sizes. Design teams must also be able to visualize how the aesthetic quality changes as each component varies within its allowable tolerance (or manufacturing variation). This is because products that may be acceptable to the customer when produced from perfect components may be totally unacceptable when assembled from components towards the limit of their allowable manufacturing variation. Physical models can help the process but they are made to one size and a new model (or part of) usually needs to be created for each variation. Virtual models on the other hand can be adapted relatively easily to show different gap sizes. Thus a realistic aesthetic quality evaluation tool requires the provision of a photo realistic, interactive 3D view of the product that 'responds' to external forces and can display geometry that varies form the perfect (or nominal) due to manufacturing and assembly variation. This results in the development of the *Icona Aesthetica*™.

Aesthetic quality evaluation tasks involve positioning operations which demand high accuracy and precision. During an automotive quality check, engineers need to navigate within the environment until they have located an area of interest and then manually control the viewpoint. There is the problem of global precision. They need to define points on components in order to take measurements of values such as gap and flush. Engineers may also need to adjust the position of these points in any dimensions. There are the problems of scale and related precision. Icona feels that the cube-based two-handed spatial interface has the potential to increase the precision in aesthetic quality evaluation.

Other extension examples

One example is scientific data visualization. Visual analysis of scientific data sets is often best supported by an interactive 3D environment in which the researcher is able to view the entire data set, move forward and backward through time, search for specific values or features, obtain quantitative information about particular data locations, and manipulate objects in the data space [Baker & Wickens 1995]. Within the field of scientific visualization, data analysis activities haven been categorized [Robertson 1990]. They include: *global* (involving the entire data set), *local* (involving just some subregion of the data), and *point* (confined to the data at a particular location in the data space). Haimes and Darmofal [Haimes & Darmofal 1991] describe user goals as belonging to three categories: scanning through the entire data set, feature identification within regions of the data, and probing at particular locations. The first goal addresses the problem of global precision. And the last two goals address the problem of scale. Although some two-handed spatial interfaces have been used for scientific visualization [Haan et al 2002] , the cube-based two-handed spatial may be a good alternative tool in this field.

Another example is Interior design. An interior design system should allow the designer to conceptually perform room layouts and interior design in a virtual architectural space. The designers create, place, modify and manipulated furniture and interior decorations so they can quickly try out different designs [Hill et al 1999]. In a room design scenario, the designer needs to view the room from different directions. This addresses the problem of global precision. He or she needs to place a piece of furniture related to the other objects in the room, or hang a picture on the wall, or put a small vase on the table, etc. These address the problems of scale and related precision. It can be seen that interior design is a suitable application for the cube-based two-handed spatial interface.

7.3 Concluding Remarks

This research contributes to the understanding of task performance for interactive engineering assembly with a virtual environment. Based on the understanding of the relationship between task performance, existing interaction techniques and spatial interfaces, a number of problems of precision in spatial selection and positioning are identified. A novel cube-based two-handed spatial interface has been designed to overcome these problems. It assigns to the non-dominant hand tasks such as positioning that can be performed by a sequence of 1DOF sub-tasks. This leaves the dominant-hand to perform the tasks such as 6DOF manipulation of assemblies, selection and attachment. A physical cube is used to provide the user with a spatial frame of reference. The evaluation results indicate that the new interface has the potential to reduce the task performance time by more than 25%, over an existing one-handed spatial interface.

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Appendix A

Glossary of Terms

Virtual Environment Related

- Virtual Environment (VE): A computer generated three dimensional model, where a participant can interact intuitively in real time with the environment or objects within it, and to some extent have a feeling of actually 'being there' (the notion of presence) [Wilson 1999].

- Virtual Reality (VR): is generally used to describe a family of technologies which project a VE to the participant – aurally but principally visually – through a head mounted display (HMD), head-coupled display, desktop computer, wall screen or several screens on up to six surfaces (a CAVE) [Wilson 1999]. It is also referred to the experience of being within a VE [Bowman 1999].

- Virtual Prototype: A computer based simulation of a prototype system or subsystem with a degree of functional realism that is comparable to that of a physical prototype [Haug 1993]

- Virtual Prototyping: The process of using a virtual prototype, instead of a physical prototype, for testing and evaluation of specific characteristics of a candidate design [Haug 1993].

- Real-Time: Displayed at a frame rate that ensures that images move smoothly as time view direction changes. The minimum frame rate that is considered to be real time might be as low as 10Hz, or as high as 30Hz [Bowman 1999].

- Immersion: The feeling of "being there" that is experienced in some VEs [Bowman 1999].

- Presence: A synonym for immersion.

- Virtual assembly: the process of using computer tools to assist in engineering decisions involving the analysis, prediction, visualization, and presentation of component assembly problems without the need to physical realize the product or supporting processes [Connacher et al 1995].

Human Computer Interaction Related

- Human-Computer Interaction (HCI): The exchange of information between human beings and computers during a task sequence for the purpose of controlling the computer (from the point of view of the human) or informing the user (from the point of view of the computer). This interaction usually has the goal of increasing human productivity, satisfaction, or ability [Hix & Hartson 1993].

- User Interface(UI): The hardware and software that mediated the interaction between humans and computers. The UI includes input and output devices, such as mice, keyboards, monitors, and speakers, as well as software entities such as menus, windows, toolbars, etc [Hix & Hartson 1993].

- Interaction Technique: A way of using a physical input/output device to perform a generic task in a human-computer dialogue [Foley et al 1990].

- Tracker: A device that measures 3D position, and sometimes orientation, relative to some known source. Common tracker types are electromagnetic, optical, ultrasonic, gyroscopic, and mechanical linkage [Meyer & Applewhite 1992].

Mechanical Engineering Related

- Component or part: a unit object is treated for a given purpose as non-decomposable [Munlin 1995].

- Assembly: A part which is made up of two or more parts [Munlin 1995].

- Features: represent a set of geometric shapes on a component with specific quantifiable properties.

- Kinematics: the description of movable mechanical structures consisting of joints and links including the number, location and orientation of the joints [Munlin 1995].

- Mating condition or mating relationship: the description of the connection between parts [Mulin 1995].

- Assembly modeling: focus on the representation of assembly mating conditions and the aggregation of these mating conditions into structured assembly models [Mulin 1995].

Appendix B
Evaluation in Chapter 3

B.1 Post-questionnaire

(Question 1-11 for both environments. Question 12– 16 only for virtual environment)

1. Selecting a part was

------------------------------*---------------*---------------*

too easy easy neither easy nor difficult difficult too difficult

2. Locating a part was

------------------------------*---------------*---------------*

too easy easy neither easy nor difficult difficult too difficult

3. Finding a mating part was

------------------------------*---------------*---------------*

too easy easy neither easy nor difficult difficult too difficult

4. Attaching two parts was

------------------------------*---------------*---------------*

too easy easy neither easy nor difficult difficult too difficult

5. Accurate positioning was

------------------------------*---------------*---------------*

too easy easy neither easy nor difficult difficult too difficult

6. Changing a part was

------------------------------*---------------*---------------*

too easy easy neither easy nor difficult difficult too difficult

7. General mental effort required for operation was

------------------------------*---------------*---------------*

too low low neither low nor high high too high

8. General physical effort required for operation was

------------------------------*---------------*---------------*

too low low neither low nor high high too high

9. General operation speed was

------------------------------*---------------*---------------*

too slow slow neither slow nor fast fast too fast

10. The overall satisfaction with the system was

------------------------------*---------------*---------------*

quite dissatisfied neither satisfied nor dissatisfied quite satisfied

11. General comfort

------------------------------*---------------*---------------*

very uncomfortable very comfortable

12. I like using 2D mouse in:

a) Selecting b)moving c)rotating d)none of them

13. I__________ using keyboard in this experiment:

a) Like b)unlike c)I don't know

14. How much do you pay attention to the text prompt?

------------------------------*---------------*---------------*

none little a little a lot quite a lot

14. What is the best thing in the system?

15. What is the most frustrating thing in the system?

16. Would you like to make other comments?

B.2 User Feedback

(N mode: *Direct Selection;* Mode: *Direct Manipulation)*
User 1:
Observations
He liked to begin with bigger part
When he was deciding the next step, he moved the mouse unconsciously so that the cursor moved around on the screen.
Comments:
"Rotation is difficult" "Remembering keys are not easy" "N mode is easier than M mode."
"Interface is complicated" "Changing a part is not easy if the model is not simple"
"I think the best thing in the system is automatic attachment once the constraint is identified"
"Compared with the E1, Automatic finding constraint and satisfying constraint techniques are more effective. " "I like using mouse in selecting and moving an object"
"Errors occurred during using M mode"

User 2:
Observations:
He was the fastest one among all the subjects in E2.
He got used to use the left button to move instead of rotate. When he planned to move a part, he pressed the left button result in rotating the object several times before he realized the wrong action. ***/ lack of visual cues to distinguish the start state of move and rotate/***
He found a constraint. He was happy. But suddenly the constraint disappeared as he didn't stop the movement in time. He was disappointed. /***The continuous move or rotation is caused by press & drag & delayed-release mouse button. The right action should be press & drag & immediate-release. I think the continuous move or rotation should be disabled in this mode.*** /
When he moved an object, he pressed middle button (he should press right button), the object zoomed out a little bit, he changed the button a little bit nervously and calmed down when going back to the right action.
He put the G2 in an opposite orientation. He broke the constraint between G2 and S2 and changed the orientation.
Comments:
"I think rotation is not easy at first, but it's not bad when you get used to it"
"I don't think the physical model could help me to understand very much the assembly in the IVPS. If you only show me the virtual model, I can also understand it. Eh, but I don't know what it would be if the model is much more complicated"
_ *"Which mode M and N is easier to use ?"*
_ *"N. eh…I don't know. Depends on… I don't know"*
"I don't know what is the best thing in the system.
"It would be nice if objects stopped moving to give the user an opportunity to accept a constraint"
"Quite impressive. Not easy to manipulate (rotate) objects at first"
"Easy to assemble; little difference between the physical object and the screen representation."

User 3
Comments
She said she couldn't feel as much comfortable as in real world because she couldn't feel the objects.
She thought the best thing in the system was the constraint based manipulation
She thought the most frustrating thing was the procedure of finding mating condition.
She likes using mouse in selecting, moving and rotating and didn't like using keyboard in this experiment.
She thought appropriate prompt was important.

User 4
Observation:
When He manipulated part G2 in a position where its axis was nearly parallel with the axis of S2, but the system didn't recognize the constraint between them. **/system should response. System bug!!/**
He thought the position was not accurate enough and navigated around to exam it. But He couldn't figure out the reason He moved the object to in a distance to Part S2 and finally found the concentric constraint
He said he felt frustrating.
Comments
He thought selection and navigation were the best things in the system. And rotating was the most frustrating thing.
He said he liked the idea to find constraint and satisfy it. But he thought it was not easy to use.

He even didn't notice there was text prompt in system.

User 5 (the one who failed completing the task)

Observations:

It took him long time to put everything together.
He spent a lot time in learning and understanding N mode and M mode.
But When he used N mode to select the inner surface on G2 and then the surface on S2, but the system didn't response **/Bug!!** ***This kind of surface is not a cylindrical surface and not considered in the system. (We missed some constraints). User will have to use the cylindrical surface on the both parts and make them assembled*/**
He then wouldn't like to try to rotate the part to the appropriate position and used M mode and hoped the constraint would be found automatically. Finally he saw the red highlighted text "against constraint" and thought he found the constraint. /***He didn't pay attention to the text, just the color change***/
He asked me what he was going to do next. /***The change color give a cue to the next action, but he is not clear what on earth is the next action/***
I told him he should find the concentric constraint with the blue highlight. /***He recognised the text but he was not clear about the meaning of "against constraint" or "cylindrical constraint"***. ***Understanding the text need some knowledge of mechanical engineering.*** *He just knew he need to get the blue color instead of red color.* /
He had to continue to find the concentric constraint. Finally he got the blue highlighted and asked for his next action. /***The next action is not clear/***
He was told to pressed "I" and part G2 finally mounted to S2.
He put G3 on the S2 in the same way. But the orientation of G3 was reversed.
He broke the constraint by pressing "o" key and repeated the procedure, but it was not easily to find the concentric constraint by manipulating G3. **He was so frustrated.** And said he would like to leave it to the last stage. And finish the G1 first.
After he finished G1 still using M mode. He went back to G3. He forgot to pay attention to the orientation of G3 and the same error occurred.
He wouldn't like to change the orientation again and finished the experiment.

Comments

He used N mode to find out the gearing fit easily and he thought it was the best thing in the system. He thought rotation was the most frustrating this in the system.

User 6

Observations and Comments

She quite enjoyed the assembly task and thought it was interesting although she couldn't complete it quickly and even she got the errors. She was satisfied with the system except she needed to remember the use of the keys.. After she finished the task, she enjoyed her achievement.

Appendix C
Evaluation in Chapter 4

C.1 Post-questionnaire

Part A. Questions for each task
<u>Task: Picking/Grabbing a component</u>
Questions:

1. How easy it is for you to select a component?

1	2	3	4	5	6	7

Difficult Medium Easy

2. How satisfied are you with the red bounding box which attempt to give you the feedback to tell you the highlighted component is ready to be selected?

1	2	3	4	5	6	7

Not Satisfied Satisfied

3. How easy it is for you to go ahead and pick or grab a component? (Confirm a selection)

1	2	3	4	5	6	7

Difficult Easy

4. How satisfied are you with the green bounding box which attempt to give you the feedback to tell you the highlighted component has been selected?

1	2	3	4	5	6	7

Not Satisfied Satisfied

5. Score the amount of mental effort needed for completing the whole process for this task

1	2	3	4	5	6	7

Low High

6. Score the amount of physical effort required for completing the whole process for this task

1	2	3	4	5	6	7

Low High

7. How easy it is for you to deselect a component?

1	2	3	4	5	6	7

Difficult Easy

<u>Task: manipulating a component</u>
Questions:

1. Moving a component to a desired position is

1	2	3	4	5	6	7

Difficult Easy

2. Rotating a component to a desired orientation is

1	2	3	4	5	6	7

Difficult Easy

3. The amount of mental effort required for manipulating a component is

1	2	3	4	5	6	7

Low High

4. The amount of physical effort required for manipulating a component is

1	2	3	4	5	6	7

Low High

<u>Task: Attaching two components by direct selecting two surfaces</u>

Questions:

1. How easy it is for you select a surface?

1	2	3	4	5	6	7

Difficult Easy

2. How satisfied are you with the red highlighted surface which give you the feedback that this surface is ready to be selected?

1	2	3	4	5	6	7

Not Satisfied Satisfied

3. How easy it is for you to go ahead and pick a surface?

1	2	3	4	5	6	7

Difficult Easy

4. How satisfied are you with the green highlighted surface which give you the feedback that this surface has been selected?

1	2	3	4	5	6	7

Not Satisfied Satisfied

5. How easy it is for you to find a second surface to mate with the first?

1	2	3	4	5	6	7

Difficult Easy

6. How satisfied are you with the feedback which represents the potential constraints between the first and second entities ?

1	2	3	4	5	6	7

Not Satisfied Satisfied

7. The amount of mental effort required for completing the whole process of this task is

1	2	3	4	5	6	7

Low High

8. The amount of physical effort required for completing the whole process of this task is

1	2	3	4	5	6	7

Low High

<u>Task: Attaching two components by direct manipulating a component</u>

Questions:

1. How easy it is for you to find the constraints you want between two components?

1	2	3	4	5	6	7

Difficult Easy

2. How satisfied are you with the feedback to tell you the possible constraints between the first and second entities ?

1	2	3	4	5	6	7

Not Satisfied Satisfied

3. How easy it is to go ahead and achieve the constraint?

1	2	3	4	5	6	7

Difficult Easy

4. The amount of mental effort required for completing the whole process of this task is

1	2	3	4	5	6	7

Low High

5. The amount of physical effort required for completing the whole process of this task is

1	2	3	4	5	6	7

Low High

Task: Removing constraints (undoing a mistake)

Questions:

1. Removing the constraint between two constrained components is (Answer only if you did it)

1	2	3	4	5	6	7

Difficult Easy

2. How satisfied with the red bounding box plus the white diagonal lines to give you the feedback to tell you that the constraints associated with the highlighted component is going to remove?

1	2	3	4	5	6	7

Not Satisfied Satisfied

Task: Navigation

Questions:

1. How satisfied are you with the way we provided for navigation? Any comments?

1	2	3	4	5	6	7

Not Satisfied Satisfied

2. The amount of mental effort required for navigation is

1	2	3	4	5	6	7

Low High

3. The amount of physical effort required for navigation is

1	2	3	4	5	6	7

Low High

PART B: Overall Questions

1. How easy it is to switch between modes to perform the tasks you want to carry out?

1	2	3	4	5	6	7

Difficult Easy

2. How satisfied are you with the different colour applied to the icon to give you the feedback to tell you in which modes you are at the moment?

1	2	3	4	5	6	7

Not Satisfied Satisfied

3. How easy to complete the whole task is

1	2	3	4	5	6	7

Difficult Easy

4. The amount of mental effort required for completing the whole task is

1	2	3	4	5	6	7

Low High

5. The amount of physical effort required for completing the whole task is

1	2	3	4	5	6	7

Low High

6. The amount of stress you felt during performing the task is

1	2	3	4	5	6	7

Low(Relaxed) High(Tense)

7. The amount of fatigue you felt during performing the task is

1	2	3	4	5	6	7

Low(Alert) High(Exhausted)

8. How easy it is to learn how to use the system?

1	2	3	4	5	6	7

Difficult Easy

9. How satisfied are you with your performance?

1	2	3	4	5	6	7

Not Satisfied Satisfied

10. How do you feel about the input device?
    a) Felt comfortable b) Felt uncomfortable c) It was fun d) It was boring
    e) Felt easily controlled f) Not easily controlled g) Felt natural h) Felt artificial
11. What is the best thing in the system?
12. What is the most frustrating thing in the system?
13. Would you like to make other comments?

PART C: Final questions after finishing all the experiment sets

1. Which input device is your favorite?
2. Which input device is the easiest?
3. Did you perceive the depth provide by stereo?
   a) Yes b) No
   If the answer is Yes, did the depth perception help you performing the task?
   a) Yes b) No difference c) It hindered me
4. How do you feel about the image the output device produced?
   a) Felt like life size parts b) Felt like wrong scaled parts
   c) Felt like physical parts d) Felt like artificial parts
5. How do you feel about the shutter glasses?
   a) Felt comfortable b) Felt uncomfortable c) Made my eyes tired

C.2 User Feedback

Overall feedback

- **Feedback for stylus interface**

Subjects	Time (min)	Task difficulty *1 difficult* *7 easy*	Mental effort *1 low* *7 high*	Physical effort *1 low* *7 high*	Stress *1 low* *7 high*	Fatigue *1 low* *7 high*	Satisfaction *1 Not satisfied* *7 satisfied*	Learnability *1 Difficult* *7 Easy*
1	10	3	7	2	5	4	3	3
2	3	6	3	3	2	2	5	7
3	11	4	4	3	2	1	6	7
4	5	5	3	2	1	1	5	6
5	5	5	5	4	4	4	5	3
6	4	6	2	2	1	1	6	6
7	4	6	2	1	2	3	7	6
8	4	6	4	3	2	3	6	6
9	3	6	2	2	1	3	6	7
10	3	6	3	3	3	3	6	6
11	4	6	3	1	3	3	6	6
12	3	7	2	3	1	1	7	7
Means	4.9	5.5	3.3	2.4	2.3	2.4	5.7	5.9

- **Feedback for glove interface**

Subjects	Time (min)	Task Difficulty *1 difficult* *7 easy*	Mental effort *1 low* *7 high*	Physical effort *1 low* *7 high*	Stress *1 low* *7 high*	Fatigue *1 low* *7 high*	Satisfaction *1 Not satisfied* *7 satisfied*	Learnability *1 Difficult* *7 Easy*
1	5	5	5	7	2	6	6	7
2	6	6	3	3	2	2	5	7
3	6	4	4	4	2	3	6	7
4	7	4	3	4	1	2	3	6
5	6	5	3	6	4	6	5	5
6	6	5	3	4	6	3	5	6
7	10	3	4	4	4	5	6	4
8	5	4	4	5	2	5	6	6
9	4	5	3	3	2	3	6	7
10	5	6	4	4	4	3	6	6
11	5	3	6	4	4	4	5	6
12	7	6	2	5	2	4	7	6
Means	6	4.7	3.7	4.4	2.9	3.8	5.5	6.1

- **Preference of input device**

	glove	Stylus
Favorite device	7	4
Easiest device	2	10

Feedback on Performing Each Subtask

- **Task: Picking/Grabbing a component**

Stylus interface

Subjects	**Task Difficulty (① & ②)** *1 Difficult* *7 easy*	**Mental effort** *1 low* *7 high*	**Physical effort** *1 low* *7 high*
1	3 & 5	7	2
2	6 & 6	4	2
3	6 & 7	4	2
4	6 & 6	5	2
5	6 & 6	5	4
6	7 & 7	3	2
7	6 & 6	2	1
8	6 & 7	4	5
9	7 & 7	2	2
10	5 & 6	3	3
11	7 & 7	3	3
12	7 & 7	2	3
Means	6 & 6.4	3.5	2.6

Glove interface

Task Difficulty (① & ②) *1 Difficult* *7 easy*	**Mental effort** *1 low* *7 high*	**Physical effort** *1 low* *7 high*
7 & 7	5	6
4 & 5	3	4
6 & 5	3	3
6 & 6	3	3
4 & 6	4	6
6 & 5	2	2
4 & 6	3	3
2 & 2	5	6
6 & 4	5	4
7 & 7	4	4
5 & 6	4	4
6 & 7	2	5
5.3 & 5.5	3.6	4.2

(① Selecting ② Picking or Confirming a selection)

- **Task: Manipulating a component**

Stylus interface

Subjects	**Task Difficulty (① & ②)** *1 Difficult* *7 easy*	**Mental effort** *1 low* *7 high*	**Physical effort** *1 low* *7 high*
1	5 & 4	7	1
2	5 & 3	3	3
3	6 & 6	2	2
4	6 & 5	4	4
5	5 & 5	5	4
6	7 & 7	2	2
7	5 & 4	4	4
8	6 & 4	4	5
9	7 & 4	1	1
10	6 & 6	4	4
11	6 & 4	5	3
12	7 & 6	2	3
Means	5.9 & 4.8	3.6	3

Glove interface

Task Difficulty (① & ②) *1 Difficult* *7 easy*	**Mental effort** *1 low* *7 high*	**Physical effort** *1 low* *7 high*
7 & 5	4	5
5 & 4	3	4
5 & 5	3	3
6 & 5	4	4
4 & 4	3	5
7 & 4	3	3
4 & 2	4	5
6 & 5	6	6
5 & 4	5	3
5 & 5	4	4
4 & 2	6	4
6 & 4	2	5
5.3 & 4.1	3.9	4.3

(① Translation ② Rotation)

- **Task: Attaching two components by *Direct Selection***

Stylus interface

Subjects	Task Difficulty (① & ② & ③) *1 Difficult 7 easy*	Mental effort *1 low 7 high*	Physical effort *1 low 7 high*
1	4 & 4 & 1	7	1
2	5 & 6 & 6	3	2
3	5 & 7 & 5	2	2
4	6 & 5 & 4	4	2
5	6 & 6 & 6	5	4
6	5 & 6 & 6	2	2
7	5& 4 & 7	2	2
8	6 & 4 & 6	3	3
9	7 & 5 & 6	3	3
10	3 & 6 & 6	3	3
11	5 & 4 & 5	4	3
12	7 & 7 & 7	2	3
Means	5.3 &5.3 & 5.4	3.3	2.5

Glove interface

Task Difficulty (① & ② & ③) *1 Difficult 7 easy*	Mental effort *1 low 7 high*	Physical effort *1 low 7 high*
3 & 2 & 6	4	6
3 & 4 & 4	3	3
6 & 5 & 6	3	4
2 & 3 & 4	4	5
3 & 5 & 3	5	5
6 & 6 & 6	2	4
3 & 2 & 5	5	6
6 & 6 & 5	4	5
5 & 7 & 5	1	3
5 & 5 & 5	4	5
1 & 5 & 3	6	5
4 & 6 & 6	2	5
3.9 & 4.7 & 4.8	3.6	4.7

① Selecting a surface ② Picking the surface ③ Picking the mated surface

- **Task: Attaching two components by *Direct Manipulation***

Stylus interface

Subjects	Task Difficulty (① & ②) *1 Difficult 7 easy*	Mental effort *1 low 7 high*	Physical effort *1 low 7 high*
1	6 & 5	6	1
2	3 & 4	3	3
3	4 & 4	4	4
4	4 & 3	4	3
5	4 & 6	6	5
6	6 & 6	2	2
7	5 & 4	5	4
8	3 & 3	4	4
9	7 & 6	3	2
10	6 & 6	4	4
11	2 & 2	6	4
12	7 & 7	2	3
Means	4.8 & 4.7	4.1	3.3

Glove interface

Task Difficulty (① & ②) *1 Difficult 7 easy*	Mental effort *1 low 7 high*	Physical effort *1 low 7 high*
5 & 5	4	5
2 & 2	3	4
4 & 6	3	4
6 & 6	3	3
4 & 3	3	6
1 & 1	6	5
2 & 4	6	5
7 & 4	4	5
6 & 6	1	3
3 & 5	4	4
4 & 4	5	3
7 & 6	2	5
4.3 & 4.3	3.7	4.3

① Finding a constraint ② Achieving the constraint

- **Task: Scene positioning**

Stylus interface

Subjects	Task Difficulty *1 Difficult 7 easy*	Mental effort *1 low 7 high*	Physical effort *1 low 7 high*
1	4	6	1
2	6	2	4
3	7	2	1
4	7	3	3
5	6	5	3
6	6	1	1
7	6	2	2
8	7	3	3
9	7	2	1
10	6	3	3
11	6	3	1
12	7	2	3
Means	6.3	2.9	2.2

Glove interface

Task Difficulty *1 Difficult 7 easy*	Mental effort *1 low 7 high*	Physical effort *1 low 7 high*
7	3	7
7	2	3
7	5	3
6	3	4
5	3	3
6	3	2
4	4	5
5	5	6
7	3	2
6	4	4
4	5	5
7	1	4
5.9	3.4	4

Comments from Each Subject

Subject 1:

- *Not easy to remember the button command.*
- *The sensor is not stable to make selection difficult.*
- *Stereo glass gave the depth, but not help.*
- *You know where the finger. But not easy to remember the button number.*
- *The bigger the object is, the easier to select using stylus.*
- *Too sensitive. Sometimes the cursor moves just before selection.*
- *The mental effort is high for stylus navigation is because of hand-eye co-ordination.*
- *Felt stylus not easily control.*
  Felt glove comfortable, fun, easily control.
- *The frustrating for stylus is trying to move the cursor*
  For glove, pointing with one finer at an object---precise selection
- *Direct selection tense muscle shoulder.*
- *For glove, felt fatigue only in the shoulder.*
- *I felt fun and easy using glove. You can see your hand move. Move relating, no remembering button.*

Subject2:

- *Damp for move component, otherwise overshoot.*
- *Mental effort for stylus selection is 4 because mainly thinking about procedure.*
- *For stylus system control, remembering which buttons.*
- *Felt stylus comfortable, fun, natural*
  Felt glove comfortable, fun, easily control, artificial.
- *The frustrating thing for stylus is correct spatial awareness.*
  The frustrating thing for glove is difficult to get highlight on Direct Manipulation.
- *Difficult to do THREE gesture.*

Subject3:

- *Grab a component with hand and then easily lost it because his hand move two fast.*
- *Prefer direct selection, but maybe direct manipulation could be good if more practice.*
- *Felt stylus comfortable, fun, easily control and natural.*
  Felt glove comfortable, fun, easier than stylus, natural
- *The frustrating thing is direct manipulation when you try to move the whole shaft and individual components slide up and down it. (constraint based manipulation)*
  For glove, getting your hand flat to select a component. (Flat-hand gesture)
- *For system control, with the stylus needed to look at the buttons to check which one I was pressing; with my hand I know if I am pointing fingers or not.*

Subject4:

- *Glove navigation, very small movement cause big movement.*
- *Need time to get used to equipment, then not much mental effort required.*
- *Felt stylus comfortable, fun, easily controlled and natural.*
  Felt glove comfortable, fun, not easily control and natural
- *The most frustrating thing for stylus is adapting to the system initially.*
  For glove, is direct selection of a surface.
- *I was very enjoyable.*
- *Direct selection is hard because system very sensitive to small movements.*
- *Navigation for glove due to orientation of hand and sensitivity system.*
- *Hand is easier for system control than button. More natural.*

Subject5

- *Felt glove comfortable, fun, easily control, natural.*
  Felt stylus comfortable, fun (Less than glove), easily control, artificial.
- *Pointing to select a surface was quite hard, as the hand scrolled too easily. It's the frustrating thing in system. So sensitive that final one.*
  The frustrating thing for stylus is learning the buttons combinations.
- *The best thing for glove is the viewpoint manipulation. The best thing for stylus is the object and surface is much easier than the hand, the button is easier.*

- *For system control, hand is more natural, prefer using hand.*
- *The stylus is harder to learn, less fun, but more productive than the hand.*

Subject6

- *Direct selection and Direct manipulation using glove can require extremes of arm movement. In Direct Manipulation, often hard to find mating surface. Achieving constraint is difficult because of slight time delay. Direct manipulation is hard.*
- *Remembering exact finger movement(gesture) is hard at first.*
- *The stress using glove is high result from making repeated mistakes.*
- *Felt glove comfortable, fun, easily control, nature(depends on task)*
  Felt stylus comfortable, fun(less than glove), easily control, natural.
- *The best thing is no menu. Can do several operations quickly without menus.*
- *The frustrating thing for glove is Direct manipulation.*
  No frustrating thing for stylus. Generally easier than using glove.
- *Easier than a mouse in some ways, because the movements are more intuitive.*
- *Stylus seems much more accurate and sensitive.*
- *For system control, stylus is easier to remember and operate. But the icon color feed back not very satisfied as he tend not to rely on color. Adding some text would be better.*

Subject7:

- *Finding a constraint in Direct Manipulation is quite difficult due to the orientation of hand.*
- *Making gestures is hard.*
- *I was trying to complete hand navigation in one stage rather than using 2 or 3 stages.*
- *Felt glove fun, not easily controlled.*
  Felt stylus comfortable, fun, easily control, natural
- *The best thing in glove system is graphics.*
  The best thing in stylus system is more control over pointer, easier to use.
- *The frustrating thing in glove system is hand gestures.*
  The frustrating thing in stylus system is sense of depth, difficult perception-need reference points, objects, etc.
- *Need to improve hand gesture recognition system. Universal gesture.*
- *Stylus for direct selection is easier than glove.*

Subject8:

- *Felt glove comfortable, fun, need practice.*
- *The best thing of the glove system is the hand.*
  The best thing of the stylus system is easier to press button than hold out fingers.
- *The frustrating thing of the glove system is getting used to 3 dimensions.*

Subject9:

- *Difficult to remember the gesture.*
- *Mapping the movement of hand to object is tricky. (Mapping, scaling issue)*
- *Gesture mix ups made parts of task stressful. Some gestures made it tricky.*
- *Felt glove comfortable, fun, easily control, artificial.*
  Felt stylus comfortable, fun, easily control, artificial.
- *The best thing in glove system is the feeling of being within the environment set up*
  The best thing in stylus system is to control over what was being done.
- *The frustrating thing in glove is the gestures to remember.*
  The frustrating thing in stylus is more sensitive than glove.
- *Using stylus for translation is easy. But rotation is more difficult than with hand .*
- *Stereo darken the environment.*

Subject10:

- *Felt glove comfortable, fun, easily control and natural*
  Felt stylus comfortable, fun, easily control and natural
- *The frustrating things are delay, remove constraint(part moves back not sideways), and constraint feed back is hidden behind hand in Direct manipulation.*
  The frustrating thing in stylus system is selecting surfaces.
- *Delay using stylus is less than glove.*

- *Felt selection using stylus more difficult because of less feeling of penetration.*
- *Stylus cursor color feedback is too dark with stereo glasses on.*

Subject11:

- *Felt glove comfortable, fun, but not easily controlled and artificial.*
  Felt stylus comfortable, fun, easily controlled and artificial.
- *The frustrating thing using glove system is selecting surfaces.*
  The frustrating thing using stylus system is Direct manipulation.
- *Prefer using one button for stylus navigation*
- *Prefer using gesture for system control, it's easy to remember*
- *Think one glove learning easier than stylus but harder to use*

Subject 12:

- *stylus is easier because you have more control as you are holding something.*
- *The reason to give visual feedback 3 points in Direct manipulation using glove is:*
  Sometimes the words are hidden behind the hand.
- *The reason to give visual feedback 6 points in Direct manipulation using stylus is:*
  Lack of an area of approach which would make it easier.
- *gesture for system control is a little harder than using stylus. The reason is It failed to recognize the OK gesture all the times*
- *Felt glove comfortable, fun and easily controlled. But are not sure if felt natural or not which would depend on different tasks.*
  Felt stylus comfortable, fun and easily controlled and artificial.
- *The best thing in system using glove is easy to learn and to use.*
  The best thing in system using stylus is more precise than using glove
- *The most frustrating thing in system using glove is Direct selection (not highly frustrating just a little difficult). The reason is it's a little bit oversensitive.*
  No frustrating thing using stylus.

Appendix D
Evaluation in Chapter 6

D.1 Post-questionnaire

1. The amount of mental effort required for completing the task is

1	2	3	4	5	6	7

Low Medium High

2. The amount of physical effort required for completing the task is

1	2	3	4	5	6	7

Low Medium High

3. The amount of fatigue you felt during performing the task is

1	2	3	4	5	6	7

Low(Alert) Medium High(Exhausted)

4. The amount of stress you felt during performing the task is

1	2	3	4	5	6	7

Low(Relaxed) Medium

5. How easy to interact with the system using the Stylus

1	2	3	4	5	6	7

Easy Medium difficult

6. Do you feel comfortable to interact with the system using both hands?

1	2	3	4	5	6	7

Uncomfortable Medium Comfortable

7. How easy to interact with the system using the stylus

1	2	3	4	5	6	7

Easy Medium difficult

(8-10 only for two-handed users)

8. Is this cube understandable?

1	2	3	4	5	6	7

Not at all Medium very much

9. How easy to interact with the system using the cube by the left hand?

1	2	3	4	5	6	7

Easy Medium difficult

10. Do you feel comfortable to interact with the system using both hands?

1	2	3	4	5	6	7

Uncomfortable Medium Comfortable

11. Is there anything distract your attention? What is it?

12. How enjoyable when you performing the task?

1	2	3	4	5	6	7

Not at all Medium very much

13 What is the best thing in the environment?
14 What is the most frustrating thing in the system?
15. From an engineer's point of view, what's your commence on the use of system?

D.2 User Feedback

- **Subjective feedback**

Table D-1 Subjective feedback from the two-handed users

Users	Learn (1 easy 7 difficult)	Difficulty (1 easy 7 difficult)	Mental (1 low 7 high)	Physical (1 low 7 high)	Fatigue (1 low 7 high)	Stress (1 low 7 high)	Stylus (1 easy 7 difficult)	Cube (1 easy 7 difficult)
Rob	3	4	2	3	3	2	2	2
John	2	2	1	1	2	1	2	3
Oliver	4	3	6	2	2	3	4	3
Jule	1	1	1	1	2	1	1	1
Tom	5	3	5	2	2	3	3	4
Thomas	2	3	3	1	3	4	2	2
means	2.8	2.7	3	1.7	2.3	2.3	2.3	2.5
5-point	2	1.9	2.1	1.2	1.6	1.6	1.6	1.8

Table D-2 Subjective feedback from the one-handed users

Users	Learn (1 easy 7 difficult)	Difficulty (1 easy 7 difficult)	Mental (1low 7 high)	Physical (1 low 7 high)	Fatigue (1 low 7 high)	Stress (1 low 7 high)	stylus (1 easy 7 difficult)
Nic	2	5	2	5	5	6	7
Tom	1	2	2	5	3	5	4
Martin	5	4	4	2	2	4	5
Gareth	3	3	3	2	2	2	3
Ben	4	5	3	1	1	3	1
Matt	3	6	4	3	6	7	7
Means	3	4.1	3	3.1	3.2	4.5	4.5
5-point	2.1	2.9	2.1	2.2	2.3	3.2	3.2

- **Two-handed users' comments:**

- Cursor and stylus are very much better for manipulating and selecting surfaces or objects as opposed to using a mouse & keyboard.
- The best thing is the ability toe move in all dimensions
- Simplicity, it doesn't take very long to understand the basics.
- Very useful regarding to modeling
- The frustrating thing is losing the pointer behind components
- Very good, realistic
- The frustrating thing is the cursor kept disappearing into the model
- Very good, very easy to use. I personally thought the zoomin/zoom-out functions on the cube should be inverted.
- The best thing is manipulation using both hands.
- It could be good to be able to rotate about all sides
- The best thing is quick movements in all directions, good sensitivity
- The frustrating thing is surface selection due to same coloured component
- The best thing is being able to interact with the system using 3D input tools.
- I preferred using two hands to control the system as I believe it makes for more flexible control of the objects in 3D.
- Clear to visualize the assemble without physical contact, no menus
- I really liked it. It was a lot easier and more fun than anything I had used before (e.g. IDEAS).
- Sometimes the joystick didn't feel quite right, maybe a bit sensitive.

- I liked how you had 2 things to use as a control using both hands. Meant not everything was done to just one hand and lots of controls.

- **One-handed users' comments:**

- The frustrating thing is not being able to see the stylus
- Too hard & Frustrating to be used on a daily basis.
- The best thing is the kinematic behariour of an assembly.
- The frustrating thing is sleeting small holes.
- Seems good, with practice could be useful, easy 3D visualization of assembly.
- The frustrating thing is pointer disappearing
- Every easy to pick a component
- Maybe the cursor is not quite as accurate as a mouse/ball
- Very good graphics and 3D manipulation
- Unsure as to the direction of the cursor
- Looks quite useful, especially from the manipulation side.
- I liked the use of dotted lines and colour to show the constraints between the parts
- I liked how simple it was, for example just the pointer and the components on the scree
- The frustrating thins is trying to highlight the areas when constraining