Evaluation of Gaming Environments for Mixed Reality Interfaces and Human Supervisory Control in Telerobotics

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Declaration

This thesis contains the results of my own original research and has not been submitted for a postgraduate degree at any university or institution, except where specific reference or acknowledgment is made to the work or contribution of others. Much of this content research has either been published or submitted for publication as conference and journal proceedings, short paper, workshop presentation, poster, and exhibition. The following is a list of these publications:

Paper conference and journal proceedings:

- **I.B.K. Manuaba,** K. Taylor, & T. Gedeon (2012): "Evaluation of Response Models to a Series of Commands in a Telerobotics Supervisory Control System". In the proceedings of the 5th International Conference on Intelligent Robotics and Applications. Montreal, Quebec, Canada, October, 2012, LCNS 7508, Springer, Part III, pp. 73-84.
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- **I.B.K. Manuaba,** K. Taylor, & T. Gedeon (2011): "Exploration of Mixed Reality Environment for Telerobotics Interface: An Option to Provide Effective Information". In the proceedings of the Australian Journal of Intelligent Information Processing Systems, Special issue for the International Workshop on Bio-inspired Computing for Intelligent Environments and Logistic Systems (IWBCIELS2011), Vol 13, No.1, 2011, pp. 31-38.
- **I.B.K. Manuaba,** K. Taylor, & T. Gedeon (2011): "Comparison between Two Mixed Reality Environments for Telerobotics Interface". In the proceedings of the IEEE International Conference on Robotics and Automation (ICRA2011). Shanghai, China, May, 2011, pp. 1335-1340.
- **I.B.K. Manuaba,** K. Taylor, & T. Gedeon (2010): "Exploration of Second Life as a Virtual Gaming Environment for Telerobotics". In the proceedings of the International Conference of Asian Pacific Computer Human Interaction (APCHI2010). Sanur-Bali, Indonesia, July, 2010, pp. 674-679.

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- **I.B.K. Manuaba** (2011): "Applying a Mixed Reality Interface with Human Supervisory Control for Telerobotics". In Science and Engineering Expo Graduate Research 2011. CSIRO ICT Centre, Canberra, Australia, August 2011.
- **I.B.K. Manuaba,** K. Taylor, & T. Gedeon (2011): "Exploration of Mixed Reality Environment for Telerobotics Interface: An Option to Provide Effective Information". In the International Workshop on Bio-inspired Computing for Intelligent Environments and Logistic Systems (IWBCIELS2011). The Australian National University, Canberra, Australia, March 2011.
- K. Taylor, & **I.B.K. Manuaba, I.B.K.** (2010): "Using computer gaming environments to develop situated virtual reality methods for telerobotics of mining equipment". In OzViz 2010, Queensland Bioscience Precinct, University of Queensland, 2 December 2010.

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To my beloved Family and Friends.

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Glossary of Abbreviations

AJAX	Asynchronous JavaScript and XML
ANU	Australian National University
API	Application Programming Interface
AR	Augmented Reality
AV	Augmented Virtuality
cdf	cumulative distribution function
CPU	Central Processing Unit
crv	continuous random variables
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DDX	Dynamic Data eXchange
DOF	Degree of Freedom
E	Rijsbergen's effectiveness (Chapter 5)
FIFO	First-In-First-Out
FS	Full Stop
HSC	Human Supervisory Control
HTTP	The Hypertext Transfer Protocol
ICT	Information and Communication Technology

iHcc	Information & Human Centred Computing
info	Information
IP	Internet Protocol
KB	Kilo Bytes
LAN	Local Area Network
LGPL	Lesser General Public License
LiSA	Localization and Semantics of Assistance
LSL	Linden Scripting Language
MB	Mega Bytes
MR	Mixed Reality
OpenCV	Open Source Computer Vision
OR	Odd Ratio
P / p – value	Probability Value
PC	Personal Computer
PDA	Personal Data Assistant
Pdf	probability density function
PHP	Hypertext Preprocessor
PPV	Position Predictive Value
PTZ	Pan Tilt Zoom
R	*number of requests (Chapter 6)*
R^2	*Chi-square goodness fit test*
RAM	Random Access Memory

ROM	Read Only Memory
RPC	Remote Procedure Call
SA	Situational Awareness
SD	Standard Deviation
Sec	Seconds
SL	Second Life
Sm	Simmersion
T	*length of playing (Chapter 6)*
TCP	Transmission Control Protocol
TS	Temporary Stop
TUI	Telerobotics User Interfaces
UAV	Unmanned Aerial Vehicle
UDP	User Datagram Protocol
USAR	Urban Search and Rescue
UWA	University of Western Australia
VGA	Video Graphic Array
VR	Virtual Reality
VRML	Virtual Reality Modelling Language
WEB	Website
X^2	Chi-square / *Chi-square goodness fit test*
X3D	Extensible 3D

XML	eXtensible Markup Language

Others

2D	Two Dimensions
3D	Three Dimensions
β	Beta / *Shape* Parameter (*Weibull* parameters)
δ	Delta / *Location* Parameter (*Weibull* parameters)
θ	Teta / *Scale* Parameter (*Weibull* parameters)

Abstract

Telerobotics refers to a branch of technology that deals with controlling a robot from a distance. It is commonly used to access difficult environments, reduce operating costs, and to improve comfort and safety. However, difficulties have emerged in telerobotics development. Effective telerobotics requires maximising operator performance and previous research has identified issues which reduce operator performance, such as operator attention being divided across the numerous custom built interfaces and continuous operator involvement in a high workload situation potentially causing exhaustion and subsequent operator error.

This thesis evaluates mixed reality and human supervisory control concepts in a gaming engine environment for telerobotics. This concept is proposed in order to improve the effectiveness of current technology in telerobotic interfaces. Four experiments are reported in this thesis which covers virtual gaming environments, mixed reality interfaces, and human supervisory control and aims to advance telerobotics technology.

This thesis argues that gaming environments are useful for building telerobotic interfaces and examines the properties required for telerobotics. A useful feature provided by gaming environments is that of overlying video on virtual objects to support mixed reality interfaces. Experiments in this thesis show that mixed reality interfaces provide useful information without distracting the operator from the task.

This thesis introduces two response models based on the planning process of human supervisory control: Adaptation and Queue response models. The experimental results show superior user performance under these two response models compared to direct/manual control. In the final experiment a large number of novice users, with a diversity of backgrounds, used a robot arm to push blocks into a hole by using these two response models.

Further analyses on evaluating the user performance on the interfaces with two response models were found to be well fitted by a *Weibull* distribution. Operators preferred the interface with the Queue response model over the interface with the Adaptation response model, and human supervisory control over direct/manual control.

It is expected that the increased sophistication of control commands in a production system will usually be greater than those that were tested in this thesis, where limited time was available for automation development. Where that is the case the increases in human

productivity using human supervisory control found in this experiment can be expected to be greater.

The research conducted here has shown that mixed reality in gaming environments, when combined with human supervisory control, offers a good route for overcoming limitations in current telerobotics technology. Practical applications would benefit by the application of these methods, making it possible for the operator to have the necessary information available in a convenient and non-distracting form, considerably improving productivity.

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Chapter 1

Introduction

1.1 Telerobotics

1.1.1 What is Telerobotics?

The term telerobotics consists of two words “tele” and “robotics”, and refers to a branch of technology that utilises a computer system for control, sensor feedback and the processing of information from a robot at a distance. There are several definitions of telerobotics used by different researchers [1-3]. In general, telerobotics is defined as an interaction between the human operator and the remote machine. Figure 1.1 shows the general architecture of telerobotics.

Figure 1.1: General telerobotics architecture. In the local area, the operator generates commands, performs manipulation and receives feedback from the system interface; while the remote machine performs the command, sends feedback and has some level of autonomy.

Using internet connection, telerobotics is widely used in many areas, such as mining, space and medical areas [1, 4, 5]. The technology has been applied in various applications such as from navigation systems [6-9], underwater telerobot [10, 11] and tele-surgery [12].

The advantages of using telerobotics technology are being able to allow the operator to interact with an uncertain or dangerous environment; to reduce operating costs; and to increase human comfort in operating a machine. Moreover, this technology allows the operator to perform a range of undefined tasks from a remote location [13]. However, telerobotics systems can face several problems. These problems can significantly degrade the effectiveness of control and could lead to safety issues. These problems are: Firstly, human operator cognitive fatigue [14], which is caused by telerobots that force the operator to be focused on the screen at all times. Secondly, in real-time control interactions, latency affects the efficacy of telemanipulation under manual control [15, 16]. In direct/manual control, the operator continually controls the robot movement. Delay in the response from the telerobot can cause the operator to overcorrect for errors that are different from the actual robot errors. This causes the robot to move in ways unexpected by the operator and the operator to provide further corrections, which again do not reflect the errors at the robot. Errors tend to grow and this is often referred to as instability. With some forms of feedback e.g. force feedback it is impossible for the operator to avoid instability when the delay is too great. With other forms of feedback, and where the situation at the robot is not varying much, an operator can sometimes avoid instability by making a series of movements, then stopping and waiting longer than the delay period to observe the result before repeating the process. Thirdly, incomplete information from the remote location. According to a number of researchers [3, 6, 10, 13], providing complete information about the remote location into a single interface is a major challenge in telerobotic scenarios. For example, a limited range of vision from a remote video camera cannot replace operator eyes that are able to explore the remote environment directly and which can be moved to a different view point if required. This missing information can lead to degradation in operator performance. The fourth issue is having unfriendly user interfaces. Interfaces sometimes can be difficult to use which can be caused by using too many graphical components (e.g., buttons, sliders or graphics) to control the telerobot or non-intuitive graphical representations and controls [28, 33]. This can make the operation unnecessarily complicated.

Currently, the *Line-of-sight* remote control is a form of telerobotics technology, which is widely used in mining and other industries [6]. This technology has been proven to be effective in protecting the operator from hazards, for example the underground *Load-Haul-Dump (LHD)* vehicle operating in a location where the roof is unsupported and there is occasioned rock falls. Nonetheless, the operator still needs direct vision to control the machine, which may compromise the safety of the operator. According to Fong and Thrope [1], there are three characteristics which distinguish the term telerobotics from the remote control (*Line-of-sight* remote control). As the impact of the different location between operator and remote machine, compare to remote control, telerobotics requires: Firstly, a more reliable navigation system; Secondly, more efficient motion commands; and Thirdly, better remote sensors to provide the information that is needed by the operator.

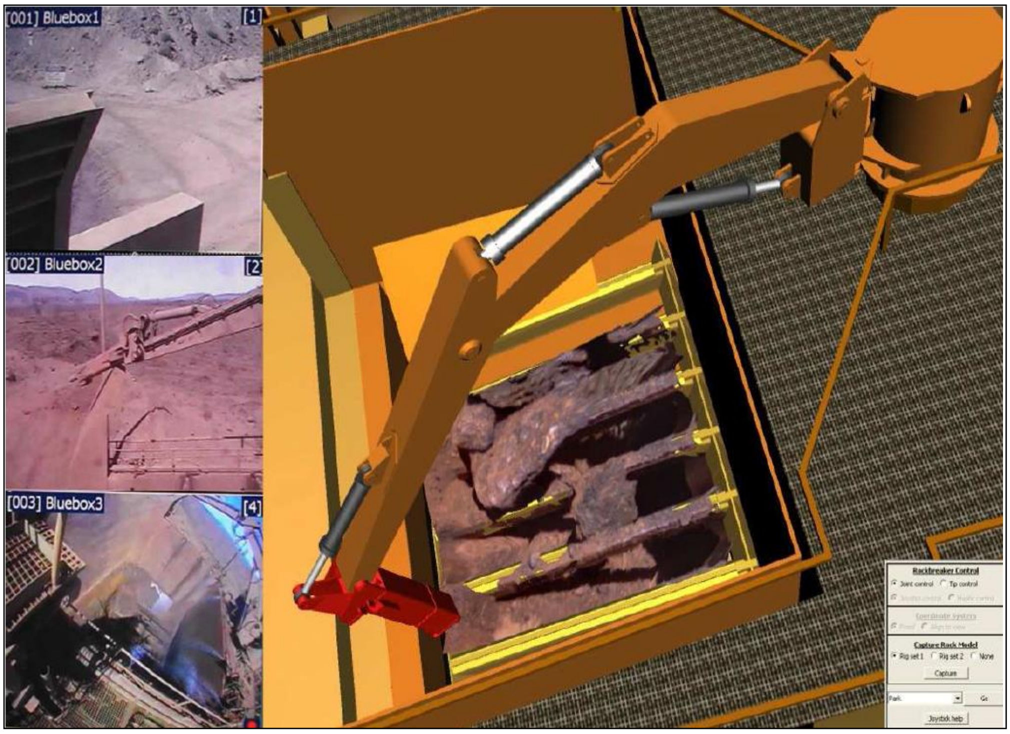
1.1.2 Type of Telerobotics

According to Fong et al. [17], telerobotics can be categorised into vehicle telerobotics and telemanipulation. The general difference between these two categories relates to the function of the remote machine. Vehicle telerobotics can explore areas that are difficult for humans to reach; for telemanipulation, however, the remote machine typically performs its tasks in one static position. Many telerobotics systems are built using a combination of these two categories, depending on their purpose and task.

A vehicle telerobotic is widely used to explore an area or space when it is hard or dangerous for a human to reach yet still requires human intelligence [18]. Research conducted by Monferer and Bonyuet [11] is one of many examples of vehicle telerobotics. Their research investigated cooperative control for underwater telerobotics also known as *'GARBI' (underwater robot).* Utilising a virtual reality (VR) interface, Monferer and Bonyuet tested the possibility of sharing information and collaborating in the underwater environment with two users. Lin and Kuo [10] conducted a similar experiment which investigated pilot training for underwater telerobotics using a VR environment.

For telemanipulation applications, research as reported by Duff et al [5] shows the telemanipulation of a large *Rockbreaker* robot (Figure 1.2) in iron ore mining. They built a telerobotics system for a large *Rockbreaker* that was located over 1,000 km from the operator.

Figure 1.2: *Rockbreaker* robot arm from [5]



● Joint control ○ Tip control

● Rig set 1 ○ Rig set 2 ○ None

Park

Figure 1.3: TUI (Telerobotics User Interfaces) for telerobotics *Rockbreaker* from [5]

In their research, Duff'et al's telerobotics user interface (Figure 1.3) consisted of three live videos and a 3D model of the robot arm *Rockbreaker* in a single display. The three live videos showed different viewpoints from remote cameras. Two cameras showed information on the bin and the arm's position from different angles. The third camera provided information on the view from the front of the bin, where the truck loads the rocks into the bin.

As indicated by Duff et al's research [5], when the operator is collocated with the machine, the operator can concentrate on the task and simultaneously manage other duties. On the contrary, when the operator was in a remote location, their attention was divided across monitoring numerous custom built interfaces, hence potentially reducing operator performance. Hainsworth [6] identified a related problem. He argued that implementing direct/manual operator control using multiple screens for telerobotic interfaces has ergonomic disadvantages (see Figure 1.4), whereby the operator is forced to continuously focus on the screen in order to identify the position of the desired control and the degree of control input being applied. When compounded by a high workload, this becomes exhausting and eventually leads to operator error.

Figure 1.4: Mining telerobotics user interface from [6]

1.1.3 Human Factor in Telerobotics

In building a good telerobotics system, it is essential to identify the operator’s requirements as part of a closed loop telerobotics model [19]. Given the range of applicability of telerobotics technology, the operator's needs and the interface characteristics can be vary for different scenarios.

Telerobot interfaces have two important functions, which are to communicate to the operator the status of executed tasks in the remote location and to accept commands from the operator in order to properly control the telerobot [19]. In order to reduce the ergonomic disadvantages, which were identified from research conducted by Duff et al. [5] and Hainsworth [6], a challenge in building telerobotic interfaces is to reduce ergonomic disadvantages by designing multi-modal or different human sense system interfaces. The challenge can be addressed by considering human perception capabilities to obtain improved interface interaction. For example: (1) by displaying information to represent the remote environment in a natural manner (telepresence), which implies a feeling of presence at the remote site and; (2) by providing multi modal interfaces such as haptic input devices . “A good degree of telepresence guarantees the feasibility of the required manipulation task”[19].

Telerobotic scenarios, such as task manipulation in mining operations, require operator to be aware of the situation at a remote location [5]. A limited multi-modal system can display an incorrect target object (e.g., rocks), resulting in delay of the manipulation process, which can endanger the telerobot and lead to interruption of the entire production process. As with telerobotics used in space [21] or forestry operations [22], inaccurate or missing information about the remote environment can put the operation at risk; it can trigger a situation that damages the environment, including the telerobot. Besides sufficient information of the remote environment, the operator needs feedback on the congruence between the commands given and the telerobot's execution of those commands. Aracil [19] describes a situation where incorrect visual adjustments between commands and the observed motion of the telerobot existed (shown in Fig. 1.5). In this instance, the incorrect adjustments resulted from kinematic transformation and the relative movements between object and camera resulting in incoherence in the visual reference, giving the operator a false perception of the actual remote conditions. Using techniques such as information redundancy, and providing stimulus fidelity of the information is essential for providing the operator with an accurate perception of the remote environment [19].

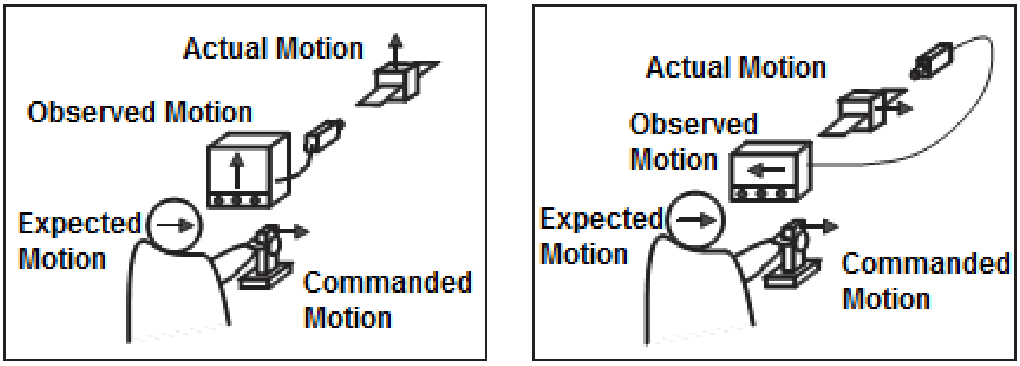


Figure 1.5: An example of incorrect visual adjustment due to kinematic transformation (left) or relative movements (right) from [19]

The role of the human operator is an important consideration in developing telerobotics technology Sheridan’s [2] and Verna’s [23] closed loop models for the telerobotics system demonstrate that the human operator is an integral part of telerobotics systems - regardless of the specific telerobotic scenario, the human operator affects the system effectiveness. Hence, any study of the effectiveness of such systems requires experiments that involve a human operator.

Steinfeld et al. [24] identified a common metrics of human-robot interaction for telerobotic applications. Even though it is not feasible to identify a metric to accommodate all human-robot applications, common methods of subjective rating scales (e.g., the *Likert* scale) can be used to identify telerobot performance based on operator perspective.

1.1.4 Technology of Telerobotics

Direct/manual control is the most common type of control method for telerobotics [1, 6 , 39, 60]. In this control model, the operator controls a remote machine directly using a hand-controller, specifies the speed and direction of movement, and monitors and adjusts the controls continually. A number of studies have attempted to improve this direct/manual model control through adding multiple modalities, including haptic [25, 26] and other input devices [27]. In a situation where communications are substantially delayed, relative to the speed of movement, the resulting instability requires that the system be able to run independently—requiring little input from the human operator. HSC [2] addresses this issue, increasing productivity and making it easier for the operator to perform tasks. HSC allows the operator to specify tasks for an intelligent system without continuous operator involvement. This also reduces operator workload.

In terms of further development of telerobotics, previous research has been undertaken related to gaming environments with telerobotics systems. Wang et al [28] used a virtual tournament computer game as a USAR (Urban Search and Rescue) facility simulation for simple telerobotics. They built a simulated telerobot in a gaming environment and controlled it from their custom built interface as a telerobotics scenario (see Figure 1.6). Furthermore, Ponto et al [29] introduced a mixed reality (MR) environment called '*Virtual Bounds'* that utilised a combination of physical and computer-generated objects for the simulation of a remote control environment (see Figure 1.7). Based on their case study, they mentioned that the pervasive nature of computer games and interface technology are well suited as a MR test bed, and the exposure (previous experience) of users allow for a natural and intuitive transition of skills in their application in telerobotics. Other MR projects have used remote control vehicles for gaming purposes [30, 31]. These systems have a control structure similar to the *'Virtual Bounds*' application.

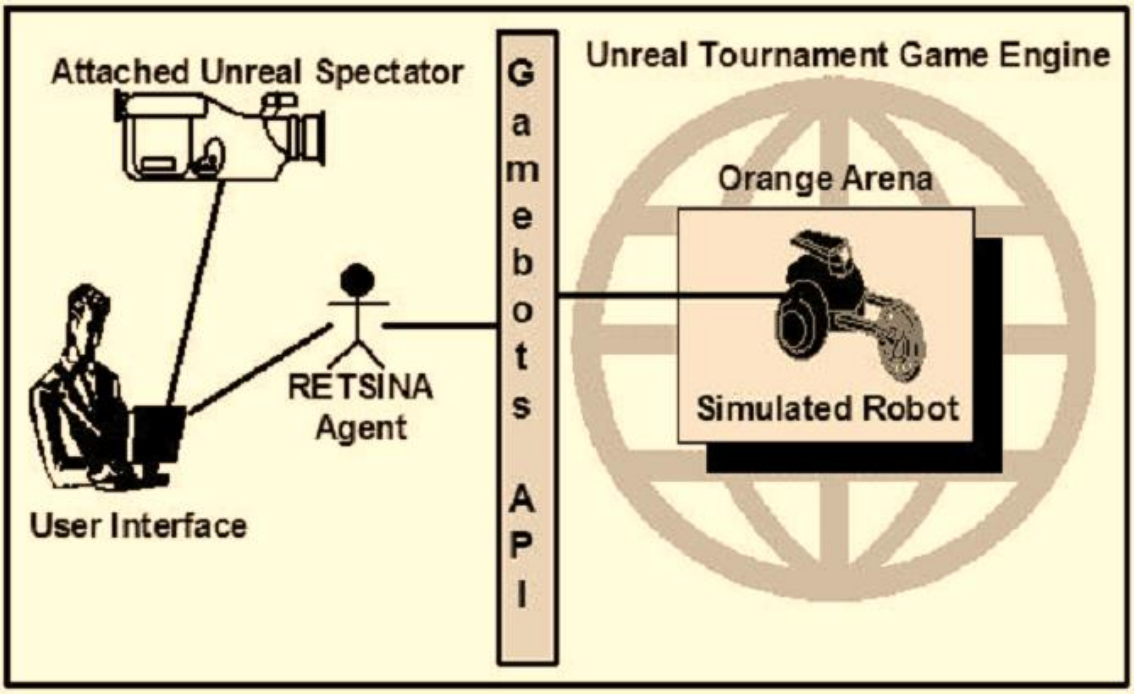


Figure 1.6: Architecture of USAR system application which was utilising a gaming engine as simulation telerobot [28]

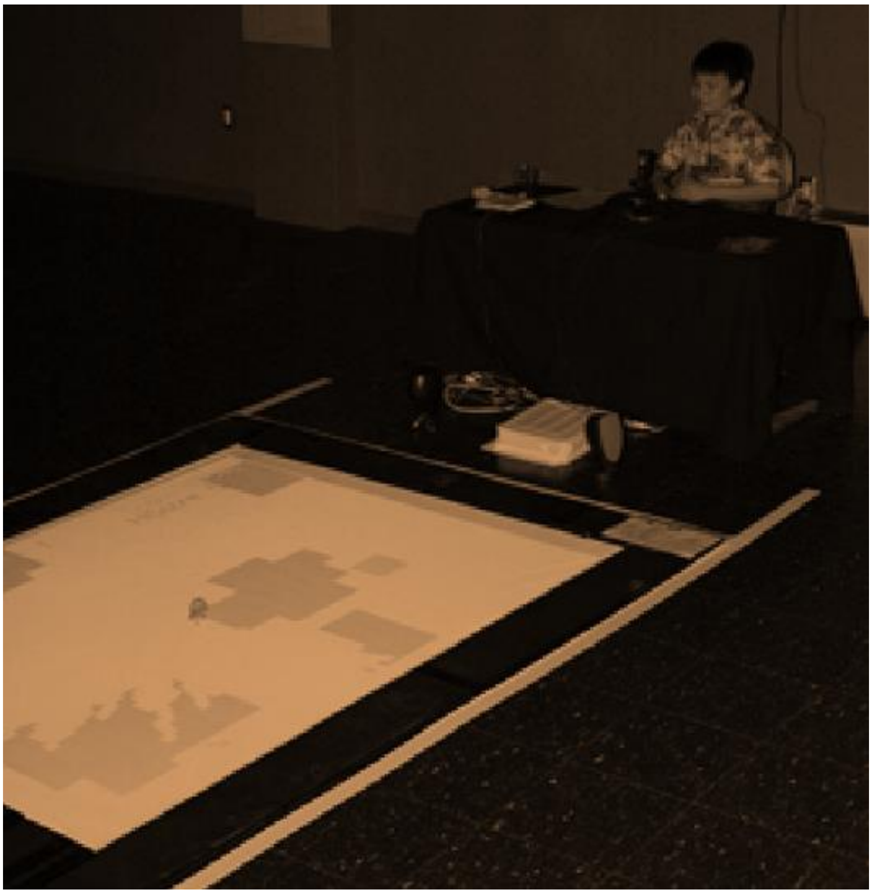


Figure 1.7: Mixed reality test bed environment in *'Virtual Bounds'* application interface [29]

A review of existing literature indicates that advances in the gaming environment may allow it to be utilised as a telerobotic interface. Moreover, virtual gaming provides a sophisticated setting to build and define a 3D model. It can also be used to communicate information within the virtual world or between virtual and real world applications (e.g. client-server communication). Virtual gaming is usually designed to be easy to operate (user friendly). By utilising the multiplayer functions, a virtual gaming environment, which is played online through the internet, can possibly be utilised for collaborative control of telerobotics systems. However, there are some differences between a telerobotic interface and a virtual gaming environment. Firstly, virtual gaming has task scenarios without any consequences if the user fails to accomplish the task. While in telerobotics, a failure in task accomplishment would not be acceptable as it has real-life consequences. Secondly, in providing incomplete simulated information, gaming visualisations are already video simulations, and telerobotic interfaces can be equipped with video.

Regardless of the advances in virtual gaming environments, it is difficult to provide real-time complete information of remote situations. This occurs because of inadequate sensing that leads to inaccurate and incomplete models of the remote environment sensor cannot provide the information due to frequently changing conditions in many mining. A simulation is easier because the robot situation is precisely understood by the operator interface. In a real system there is only limited knowledge of the external system state.

To overcome these shortcomings, I propose building telerobotic interfaces using gaming environments with a concept of mixed-reality (MR) environment and the principle of human-supervisory-control (HSC). Both MR and HSC have been utilised in many applications [32]. However, applying these two concepts into a gaming environment for the telerobotics scenario is not common, since gaming and telerobotic interface are seen as different domains. This thesis explores the features of the gaming environments, which are useful in applying MR and HSC, to improve the system and overcome the existing limitations from the current telerobotics scenario. Further exploration on MR and HSC concepts in gaming environments are discussed through the conducted experiments in the following chapters.

1.2 Research Topic

The thesis evaluates gaming environments for mixed reality (MR) interface and human supervisory control (HSC) in telerobotics.

The research project goals are to improve telerobotics interfaces for manipulation scenarios, and apply an alternative remote interface with current immersive technologies, normally used for gaming.

The research project aims to develop an application prototype for telerobotics in remote mining equipment scenarios by utilising the features of gaming environments. This project investigates MR interfaces and the use of HSC concepts for the control model, and conducts usability testing to determine the effectiveness of the scenario based on operator satisfaction.

This research is associated with the “Future Mining” theme under the CSIRO Minerals Down Under (MDU) Flagship, with supervision by Dr. Ken Taylor (ICT Centre, CSIRO), Prof. Tom Gedeon (Research School of Computer Science, ANU) and Assoc. Prof. Henry Gardner (Head School of Computer Science, ANU).

1.3 Research Outcomes

The major outcome of this research is to improve user interfaces for telerobotics designs, particularly in telemanipulation for mining scenarios. The key components of the potential outcomes are listed below:

1. Enhanced knowledge of the features of gaming environments for telerobotics user interfaces, including assessing its feasibility and evaluating its performance.
2. Prototype telerobotic system interface:
   - Applying telerobotics user interfaces that integrate real world sensor information from remote locations (e.g. cameras) into a model in a virtual environment (which can be called a MR environment) providing sophisticated information on a single screen for the operator.
   - Applying the principle of HSC in the design of telerobotic user interfaces improves the autonomy of the remote machine and allows it to adapt to dynamic environments. This method also enables the operator to monitor and interrupt the process when needed.

1.4 Contributions

Contributions from this research are:

1. Exploring a number of virtual gaming environments that may be used as telerobotic interfaces, especially for telemanipulation in mining. This includes:
   - Identification of virtual reality interface (gaming environments) components and functionalities that are necessary and useful for telerobotics and those that are not.

  - Evaluation of user satisfactions and preferences regarding the ideal source of information and the required feature set from the gaming engine for telerobotic interfaces.
2. Evaluating user performance in using gaming environment with the principle of human supervisory control (HSC) and mixed reality (MR) for telerobotic interfaces.
3. Applying HSC and MR concepts to telerobotic interfaces in a gaming environment addresses a number of issues raised by Duff et al [5] and Hainsworth [6], including:
   - Regardless of the different types of input devices, determining whether the use of multiple information displays increases operator cognitive fatigue, which affects their attention to the interface and reduces performance.
   - Improving effectiveness and user friendliness of the telerobotic interface.
   - Reducing safety concerns and implicitly decreasing the effect of latency.

The next section presents the research design as guidance for my research direction and limitation.

1.5 Research Design

In this research, investigating gaming environments for MR interface and HSC concepts for telerobotic interfaces is proposed.

Gaming environments have been utilised by a number of previous studies such as: (1) Richer and Drury [33] which successful classify a video gaming based framework for human machine interaction. They grouped video gaming users’ interaction using this framework which could potentially be used for human machine interaction design. (2) Bourke [34] who mentioned a gaming technology is advanced as it provides a sophisticated environment for creating 3D models or programming, and (3) Chung[25] and Schou [35, 36] that demonstrated virtual gaming environments to provide an immersive environment. Based on these previous studies, I proposed to utilise a gaming environment for telerobotic interfaces.

A number of virtual gaming environments, such as Unity3D and Second Life (see Figure 1.8) can be used as a basic environment for building telerobotic interfaces. For future development, the multiplayer function provided by virtual gaming environments can be utilised for collaborative telerobotics control. Collaborative control can be defined as the collaboration of humans and semi-autonomous systems to perform a task and achieve a goal. This is described in research conducted by Fong on multi-robot remote driving [37, 38] and that conducted by Monferrer [11] on cooperation among operators in controlling telerobots.

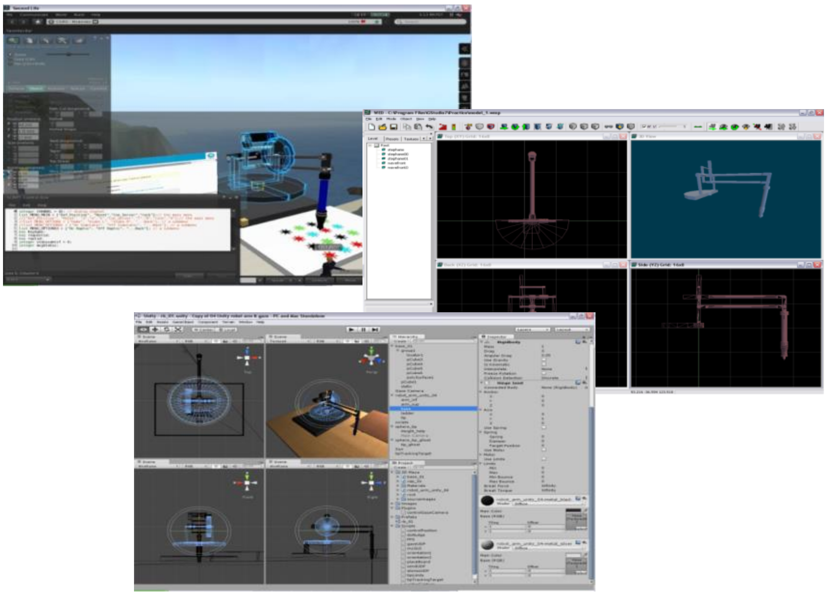


Figure 1.8: Second Life viewer, Unity3D editor, and 3D gaming editor

As part of the research design, in the following sub-sections, I present a methodology and research framework to explain the direction and limitations of my research area. In order to achieve the objectives of this research, I also describe a number of model analyses and research stages, including time frames for overall research experiments.

1.5.1 Methodology

The research aims to identify the generic properties common to gaming environments that are advantageous for telerobotics experiments and methods for effectively incorporating MR and HSC into gaming environments. This is investigated through a series of experiments.

The series of experiments assessed the concept of MR interface, and the principle of HSC, for low level telemanipulation based on a mining scenario. At the initial stage of this research, the gaming environments are explored as the basic platform to build a telerobotics user interface, followed by application of the proposed telerobotic model.

1.5.2 Research Framework, Variable and Instrument

A framework was designed to describe the area of this research. The research variables were categorised into two groups (discussed in more detail in the research variable sub-section), followed by a general description of all the research instruments used in this research.

1.5.2.1 Research Framework

The research commenced with the exploration of the gaming environment. Then, it was followed by the utilisation and investigation of the MR concept and the principle of HSC to improve human machine interfaces in a telerobotics mining scenario.

The main environment in this research is a gaming environment modified for telerobotic interfaces. The user was provided with information on the remote location through this environment. Communication between the user and the remote machine was tested and recorded. Performance variables and the times needed for accomplishing the experimental tasks were recorded, with user preferences and feedback captured in a questionnaire.

I began the research with a review of existing literature and those applications that utilised MR or HSC in the telerobotics area. A number of gaming environments were investigated to assess the feasibility of using their technologies to communicate with a number of remote machines/servers. Then, four experiments were conducted to evaluate the user performance on the proposed telerobotic interfaces. These four experiments are further discussed in the following paragraphs.

The first experiment primarily covered an exploration of the number of gaming environments. Features of gaming environments were also evaluated to encompass more detail about the effectiveness of using MR concepts for telerobotic interfaces. Since all of the information was presented on a single display, it suggested that the operators might have more or less focused into a telerobotic interface. Hence, there is an attempt to evaluate operator performance based on their level of attention in using mixed information in a single display interface.

Based on the first experimental result, it was possible to improve the MR environment by applying additional sensing to detect the block position and provide an additional 3D model of the block. Hence, the second experiment covered an evaluation of user performance in gaming environments with this additional sensing. Here, the gaming environment was also tested with additional input devices, gamepad and eye-tracking, for virtual camera control.

The third experiment encompassed an evaluation of gaming environments for human supervisory control (HSC). In this experiment, a number of features from the gaming environment were utilised. These features included the concept of the first person viewpoint for camera control, a path finding algorithm, and additional virtual information such as planning and feedback. These features were tested using two response models, the Queue and the Adaptation response models, as a method of dealing with multiple commands in HSC. A gaming feature, such as predictive display for the planning process, was also used in this experiment. Hence, a sub experiment of direct/manual control was also performed to compare operator performance.

In the fourth experiment, I tested the gaming environment using random participants from a variety of backgrounds. This gaming environment was located in an exhibition for period of three months. This gaming environment successfully recorded the variables ‘commands’ and ‘usage time’ of the participants. This experiment described general operator behaviour and satisfaction of the developed telerobotic system interfaces. I presented a distribution analysis to describe the trend of user performance in this experiment. The design of the research framework can be seen in Figure 1.9, and a description of each stage of the research can be seen in Figure 1.10.

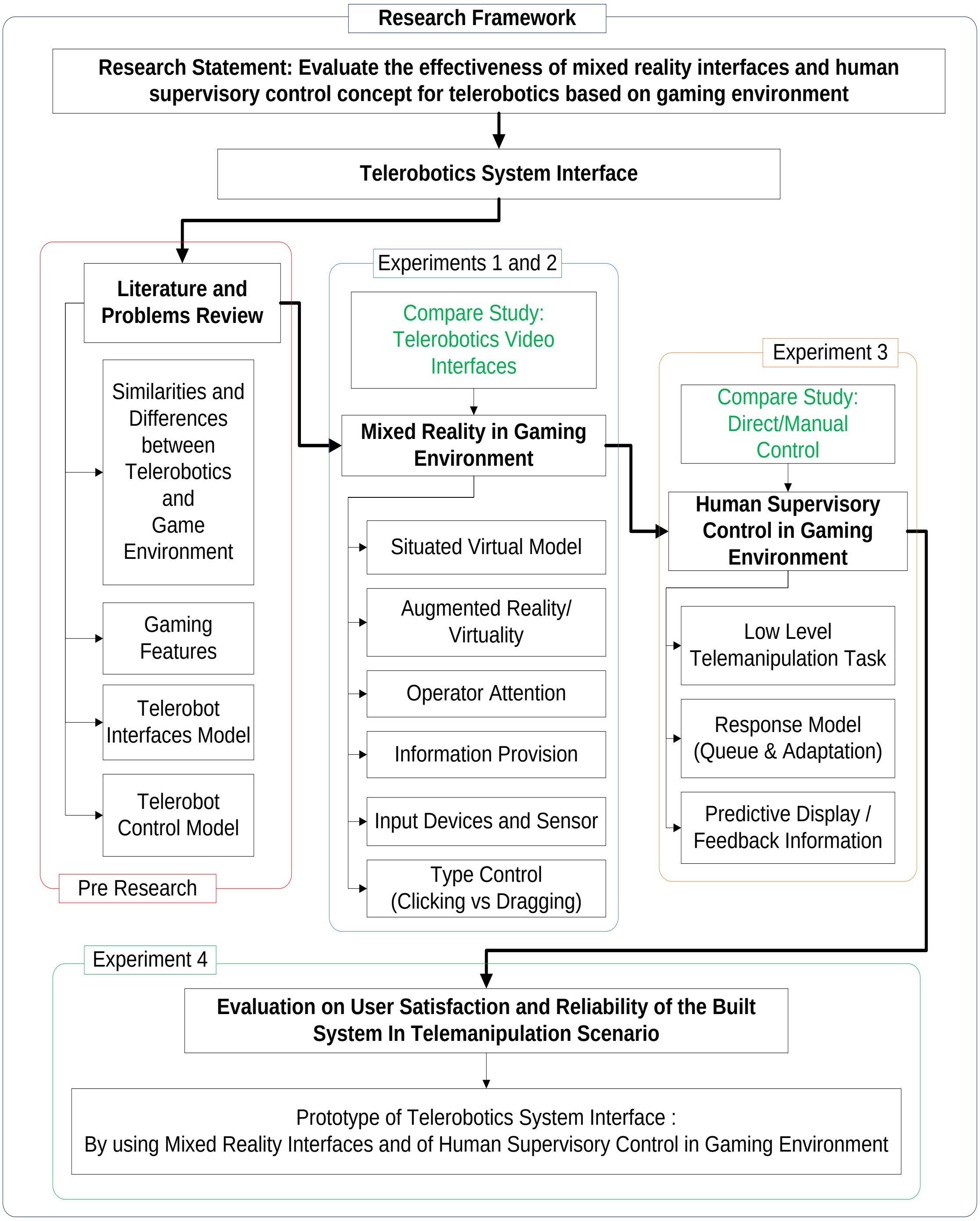


Figure 1.9: Research framework

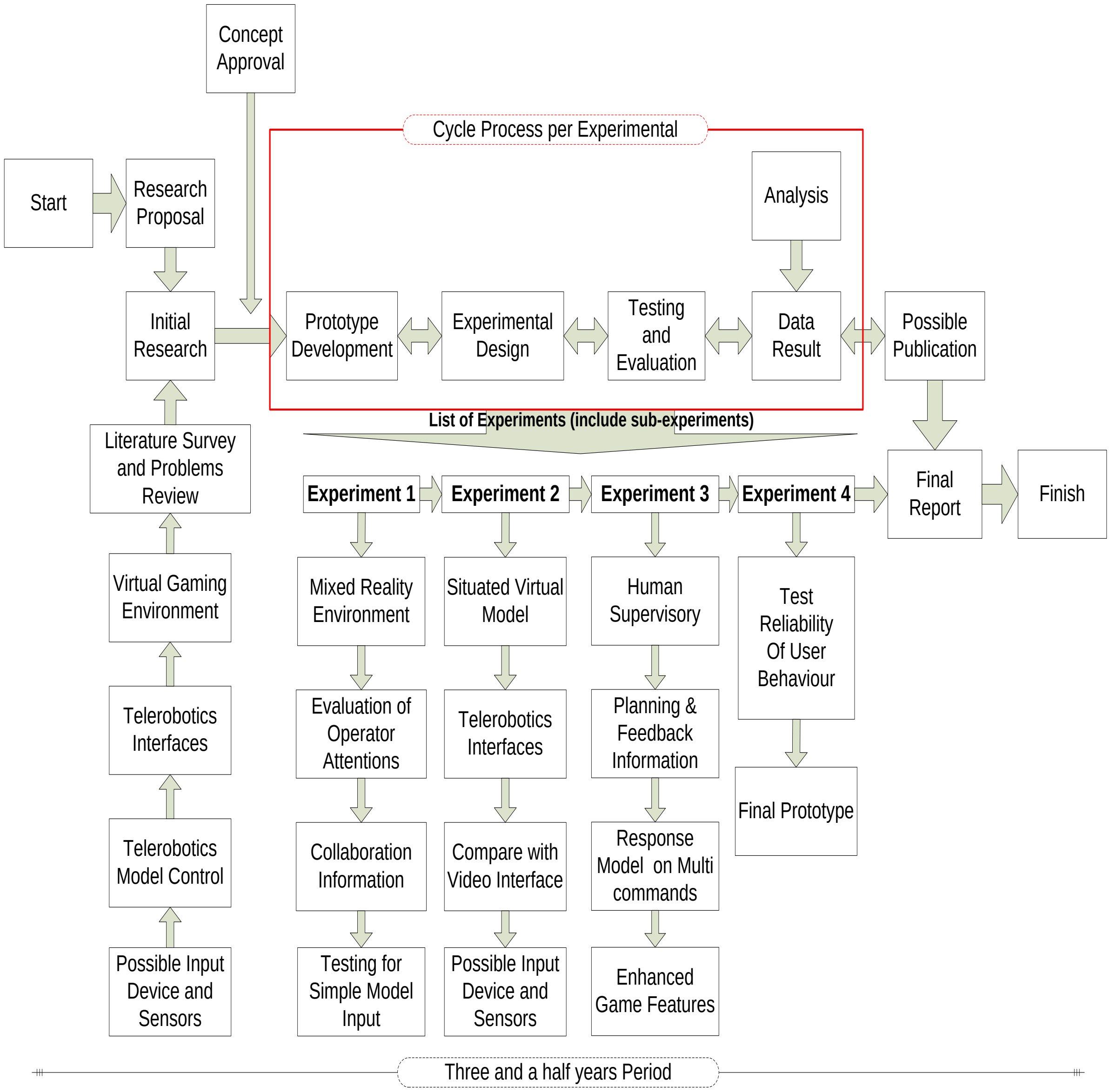


Figure 1.10: Stage of research

1.5.2.2 Research Indicators

During the experiments, information was collected through two main indicators: user performance and preference. These two indicators were analysed based on the interaction between the participant/user and the remote machine through the developed interface and are detailed in point ‘a’ and ‘b’ below:

a. User Performance Indicators

In each experiment, a number of design scenarios were tested. Most scenarios involved the manipulation of a remote machine. I defined a number of variables as user performance indicators such as success rate variables and the time taken to perform each test. A total number of requests to the telerobot were also recorded as an additional performance indicator for further analysis.

b. User Preference Indicators

After conducting the experiment, each participant was asked to complete a questionnaire using the *Likert-scale* model and ranked their model preference, while other questions were open-ended. Some participants were also asked to undergo an informal interview to provide further detail on the user prototype interaction performance.

In general, data collected in the questionnaire included a number of components: (1) personal information such as: name, age, educational background, and also how long they usually spend using computers and using computer games; and any prior knowledge of the prototype tested; (2) the performance of each model tested, and the effectiveness of the system in helping them to perform the given task. For comparison purposes, participants were also asked which model they thought was the best; and (3) feedback on the system prototype and suggestions to improve the system.

In this research, I conducted all the experiments by using participants with general background, and not directly by the user with specific knowledge (e.g. mining operator). Besides the limited access to test the application prototype with real mining devices and operator, I assumed using general participants in this research were able to produce conception about the gaming environment is reliable and capable to be used for telerobot interfaces.

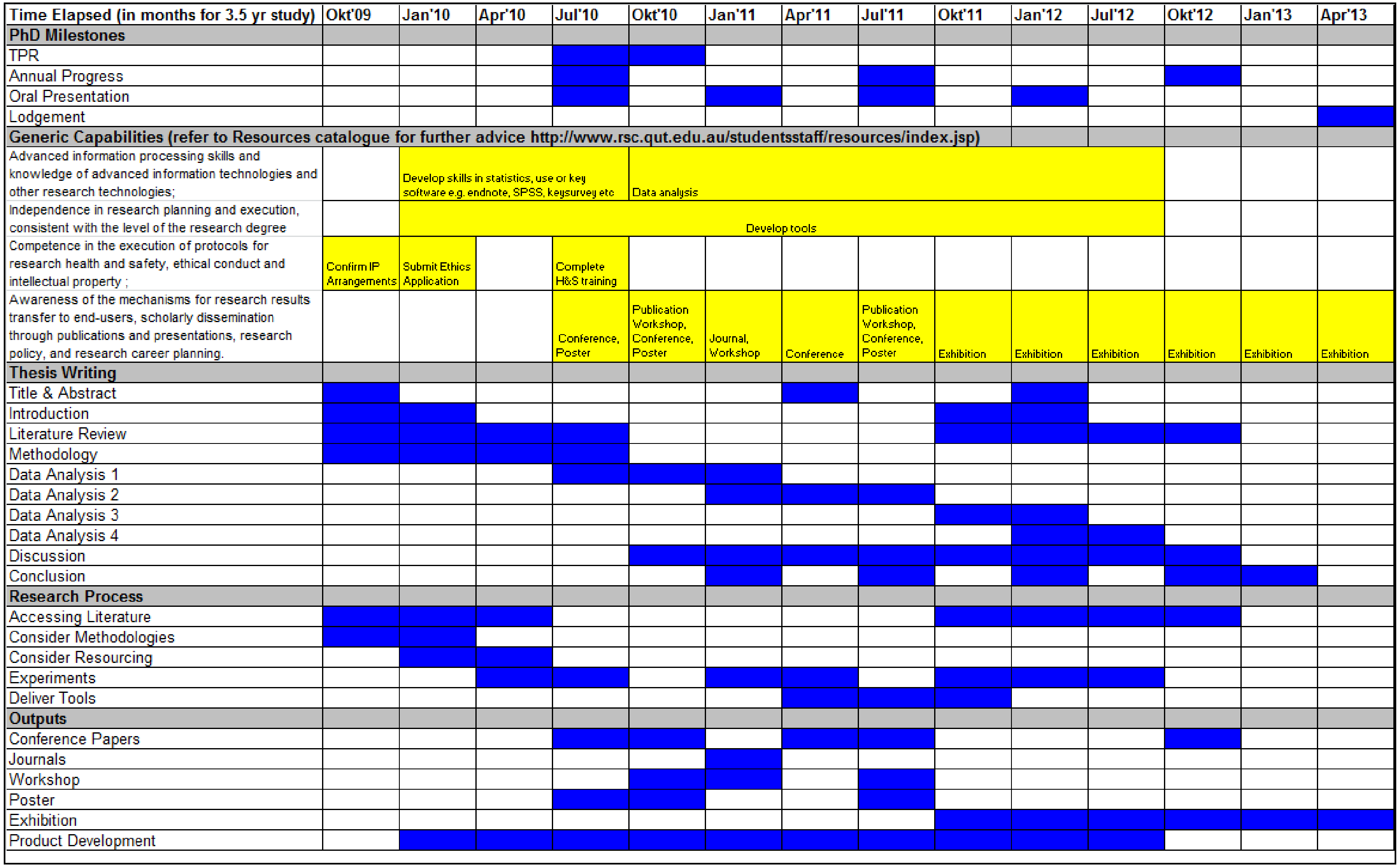
1.5.3 Model Analysis.

In this study, the data obtained were analysed by using a number of statistical tests (e.g. analysis of variance, *Chi-squared goodness fit test* and *Logistic Regression*) and; further analysed using the F_1*-score* and *Weibull* distribution. I have presented the descriptive data in accordance with observations in the field, which include:

- Investigation of the gaming engine
- Testing of operator performance in a MR environment
- Testing of multi command control with the principle of supervisory control
- Analysis of user performance using the *Weibull* distribution.

1.5.4 Timeline and Places

The design and development of the prototype for this research took place in the Immersive Laboratory CSIRO ICT Centre in the CSIT Building at ANU. A number of remote connections were available in Sydney, Brisbane, and Perth, and the prototype design was also tested publicly at the CSIRO Discovery Centre. The study was conducted between October 2009 and April 2013. The specific timeline's activities for this project are shown in Figure 1.11.



Time Elapsed (in months for 3.5 yr study)	Okt'09	Jan'10	Apr'10	Jul'10	Okt'10	Jan'11	Apr'11	Jul'11	Okt'11	Jan'12	Jul'12	Okt'12	Jan'13	Apr'13
PhD Milestones														
TPR				■	■									
Annual Progress				■				■				■		
Oral Presentation				■		■		■		■				
Lodgement														■
Generic Capabilities (refer to Resources catalogue for further advice http://www.rsc.qut.edu.au/studentsstaff/resources/index.jsp)														
Advanced information processing skills and knowledge of advanced information technologies and other research technologies;		Develop skills in statistics, use or key software e.g. endnote, SPSS, keysurvey etc			Data analysis									
Independence in research planning and execution, consistent with the level of the research degree		Develop tools												
Competence in the execution of protocols for research health and safety, ethical conduct and intellectual property ;	Confirm IP Arrangements	Submit Ethics Application		Complete H&S training										
Awareness of the mechanisms for research results transfer to end-users, scholarly dissemination through publications and presentations, research policy, and research career planning.				Conference, Poster	Publication Workshop, Conference, Poster	Journal, Workshop	Conference	Publication Workshop, Conference, Poster	Exhibition	Exhibition	Exhibition	Exhibition	Exhibition	Exhibition
Thesis Writing														
Title & Abstract	■						■			■				
Introduction	■	■							■	■				
Literature Review	■	■	■	■					■	■	■	■		
Methodology	■	■	■	■										
Data Analysis 1				■	■	■								
Data Analysis 2						■	■	■						
Data Analysis 3									■	■				
Data Analysis 4										■	■			
Discussion					■	■	■	■	■	■	■	■		
Conclusion						■		■		■		■	■	
Research Process														
Accessing Literature	■	■	■						■	■	■	■		
Consider Methodologies	■	■												
Consider Resourcing		■	■											
Experiments			■	■		■	■		■	■	■			
Deliver Tools							■	■	■					
Outputs														
Conference Papers				■	■		■	■				■		
Journals						■								
Workshop					■	■		■						
Poster				■	■			■						
Exhibition									■	■	■	■	■	■
Product Development		■	■	■	■	■	■	■	■	■	■			

Figure 1.11: Timeline

1.6 Organisation of the Dissertation

This thesis was completed as part of a collaborative project between the Information Human Centred Computing (iHcc) Group in the Research School of Computer Science (RSCS) at the Australian National University and the Information Communication Technologies (ICT) Centre at the Commonwealth Scientific and Industrial Research Organisation (CSIRO), with funding provided from the Minerals Down Under (MDU) National Research Flagship.

This thesis consists of seven chapters: an introduction, a background on telerobotics and related work that has been undertaken in this field; four chapters on the designed prototype, user studies, evaluation, discussion, and a summary of the entire work in the conclusion. The remainder of this dissertation is organised as follows:

Chapter 2 presents the literature review regarding the concepts of telerobotics systems, interface design (e.g. the possibility of utilising the gaming environment for telerobotics user interfaces) and control model (e.g. the possibility of improving the control model from one that was based on direct/manual control to one that is based on HSC), including introducing related research. This review also describes the MR environment, including types of current telerobotic interfaces, and HSC - including the spectrum of current telerobotic control models. At the end of this chapter, I demonstrate the communication implementation between a gaming environment and a number of telerobots or simulation telerobot as initial gaming features evaluation.

Chapters 3 to 6 provide descriptions of the whole evaluation and the experiments including sub-experiments that were conducted during the research. These chapters discuss the implemented prototype model for telerobotics systems MR and situated virtual model interfaces and the combination of manual and supervisory control models.

Chapter 3 discusses the utilisation of a MR interface, which combines information from streaming video and 3D generated computer visualisation, as telerobotics user interfaces. Based on previous work in Chapter 2, the MR concept is applied to a number of gaming environments. The experiment result was also analysed in relation to the operator’s level of attention to the telerobotic interfaces. This experiment is designed to compare the effectiveness of a MR telerobotic interface in providing suitable information to the operator, as an alternative to telerobotic user interface using streaming video or fully virtual interfaces.

Chapter 4 discusses a further evaluation of gaming engines in providing effective virtual modelling where the object is adapted to the physical setting. I demonstrate the usage of a scanner application in providing information of position and size of moving objects to build the 3D models. This chapter also shows the possibility of using the gaming environment to work with other potential input devices for virtual camera movements. This chapter evaluate the user performance of the improved model interfaces by closely adhering to the experimental settings of Zhu et al’s experiment [39].

Chapter 5 discusses the principle of HSC as a substitute for direct/manual control in telerobotics to improve automation and reduce the dependence of human operators on the system. The MR interfaces from the previous experiment in Chapter 4 are combined with the HSC concepts. Besides focusing on the planning process which is one of the five generic functions of HSC, the predictive and feedback information associated with the MR concept is also explored in more detail in this chapter. There are two proposed response models for HSC models which are tested. An experiment is designed to analyse the user performance of each response model interface, including a sub experiment for direct/manual control as a comparison study.

Chapter 6 provides an analysis using the *Weibull* distribution to evaluate the user performance of the latest prototype telerobotics user interface. This evaluation data was recorded from the implementation of the telerobotic system at a public exhibition held for a period of three months. In this chapter, a *Weibull* model is applied with three parameters to describe the observed sampling data from three model interfaces, including two interfaces for the HSC response model and one interface for the direct/manual model. Two statistical model approaches, the *Chi-square goodness fit test* and the *Coefficient of determination test*, are also used to test the suitability of fitting the *Weibull* curve to the observed data.

Chapter 7 presents a conclusion of the whole evaluation and a discussion of the proposed prototype telerobotics system. I determine the potential components/results from each chapter as the benefits of our prototype telerobotic interfaces, such as: (1) whether a gaming engine is able to be used as a basic environment for building telerobotic interfaces; (2) whether the MR concept succeeds in providing missing information by using a combination of streaming video and a situated VR environment; and (3) whether predictive display information, as a combination of MR and HSC concepts, succeeds in reducing operator involvement and decreases the effect of latency compared to direct/manual control. However, there are a number of shortcomings of the proposed prototype due to the limitations of research time which I describe in the suggestions and recommendations for potential further research, such as: (1) the possibility to test the telerobotics user interface by using a wide variety of telerobotic scenarios, including testing within a real telerobotic situation; (2) the possibility of utilising the multiuser function for collaboration work; and (3) the possibility to improve the machines intelligence; and (4) the possibility to evaluate other input devices and sensors.

Chapter 2

Gaming Environments for Telerobotics User Interface

This chapter presents the literature review related to my research topic, which evaluates the gaming environment for mixed reality (MR) and human supervisory control (HSC) concepts to improve telerobotics interfaces, especially in mining and related scenarios. This chapter consists of three main parts: gaming environment, interfaces and control models. Each group describes information and examples from related work that supports this research. At the end of this chapter, I discuss a preliminary research in testing a gaming environment to communicate with a number of remote applications.

2.1 Gaming Environment

2.1.1 Utilising Gaming Engines in Telerobotic Interfaces

In this research, gaming environments were selected due to its user friendly features. They serve as a powerful tool for applying MR and HSC, which are proposed to address the telerobotic interface problems discussed in the previous chapter. Moreover, gaming engines provide sophisticated and suitable environments for building and customising 3D computer-generated virtual objects, which can be used to replace conventional information displays, such as: texts, pictures and graphs. Most gaming engines also provide custom programming environments that can configure the actions and behaviour of virtual objects.

A virtual reality (VR) concept inside a gaming environment is suitable for simulating the actual environment and parameters needed locally. For telerobotic purposes, it works to reduce the bandwidth requirements and provide unlimited viewpoints of the remote location. In addition, according to Richer et al [33], successful gaming environments are able to offer users with required information and control capabilities in an engaging and enjoyable way. Richer et al [33] also mentioned that a gaming environment can bring new ideas to interface design, especially in the highly dynamic and multimedia world of robotic interfaces.

Telerobotic interfaces and gaming environments have been seen as unrelated, but I argue that they share many similarities making it possible for them, to be regarded as being in the same domain. This is supported by Gazzard [40] who stated that computer games and VR are developed using the same displays and technology. A video gaming based framework had also been introduced by Richer and Drury [33], who characterised video gaming components for human machine interaction design.

2.1.2 Type of Gaming Platforms

In this research, I explored three platforms of virtual environment which is can be categorised as a gaming engines for building a telerobotic interface. These three platforms are Second Life, Mycosm, and Unity3D. The details of each platform are explained in more detail below.

2.1.2.1 Second Life

The first virtual platform used in this research is Second Life (SL) [41-43]. White [43] defined Second Life as an Internet-based 3D world that emphasises creativity, socialising, collaboration, and self-government. Second Life is a 3D multiplayer virtual world and online gaming environment developed by Linden Labs [44, 45]. Since SL was introduced to the public in 2003, it has been played by millions of users around the world. SL has provided an environment with 3D artefact objects, buildings and social spaces where people can interact.

SL is also known as a modern gaming environment since it has distinguished environment compare to traditional gaming environment. Unlike traditional gaming, SL is not built to have specific goal to achieve or rule to play. SL provides a freedom to the player to set their own goal and the rule to play. Here, each player can explore and set SL environment according to their creativity since it is supported by sophisticated virtual environment to build and manipulated the virtual objects.

Figure 2.1: A Second Life client interface showing an avatar that is creating virtual objects; and the Second Life logo [46]

SL provides a programming language, the Linden Scripting Language (LSL) [42]. Similar to other programming languages, LSL consists of variables, library functions, constants, flow control, and one or more named states. As a state-event driven scripting language, the state contains a guide to behaviours based on events that occur when the program is in that state. When the system sends commands to the script, the script will check for compatible events, and is then able to change most aspects of the state of the object and communicate with other objects as well as an avatar (replication of user in SL). As soon as a script is added into an object, it will start to execute. As a multiuser gaming environment, SL has the ability to continue to run every action or behaviour inside the script embedded in an object even when the owner user/avatar is not logged in. In addition, any objects in the SL world can communicate with objects outside the virtual world through the Internet via email, XML-RPC and HTTP requests.

For my research purpose, I used SL viewer (SL client interfaces) as a telerobotics interface. The communication between the gaming interface and the telerobot is built through a third party server, in this case refers to the SL online server. Figure 2.1 shows the communication flow diagram among SL viewer as a telerobotic user interface, SL server as a third party server, and telerobot.

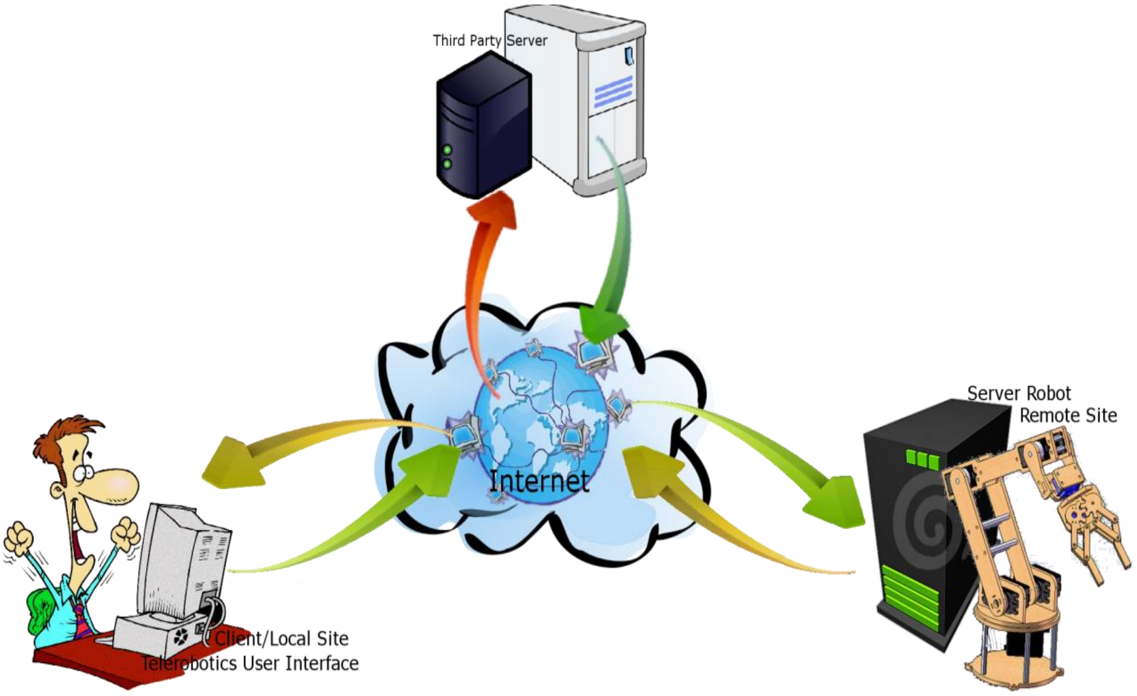


Figure 2.2: Communication flow diagram between telerobotics interface and telerobot through third party server

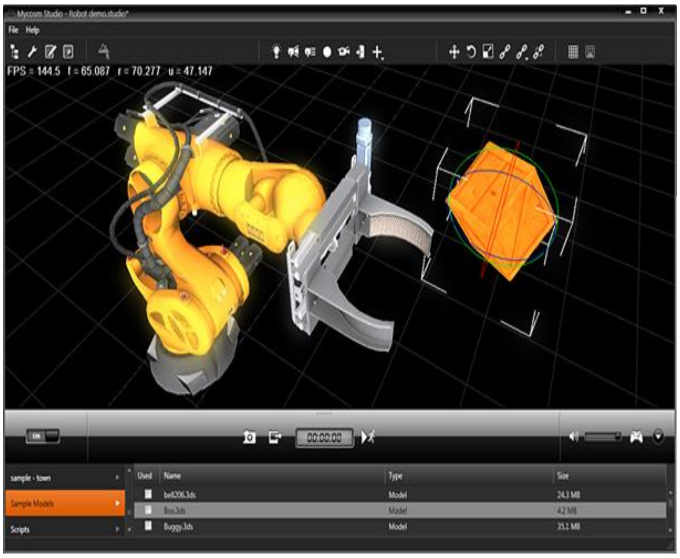
A number of advantages and disadvantages of using SL platform as telerobotic interfaces can are summarised in Table 2.1.

Table 2.1: The advantages and disadvantages of the SL platform

Advantages	Disadvantages
1. Easy access anywhere (by logging in to client games); 2. The client application can be run on most computer OS, such as Windows OS and Macintosh OS. 3. Easy to communicate with other people around the world through the use of avatars (multiuser functions default); 4. Administrative reason: less effort to maintain the network as the third party server will do it by default.	1. Reliability and availability issues: Although it requires less effort to maintain the network, there is no guarantee that the service will always be available when needed. However, many computer games have high availability and one way they achieve this is by distributed game servers, sometimes operated by multiple organisations (e.g. Beatle Field, Team Fortress 2 or Minecraft). This functionality is already built into gaming environments and can be used to make them more resilient to the failure of a single server than the telerobotic interface development tools I am aware of. 2. Security issues: e.g. distribution data and 3D objects can possibly be accessed by unauthorised users; 3. Possibility to have high network communication cost or low graphic quality since this environment can be freely accessed by multiple users; 4. Limited privilege to develop/to modify virtual object; 5. Requires an Internet connection for the development process (only online development); 6. Second Life (SL) has only limited communication protocols (only TCP/IP and XML-RPC). Since SL only allows limited access in modifying the configuration of communication protocol. This limitation cause impediment in terms of the setting of communication patterns (i.e., query response), data types, quality of service and prioritization, and others.

2.1.2.2 Mycosm

Mycosm is an real-time 3D visualization and simulation platform developed by Simmersion [47]. This platform is designed for a broad range of areas such as: education, engineering simulation, visualisation, decision support, gaming environment and more. Unlike other virtual reality software (e.g. WorldToolKit or VRML), Mycosm is supported by an IDE (Integrated Development Environment) besides the 3D development tools (Mycosm studio editor). Mycosm uses a client application which can distribute freely to be used to run 3D environment built from Mycosm studio editor. Mycosm environments also can be imported from, and exported to XML to allow interoperability with external applications, including dot NET application and databases. By using Phyton and C++ language as programming language, it offers powerful features to create 3D virtual environment and communicate it with other application which is suitable for telerobotics interface. The major weakness of this platform compare the others is that it is only able to run on Windows OS. An image of the Mycosm studio editor and logo are shown in Figure 2.3.



FPS = 144.5 f = 65.087 r = 70.277 u = 47.147

Used	Name	Type	Size
☐	bell206.3ds	Model	24.3 MB
☐	Box.3ds	Model	4.2 MB
☐	Buggy.3ds	Model	35.1 MB

mycosm®

Figure 2.3: Mycosm studio editor and logo [47]

2.1.2.3 Unity3D

Unity3D can be defined as a fully integrated development engine which provides sophisticated functionality to create games and other interactive 3D content [48]. Similar to the two previous virtual platforms, this environment is also supported by a sophisticated 3D model editor and programming languages (e.g. C# and JavaScript which is possible to be enhanced with other programing languages as a plug in). Unlike the other two platforms, Unity3D does not provide specific client application to be used. Otherwise, Unity3D-generated applications can be played on most computer operating systems (OS), such as Macintosh OS and Windows OS; on mobile operating systems, such as iOS and Android; and on a WEB browser. The Unity3D editor and logo are shown in Figure 2.4.

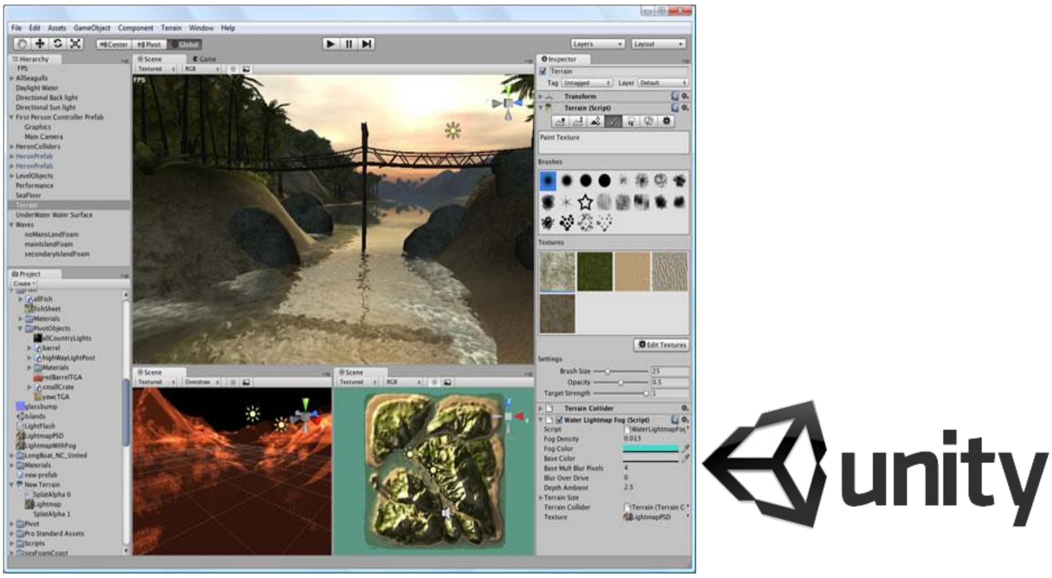


Figure 2.4: Unity3D editor and logo [48]

The **Unity3D** and **Mycosm** which are described in two subsubsection above can be referring as a '*similar platforms*' since the communication between the telerobotics user interface and the telerobot server is directly through the Internet without any third party server. Figure 2.5 shows the direct communication between the interface and the telerobot. These two platforms do not seem have fundamentally different than existing 3D simulation tools (e.g. Player-Stage-Gazebo, Actin, or Microsoft Robotics Developer Studio), but these two platforms are different from those 3D simulation tools since they provides an ultimate integrated package tool for creating gaming environment, especially for Unity3D which is claimed as the most powerful gaming engines platform[48]. This is the background why these two platforms are included in my research. A number of general advantages and disadvantages from these two platforms are summarised in Table 2.2.

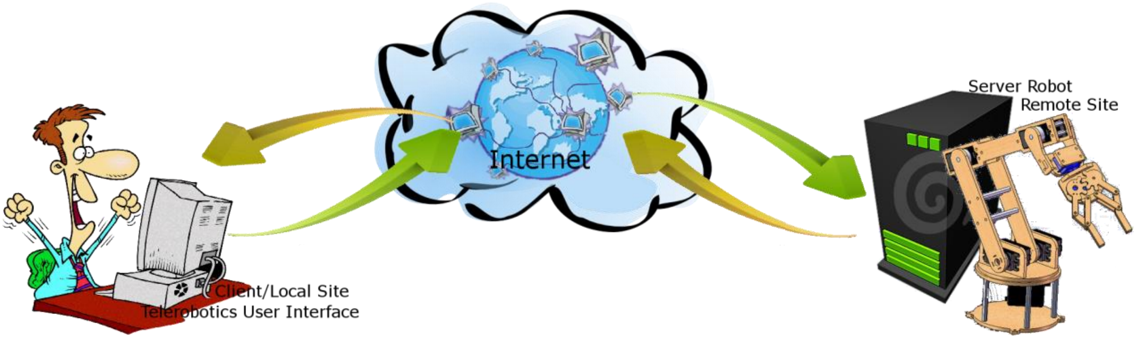


Figure 2.5: Direct communication flow diagram

Table 2.2: The advantages and disadvantages of locally-based gaming environments

Advantages	Disadvantages
1. Flexible access for offline development, including flexibility for interaction with several input devices; 2. Reliable in term of the availability of the services provided since full access to the system is allowed. 3. Customisable environment and easy to configure or update; 4. Unity3D and MyCosm support more communication protocols than the SL platform (i.e., UDP, TCP/IP and XML-RPC). These gaming platforms provide more flexibility in terms of communication patterns (i.e., query-response). Furthermore, flexibility access into the data properties can also make the customisation of data types and data prioritization easier.	1. Limited access for some debugging functions for free users; 2. Administrative issue: more effort required for maintenance of the network compared to an Internet-based gaming engine environment.

I delved deeper into the three platforms regarding to the features which are suitable for building telerobotics interface, especially in term of applying HSC and MR concept to improve the telerobotics system, and Table 2.3 shows the comparison of features among the three gaming platforms discussed in this thesis.

Table 2.3: Comparison of available gaming features suitable for telerobotic interfaces, taken from [34, 41, 43, 45-54]

Classification	Platforms		
	Second Life	Simmersion Mycosm	Unity3D
Type	telemanipulation, vehicle teleoperation		
Control	Supervisory Control		
		Direct Control	
Interface	Full Virtual Reality, Mixed Reality		
User	Single, multi user		
Input Device	Mouse + Keyboard, Joystick, Haptic		
Feedback	2D, 3D vision, force feedback, predictive display, shadow object		
Platform	Desktop application		
			web application, mobile application

Classification	**Platforms**		
	Second Life	**Simmersion Mycosm**	**Unity3D**
Media Transmission	Internet		
OS	Microsoft Windows, Unix, Mac OS	Microsoft Windows	Microsoft Windows, Mac OS. Multi OS for Web Based, iOS, Android OS
Others			
Access to environment	Free, limited	Paid	Free, limited profiling feature
Support Import model from industry-standard CAD applications	Yes .obj (less than 256 prim for 1 object), Sculpt prime texture	Yes .max, .fbx, .dae, .3ds, .dxf, .obj	Yes .3ds, .fbx, .vrml, .x3d, .obj.
Security (Login, Access to script)	Yes (Built in) Login, object and script privilege, property right	Yes (Manual) Login, compiling script	Yes (Manual) Login, compiling script
Communication	TCP, XML RPC		
		UDP	
Manipulating 3D	Yes (Built in) Drag n Drop	Yes Full script	Yes Drag n Drop
Scripting	Yes LSL (Linden Scripting Language), xml	Yes C++, embedded python, other plugins possible	Yes Java, C# embedded C++, python, other plugins possible
Server	Online	Offline, Online	Offline, Online
Multiuser	Yes (Builtin)	Possible (Manual)	Possible (Manual)
Chat & communication	Yes (Builtin)	Possible (Manual)	Possible (Manual)
Audio	Yes (Builtin)	Possible (Manual)	Possible (Manual)
Support inverse kinematics for the link of 3D robot model	No (Manual calculation)	Yes	Yes
Third party administrative maintenance	Yes, default	Yes, self-organised	Yes, self-organised

2.1.3 Characteristics of Telerobotics User Interfaces

For a gaming environment to be effective as an interface, it must possess characteristics that match those of telerobotic interfaces. Table 2.4 summarises the key characteristics essential to such a user interface.

Table 2.4: Characteristics of telerobotic interfaces and their varieties, taken from [1-3, 6, 7, 10, 12, 13, 17, 26, 28, 37, 38, 55-62]

No	Characteristics	Varieties
1	Type	• Telemanipulation • Vehicle telerobotics
2	Control	• Direct/manual control • Human supervisory control
3	Interface	• Full video only • Virtual reality (VR) • Graphical user interface (GUI)—for example, text, pictures, graphics (including buttons and sliders, and map-based points). • Mixed reality (MR) Note: augmented reality (AR) and augmented virtuality (AV) are considered as part of MR.
4	User	• Single user • Multi user
5	Input device	• Mouse and keyboard • Joystick • Haptic device • Gloves • Touch screen
6	Feedback	• 2D vision • 3D vision • Audio • Force feedback • Vibration

No	Characteristics	Varieties
7	Platform	• Mobile application • WEB application • Desktop application
8	Media transmission	• Internet
9	Target performance	• Easy (user friendly and adaptable) • Efficient • Enjoyable • Enables immersion with real task consciousness • Safety
10	Current applications of telerobotics	• Space • Undersea, oil and science application • Nuclear power plants and radioactive • Toxic waste clean-up • Construction • Agriculture • Mining • Warehousing and mail delivery • Fire fighting and lifesaving • Policing • Military operation • Assistance devices • Tele-diagnosis and telesurgery • Entertainment

2.1.4 Telerobot Model

Gaming environments present a number of possibilities in building an interface [33], as have been outlined above. However, building telerobotic interfaces by utilising a virtual gaming environment requires some description of possible features of the gaming environment itself to fit with the requirement of telerobotic interfaces. Before that, next subsections describe a number of models applied to build my proposed telerobotic interface.

2.1.4.1 Virtual Reality Model for Controlling Process

In this thesis, a number of gaming environments are used for operation control. The proposed telerobotic model utilises a VR as the simulator to generate integrated simulation interface (Graphical User Interface) and control to run the telerobotic process (see Figure 2.6).

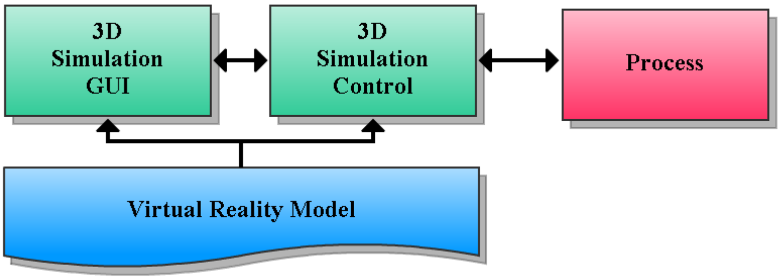


Figure 2.6: Control based on the virtual reality (VR) model

This proposed model is contrast to the conventional model from previous work in the telerobotics area, which used a virtual reality (VR)/gaming environment as a simulated telerobot to test their custom built interfaces [28, 29], The conventional model (see Figure 2.7) uses simulation as an independent element for information display separately from the control function to run the telerobotic process. This could prove problematic in presenting different information on the display and actual remote device.

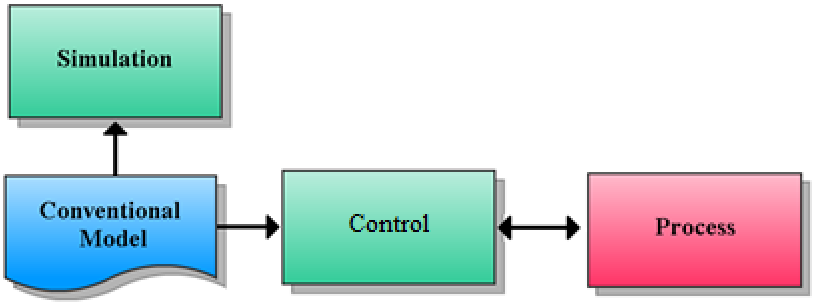


Figure 2.7: Control based on the classic model

For the proposed telerobotic model, VR is applied to handle most of the telerobotic processes including receiving the user’s commands and the telerobot’s feedback, and generating commands for the model simulation and telerobot. Figure 2.8 shows the scheme of the coordinated control system based on a VR model between the operator and telerobot.

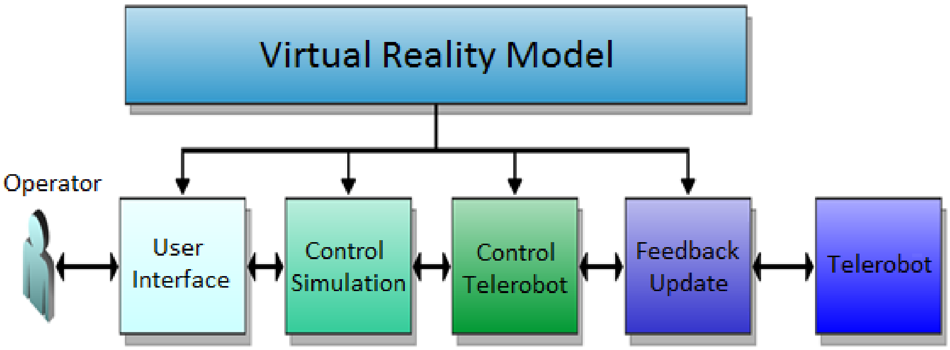


Figure 2.8: Coordinated telerobotic control system based on the virtual reality (VR) model

2.1.4.2 Looping Control System Model.

In building a telerobotics system based on VR simulation, I developed a control system from a classic looping control system model. It consists of three main elements: control, process, and feedback (see Figure 2.9). This system locates all elements of the simulation looping control system inside the telerobotic control element, which itself is one of the looping control elements in the telerobotic system (see Figure 2.10).

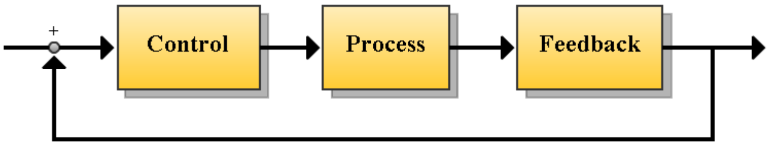


Figure 2.9: Classic looping control system

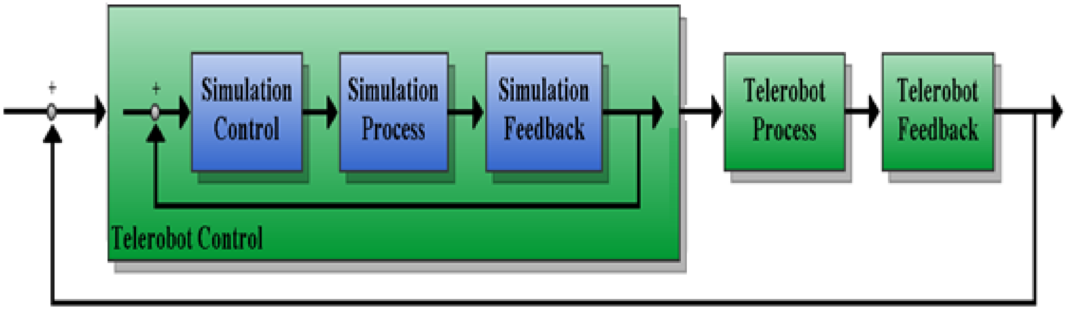


Figure 2.10: Proposed control system design based on control by virtual reality (VR) simulation

2.1.4.3 Telerobot System Architecture

The client-server communication model is a common computing model for telerobotic systems. Basically, it consists of three main parts – client, server, and telerobot (see Figure 2.11). The client side is the sub-system that is connected directly to the user/operators. It includes some input devices (e.g. keyboard, mouse, joystick, etc.) and interface displays. In the proposed system, the client side consists of a 3D telerobot model, remote environment model, and feedback information from the server.

The server side is connected directly to the telerobot controller, and communicates with the client through the Internet. In remote applications, the server manages a number of connections from several sensor devices (e.g. remote cameras and other sensors used for a different purpose) and is responsible for delivering information between clients, the telerobot and other remote sensors.

The telerobot part consists of the controller and remote machine (robot). The telerobot controller processes all generated commands from the user through the computer server to operate the robot. Besides controlling and checking the robot mechanism, the controller also collects information from each motor in the robot’s joint to calculate the position feedback.

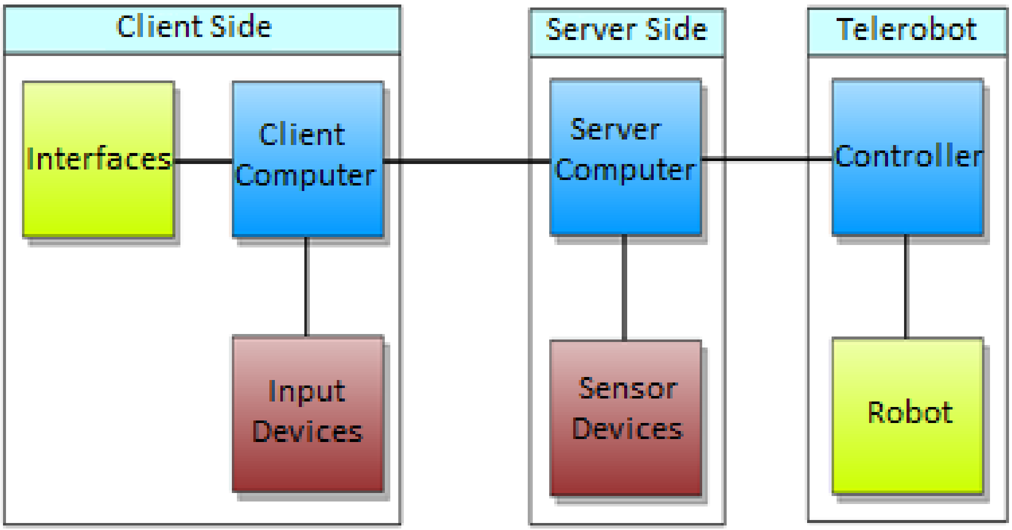


Figure 2.11: Telerobot system architecture [3]

2.1.4.4 Software Telerobot Architecture Model

Figure 2.12 shows the software architecture for the proposed telerobotic system. In general, the information shared between the operator and telerobot are request commands and feedback. Based on this control model, the software runs on the client side and processes all responses into the virtual model form. The display interface shows the generated response from the user command and telerobot feedback. There are two main responses generated on the client side: VR of the telerobot and workspace, and virtual prediction information models.

On the client side, the 3D model simulates most processes occurring at the telerobot and the remote workspace, based on operator commands. The operator selects the targets and the information is translated and simulated automatically in the 3D telerobotic representation. The information automatically provides the operator with predictions of the telerobot’s movements and sends control commands to move the actual telerobot. The simulation process assists in the planning process that runs inside the telerobotic interface.

On the server side, the server’s software manages the process of delivering generated commands to the telerobot controller and also feedback information to the client based on sensors and robot responses. The scanning software works by processing information from the attached remote sensors (e.g. from a remote camera).

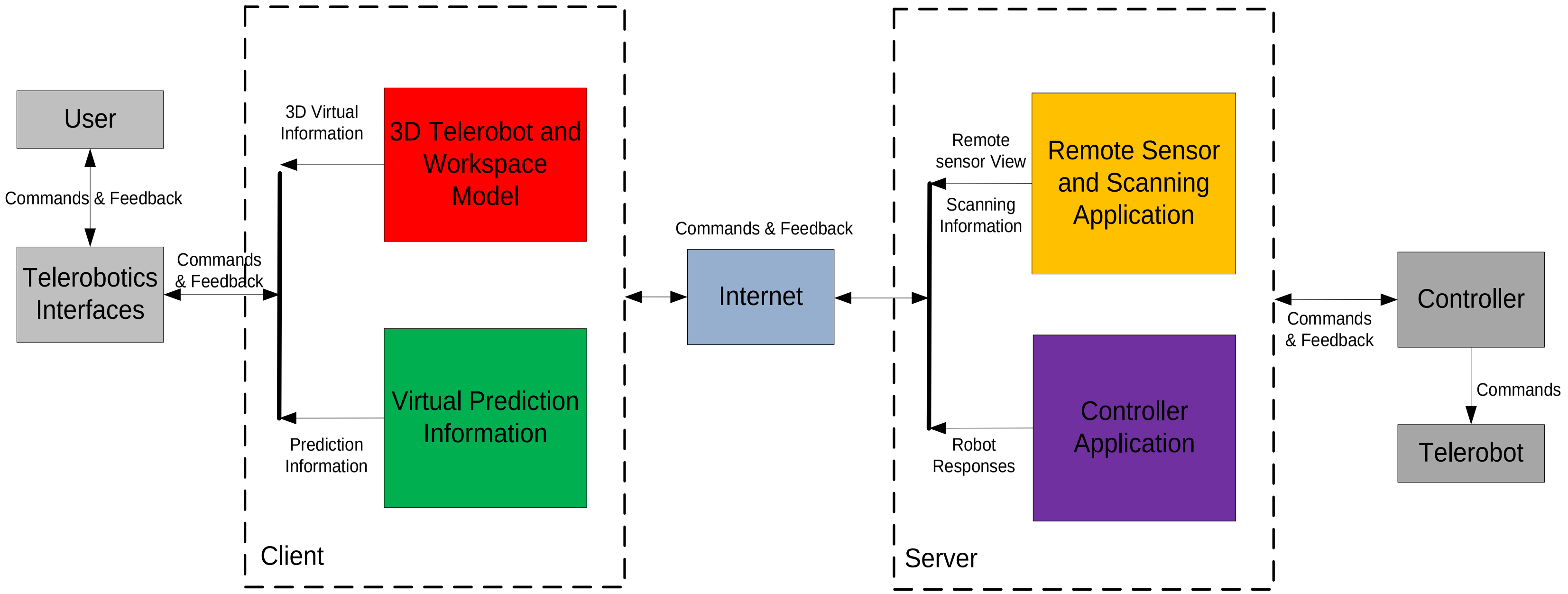


Figure 2.12: Software telerobotic architecture based on client server and operation by virtual simulation

2.1.4.5 System Configuration Model

For the proposed telerobotics system, I group the system into several elements as follows: human operator, interaction devices, master and slave applications, and the communication between them. Figure 2.13 shows the schema bloc of the system's configuration.

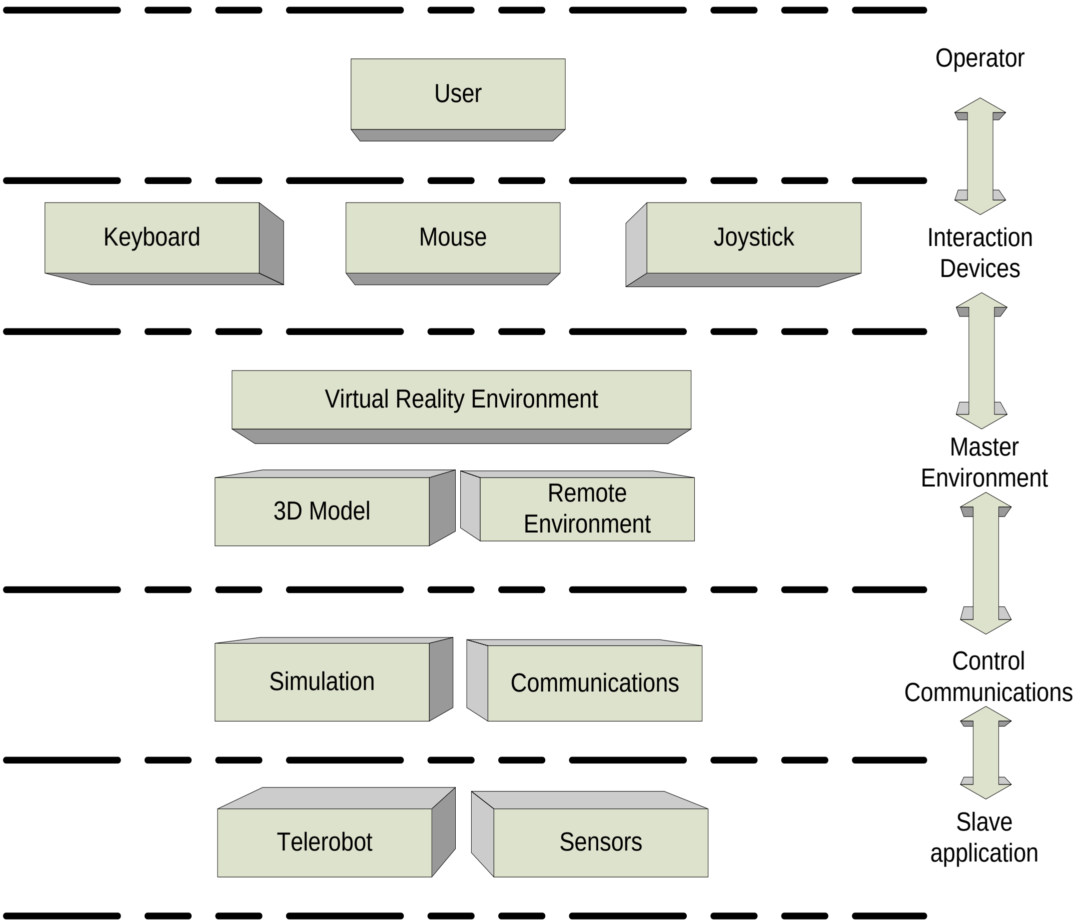


Figure 2.13: System configuration

Descriptions:

1. Operator: refers to the human operator or the user who has an interaction with the telerobotic system.
2. Interaction Devices: the system focused on exploring common input devices that are normally used in gaming interaction, such as the mouse, keyboard and joystick. However, in order to applying HCS concept, most of the conducted experiments were using mouse as the main input device in delivering commands to the interfaces.
3. Master Environment: in general, the master environment is created as a VR environment which includes a 3D virtual model of the telerobot and the remote environment.

4. Slave Application: consists of a controlled robot as a remote machine and a number of sensors that provide remote information.
5. Control communications: the telerobotics system is based on VR simulation that manages most control processes and the communication of information. Thus, the communication schema bloc consists of generated commands and feedback information between the operator and telerobot, which are tested in two model communication protocols TCP/IP and UDP.

In the previous sections, I have described a number of models to build telerobotic interfaces. In terms of evaluating the effectiveness of gaming environment with the MR concept for telerobotic interfaces, the next section describes in more detail the definition and examples of MR including information on general telerobotic interfaces.

2.2 Mixed Reality Concept for Telerobot Interfaces?

Obtaining accurate information for telerobotic interfaces remains a challenge. It is not unusual for information received by the operator at the remote location to be different from that received by the local operator, leading to reduced productivity [6]. Moreover, in some cases, such as in mining, the interface for telerobotics contains more than one custom built sub-interface to monitor each process [5] (see Figure 2.14 for more detail). The complexities of the multiple screens can distract the operator's attention from the actual task and hence result in inefficiencies.

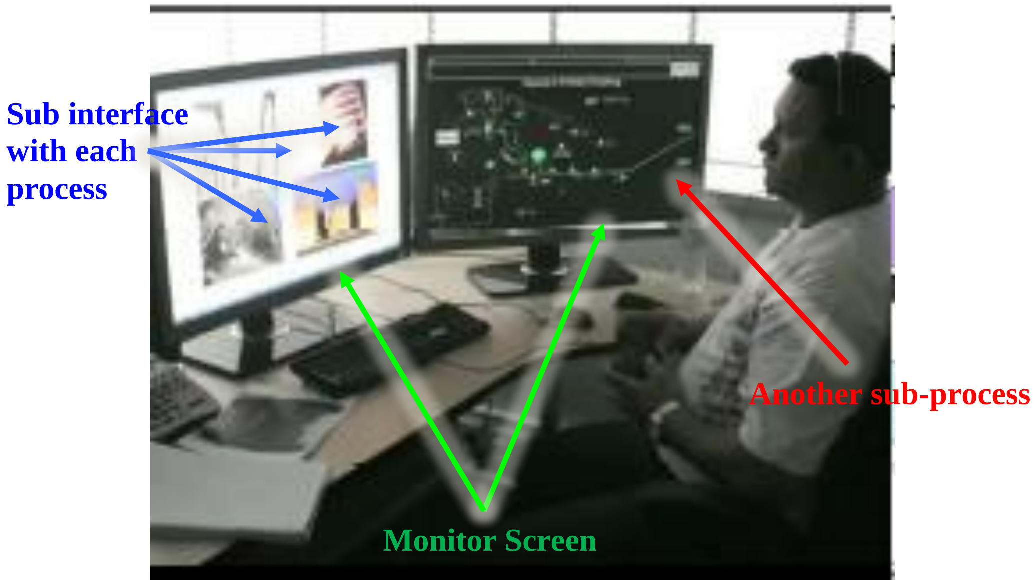


Figure 2.14: Telerobotics user interface with multiple screens to monitor each sub-telerobotics process [5]

An important aspect of telerobotics is situational awareness (SA). Situational awareness is defined as the perception of complex environmental elements with respect to time or space. It plays a significant role in telerobotics and is critical for decision makers [63]. In a telerobotic scenario, where the operator has limited information concerning the remote situation compared to an operator with direct onsite control, the role of the interface is to provide adequate information to complete the task, using simple visualisations from the remote location.

MR is able to harness the strengths of both the virtual reality model and video streaming in its delivery of information [64]. It can be used with simple displays without any loss of necessary information compared to the use of multiple streaming video. Hence I argue that integrating MR environments into telerobotic interfaces can provide most of the information the operator requires to perform the task.

Before discussing in more detail the MR concept for telerobotic interfaces, and how this concept provides all the information required, it is necessary to understand the current technology of existing interfaces. The next section describes telerobotic interfaces.

2.2.1 Telerobot Interfaces

Interfaces play an important role in providing information to the operator in a telerobotics system. An interface should also be designed to be user friendly, efficient and reliable. Therefore, two essential points should be taken into consideration when developing interfaces: the process of controlling/operating and observing/monitoring.

In describing the various forms of interfaces, based on the two essential points above, Fong and Thorpe [1] categorised the interfaces into four groups: direct interface, supervisory control interface, multimodal interface, and novel interface. The direct and supervisory control interfaces are a group of interfaces that are categorised by their control model, whereas a multimodal interface is a group of interfaces which are categorised based on the usage of more than one remote sensor to provide information. Besides the three categories of interfaces mentioned above, the other interfaces can be classified into the novel interfaces group. Examples of novel interfaces, related with telerobotics, include:

a. interfaces with particular input devices:

    (1) by using muscle and brainwave movement monitors for hands-free remote driving interfaces [27],

    (2) by using a *Haptic* feedback device for remote control devices [25, 26],

    (3) by using a *Wii* sensor as a *Gesture Driver* [65], and

(4) by using head and gaze tracking for a telerobotics camera control interface [66];

b. interfaces for particular platforms:

(1) WEB-based platform for telerobotics [67], and

(2) Personal Data Assistant (PDA) devices for remote driving control [7].

The interfaces can also be classified into three groups based on the type of information provided. These classifications will be explained in more detail in the following sub-sections.

2.2.1.1 Video Interfaces

The first classification is the video interface. Common telerobotic interfaces utilise image transmission from remote cameras over the Internet, via live video/streaming video. In a short distance telerobotics scenario, Massimino and Sheridan [68] mentioned that the video interface could provide information to the operator as well as if they were using their direct vision. Through simple block insertion task, Massimino and Sheridan successfully compared remote operation via direct operator vision and through video interface and found that there was no significant differences between direct viewing and seeing through video interfaces, when the total visual field object to be manipulated was the same.

Video interfaces suffer from some limitations. Firstly, the usual fixed-position of remote cameras restricts their range of vision, making exploring the remote environment difficult, despite the pan, tilt and zoom functions. Secondly, real-time image transmission with high resolution requires high bandwidth. Images from video interfaces can suffer from other problems, including spatial resolution, signal noise and distortion. Thirdly, the instability of the Internet connection including network delays in data transmission severely limits real-time control and feedback, particularly when there is more than one camera installed. Fourthly, when using a single camera, the method transmits two-dimensional (2D) images. It is difficult for the operator to visualise the object's position in a single projector line. Fourthly, when using a single video camera, the method transmits two-dimensional (2D) images. It is difficult for the operator to visualise the object's position in a single projector line. While a stereo video system can achieve 3D visualisation easily, it can only do this from a static single viewpoint. On the other hand, a virtual camera offers the operator freedom to view the object from any direction.

Figure 2.15 shows that any point on the projector line between A and A' is projected as A' on the projection plane (2D screen monitor), and similarly any point between B and B' is projected as B'. The fifth issue is the high cost of producing bespoke telerobotics user interfaces.

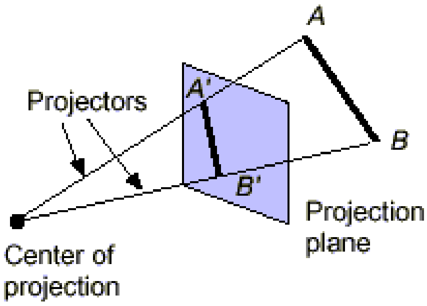


Figure 2.15: Perspective: determined by centre of projection

The video interfaces provide views from cameras that are installed at the remote location. Remote cameras provide information of the real world's views (in telerobotics this refers to the remote location), which can be viewed as if the operator is at the local site. However, this type of interface requires high bandwidth and constant human attention. Also, each camera only provides images from one viewpoint even with a PTZ (pan, tilt, and zoom) camera function. Recent research on live video interfaces has been performed by Hughes [69], who studied the effectiveness of video system designs in telerobotics, and Zhu [70], who analysed natural human interaction in the control of remote cameras in a telerobotics system. An example of a video interface is shown in Figure 2.16 which illustrates streaming video as part of a UAV (Unmanned Aerial Vehicle) control system [71].

Figure 2.16: Examples of video interfaces in a monitor as part of a UAV play load and control mechanism[71]

2.2.1.2 Virtual Reality Interface

The virtual reality (VR) environment can be used to build visualisation [72], and as a medium (or in this case an interface) to represent the real environment [73]. Yang and Chen [3] state that in order for efficient implementation, most telerobotics systems simulate the real environment by using 3D virtual environments. They showed that a telerobot virtual model could considerably reduce system traffic compared to video image transmission. It allows the robots to be controlled successfully, even when communication rates are slow (0.1-0.5 KB/sec). Hence, it is suitable for situations with poor/low bandwidth network communication. They also believe that VR interfaces can increase the efficiency of operator performance as they can choose appropriate viewpoints and additional virtual-generated information (e.g. overlay text, virtual arrows, object transparency, etc.) that are not available on live video interfaces.

Another advantage of this technology includes the possibility of achieving a quick response from the operator’s actions due to the instantaneous update of the virtual robot and its environment. Moreover, the virtual environment can also be used to create better visualisations, and help the operator achieve immersion in the environment to perform the task.

Figure 2.17 is an example of VR interfaces for The Rover Sequencing and Visualization Program (RSVP) developed by Jet Propulsion Laboratory NASA on 1997[21]. This type of interface provides all information through 3D computer-generated virtual objects and effectively replicates the remote location and the operating machine.

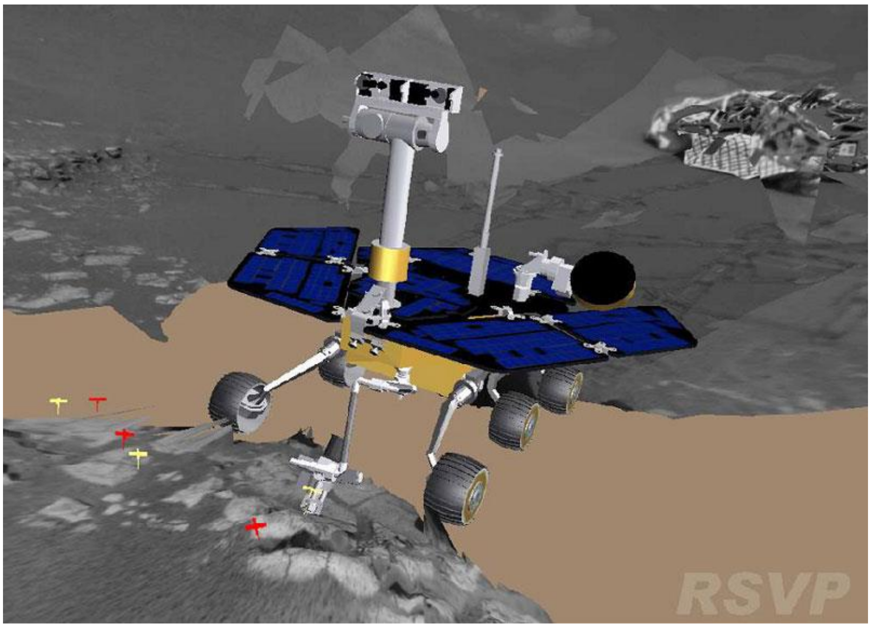


Figure 2.17: This example of a VR interface shows the RSVP-HyperDrive, which displays a graphical version of the rover that is used to drive the MER Spirit rover and place its robotic arm on rocks [21]

The VR environment is suitable for poor/low bandwidth network communication situations [3]. Monferrer [11] and Hainsworth [6] recommend VR for vehicle telerobotics as operators are not limited by the camera view being fixed in one position on the vehicle body. However, situational awareness can be reduced when relevant information is included in the model[28].

In VR environments, the operators are able to adjust their viewpoints to angles that are not available via live video interfaces. A VR interface also conquers the ‘deep feeling’ problem that is commonly found when defining three-dimensional positions from a two-dimensional screen monitor. In addition, virtual objects can be utilised in a predictive display [74, 75] to reduce the effect of time delay and to offer an immersive environment which is usually required by the human operator. However, whilst fast-changing conditions can occur in remote locations, an inadequate sensor with inaccurate sensors can also result in different conditions being presented between the remote location and the VR environment simultaneously. Therefore this environment would be best if an accurate representation of the remote scene could be projected. Hence, a further innovation would be to use of an alternative technology, such as the combination of information between a live scene and a virtual environment to minimise issues, which is described in the following sub sections.

2.2.1.3 Mixed Reality Interfaces

The third classification of interfaces which combines information from the real scene and the virtual world is known as mixed reality (MR). Milgram [64] states that the definition of MR is a representation of real and virtual world objects which are offered together within a single display (see Figure 2.18 for sample of a MR concept). It aims to link the virtual entities with the real world. This is supported by the definition from Tamura et al [32], which states that MR covers the continuum from augmented reality (AR) to augmented virtuality (AV).

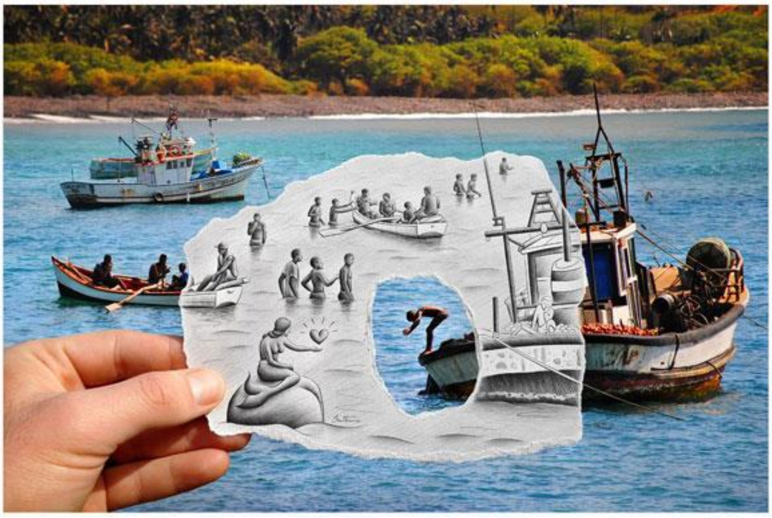


Figure 2.18: Sample of mixed reality (MR) concept

The utilisation of MR can be found in a number of publications by Jean-Yves [76] regarding the framework of MR environments, Stapleton [77] who introduced the concept of MR for entertainment, and Thomas [78] who utilised the MR concept for virtual studios in TV production.

In the field of telerobotics, the concept of MR technology is also widely used. MR can be used as an interface that mixes different pathways of visualisation, namely direct visualisation through low bandwidth video and synthetic visualisation derived from a dynamic software model of the state of the world [5]. One research example is the experiment conducted by Ponto [29], which tests a MR workspace to allow the user to control and simulate teleoperated vehicles (probes). Another example is the telerobotic *Rockbreaker* application interface with a distance of over 1,000 km between the robot and the operator developed by Duff et al [5]. They successfully applied a combination of information from a 3D model of the *Rockbreaker* machine and the workspace environment, three video views from a remote camera, and a generated image model of the rock from a stereo camera.

In Duff et al's research[5], the operator is allowed to switch between the virtual view and the camera view on the main screen. However, based on the operator's comments, it can be concluded that they still needed an interface that could reduce the cognitive load of switching from one view to another in a single display.

MR has also been a popular technique used in human computer interaction for combining virtual and real elements [79]. In 1991-1992, the term MR was commonly used only for interface concepts [64], before it rapidly expanded to many areas such as computer instruction [29], industry [5], entertainment [31, 77, 78, 80], and medical visualisation [4].

Tamura [32] mentioned that AR and AV have been used to provide enhanced information for an interface – AR brings virtual information into the real world view, while AV delivers real world information to virtual environments. MR technology has become a new interaction concept between a person and the real world, for example by providing information that was not available in the real world [81]. Hence, the term MR has a broad meaning, but can be simplified to combining information between the real and the virtual environments in a single display. A simplified representation diagram of a MR environment is shown in Figure 2.19.

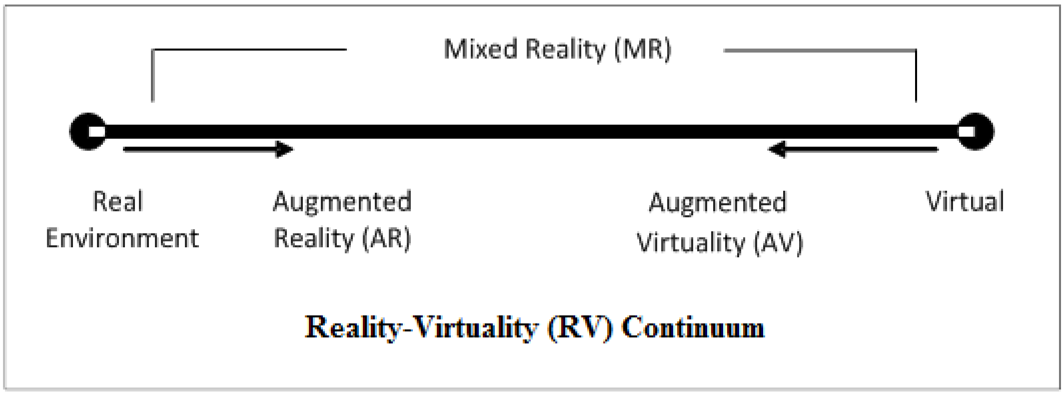


Figure 2.19: Simplified representation of MR (referred to [64])

AR and AV interfaces are described as:

a. Augmented Reality Interfaces

Augmented reality (AR) has a technology that combines information from both the live scene and the virtual world. It is a concept of interactive technology which can be simply described as the expansion of the real world with synthetic electronic data. Xiong et al [82] described AR as an advanced human machine interactive technology which enhances visual information from a real scene through embedding the 3D computer-generated virtual objects and text superimposed in real-time. Recently developed AR applications include medical visualisation [4, 83], mobile phone gaming applications [80], and human machine interaction with predictive display technology [82]. The examples of AR interfaces are shown in Figure 2.20.

Figure 2.20: Examples of AR interfaces. (Left) Embedded country flags and the names of sailors are displayed on the screen for the America's Cup race tracking display [84], and (Right) An arrow object as additional navigation interface [85]

b. Augmented Virtuality Interfaces

Augmented virtuality (AV) has the opposite concept of the AR interfaces. AV enhances virtual environments with information from the real world. Even though this concept is not as popular as AR, it contributes to technology that combines information between the real scene and the virtual environment.

The concept of AV is to bring information from the real scene into the virtual world. The video conferencing system from Regenbrecht et al [86, 87] clearly illustrates the definition of AV. Another example of this technology interface is also shown in Figure 2.21 where TV newscasters sit at a real table in a virtual studio [88].

Figure 2.21: Example of an AV interface concept from TV newscasters who sit at a real table in a virtual studio [88]

Another research that utilised AV interface is reported by Paul et al [12]. They report the results of six surgical cases where AV was used in conjunction with AR. They used AV to give an overview of the surgical area and to enable vision beyond the cortical surface. They used this method to facilitate understanding of the spatial relationship between the operative field and the preoperative 3D images of the patient.

2.2.2 Advantages of Mixed Reality Interfaces

The advantage of mixed reality (MR) interfaces is that it combines most of the benefits from both VR and video interfaces. The benefits of the adopted VR environment, such as: (1) an immersive environment (easy to build and manipulate the model); (2) lower bandwidth support for communication compared to using streaming video; (3) providing the ability to analyse, predict and plan information which is useful for reducing the effect of latency in communication; (4) adjustable and free movement of virtual camera viewpoints; and (5) gives extra information/data which is not provided in the workspace (e.g. number, text, graphic, and other virtual information). However, a VR environment that is built to simulate the real world can be incomplete. Hence, the MR concept provides the missing information by combining low bandwidth video information from the workspace, which helps the operator to evaluate the results of their performance. Current telerobotics video interfaces have successfully presented information on the actual conditions of the remote location. However, as mentioned earlier, its limitation is in its inability to convey information from all necessary directions.

Another requirement for successful telerobotics is situational awareness through visualisation. The MR environment can improve situational awareness by using information received from the virtual model, to supplement low quality and therefore low bandwidth video from the remote location rather than requiring transmission of multiple high quality video streams. The view from video is used to complement the missing information on the 3D model. This means the merits of MR is better than only using pure modelling. Implementing MR in telerobotic interfaces does require attention to avoid problems that can misdirect the operator. These include registration error between the 3D model and the telerobot, misalignment errors of the robot or target object positions, and temporal mismatches dues to delays between giving commands and actual robot movement.

In addition, a gaming engine offers a sophisticated environment that is compatible with most input devices and sensors. Since a gaming engine serves as a virtual environment, it has all the advantages of a VR environment. Hence, applying a MR concept in a gaming environment can provide better interaction between the human operator and the telerobotic interface. In addition, combining both sources of information (virtual model and video) in a single screen can reduce cognitive load cause by diversion of the operator’s attention between multiple screens.

Despite of the ability of MR in enhancing information to the operators, there is no guarantee that MR interfaces can be better for user performance compared to other types of interfaces. In addition, providing all information on one single screen can possibly lead to confusion for the human operator and hence result in lower performance. In this chapter the results from the application of the MR interface in a telerobotic scenario are discussed.

2.2.3 Design of Mixed Reality Interface in Gaming Environment

Most current telerobotic systems, especially those used in mining, contain a number of custom-built user interfaces. Typically one interface for each mining process, which needs to be monitored by the operator; hence an alternative, to reduce the cognitive load of switching from one interface to another, is to present the operator with a single interface. Besides that, the telerobotic interface should be interactive and reconfigurable, which can be achieved by using platforms built for creating virtual games environments.

The basic environment of the proposed interface is a ‘VR in a gaming environment’ with augmented streaming video (see Figure 2.22). Information from streaming video was brought into a virtual world to give information on a remote location. I used the *LiSA* (Localization and Semantics of Assistance) model as a basis for the experiment design. This is a common model in telerobotics systems, which defines a relationship between the operator, interface, network systems, manipulator, and environment. This model can also be used to describe a VR system that uses information from the real world [23]. Further details about the *LiSA* model will follow in the next section, which discusses human supervisory control (HSC) and the general spectrum of control model in the telerobot.

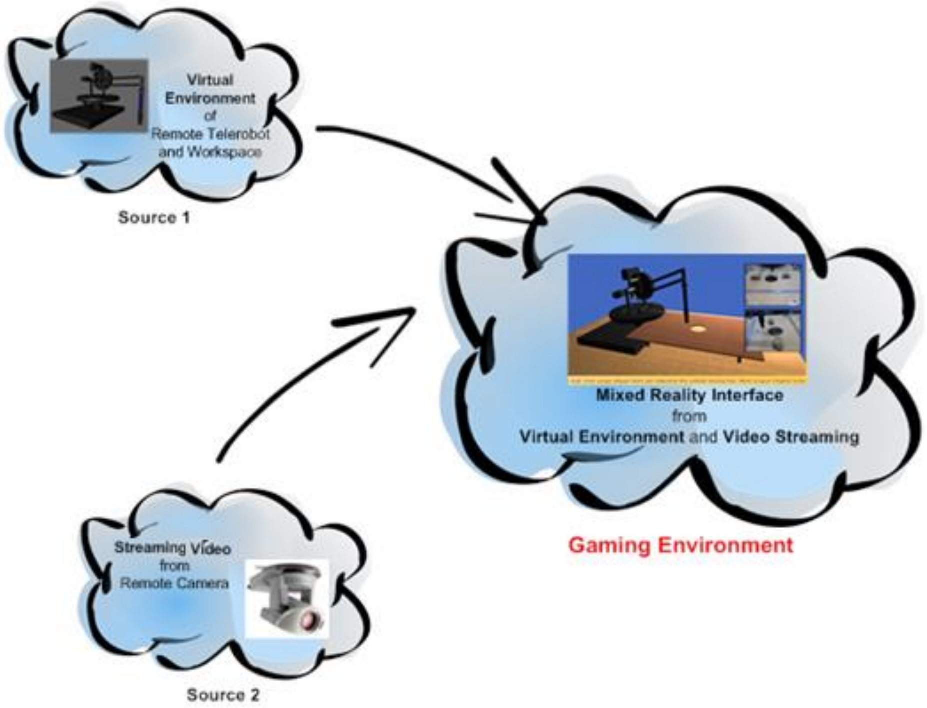


Figure 2.22: MR environment in gaming environment

2.3 Human Supervisory Control for Telerobot Control Model

The advancement of telerobotic control technology allows a move from manual operation towards full automation. Manual operation is the most common control model applied in mining areas. However, unlike factory or industrial areas which utilise machines to perform a repetitive task [2], in mining areas most scenarios are varied and require human operators to make decisions in performing the task. Hence, it is hard to change the manual control model into a full automation model.

Human supervisory control (HSC) is an alternative to manual operation that minimises human operator involvement without interfering with the machine’s performance [2, 89, 90]. In general, HSC can be defined as an interaction between a human, who acts as the supervisor, and the machine/system, which acts as the subordinate. Tendick [91] stated that HSC is a system where a human operator acts as a supervisor who has the ability to plan, monitor and interrupt the process during the execution carried out by machines.

HSC offers a number of benefits, including the ability to simplify the control process by defining movements and goals rather than requiring hands-on control; it can minimise communications latency [10, 72, 89]; and it can eliminate the requirement for continuous human attention, thereby reducing the operator workload and increasing productivity. However, HSC has some limitations that can degrade performance. HSC can suffer from: (1) information overload; (2) inappropriate levels of automation; and (3) distributed decision-making and team coordination. These limitations has been discussed extensively by Cummings [92].

According to Sheridan [60], there are five generic supervisory functions that have been delineated: planning, teaching, monitoring, intervening, and learning (see Figure 2.23). However, in contrast to industrial robot settings which mostly work by providing repetitive responses in predictable tasks within controlled environments, the learning function for a telemanipulator can be neglected since most scenarios have no repetition of the same task. Sheridan also added that the important aspect of HSC is the ability of the system (computer) to package consolidated information in a visual display to the human operator. This information is useful for planning and examining the task performance and for making a quick decision to override the process when needed.

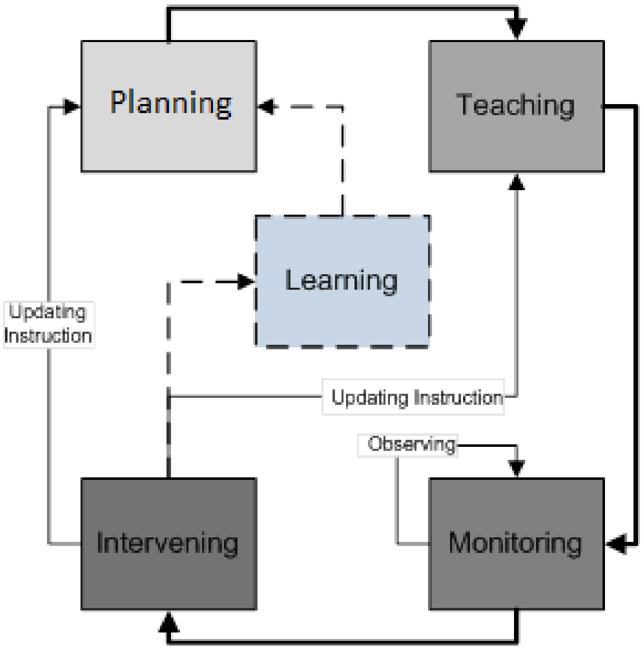


Figure 2.23: Five generic supervisor functions as nested control loop

HSC offers the advantages of: (1) achieving greater accuracy from the machine with less human effort; (2) easier control, as the operator frames instructions in terms of the goals to be met instead of operating the machine directly; (3) eliminating the requirement for continuous user attention and hence reduces the operator's workload; and (4) maintaining control even when there are time delays in the communication between the human and the remote machine (effectively reducing the adverse effects of latency[2]).

2.3.1 Telerobot Control Model

This section provides several descriptions of the telerobotic control model. In order to evaluate the effectiveness of a HSC concept for telerobotics system control, it is necessary to know the variant of the existing control model.

The telerobotic control model could be grouped into two types of control: direct/manual and HSC [1]. For further understanding of the differences between the types of control, Sheridan's spectrum control diagram [2] (Figure 2.24) describes the information flow between a human operator and task in three types of control. In this spectrum control diagram, human operator involvement is still required even in 'fully automatic control' mode. Implicitly, besides the monitoring process, the human operator still has some form of external control which can be executed by, for example, turning on/off the power.

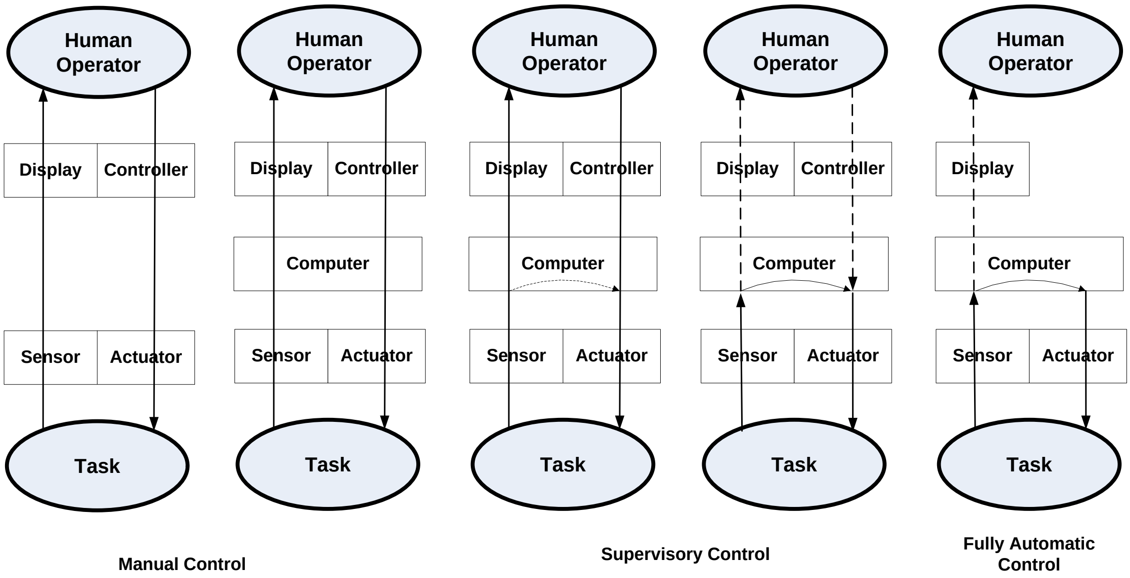


Figure 2.24: Spectrum control diagram (referred to by Sheridan [2])

In the case of a human operator as part of the spectrum model, in the *LiSA* (Localization and Semantics of Assistance) model for telerobotics [23] (see Figure 2.25), the human operator is the part of the loop which generates commands and also receives feedback information from remote locations. However, in 'full automation' mode the operator receives information from monitoring processes only. Hence 'full automation' cannot be considered as telerobotics because the operation is run independently without continuity of human interaction.

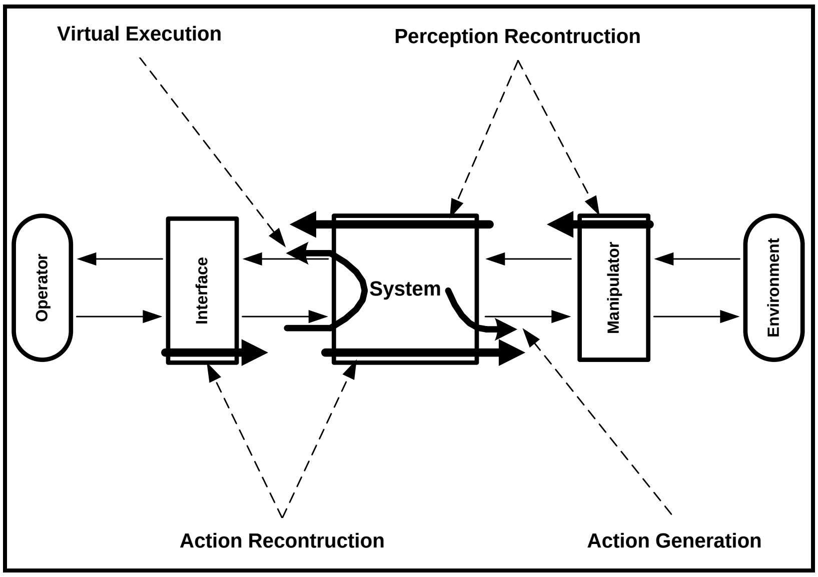


Figure 2.25: The *LiSA* (Localization and Semantics of Assistance) model concept with *perception reconstruction, virtual execution, action generation,* and *action reconstruction* model assistance (from [23])

Besides describing the relationship between the human operator and environment (in this case referring to ‘telerobot’), the *LiSA* model provides a framework to describe the common forms of assistance used in telerobotics systems [23]. There are eight common components from the *LiSA* assistance models, but only four of eight common components are largely applied in this telerobotic systems based on VR environment. The four common components from the assistance model are known as *Perception Reconstruction* and *Virtual Execution* which relate to assistance provided to the interface, and the last two are known as *Action Generation* and *Action Reconstruction* which relate to assistance provided to the operator. Descriptions of the four common components of assistance models are as follows:

A. Perception Reconstruction

The *Perception Reconstruction* model is a common component assistance model which works where the conditions of the interface are an incomplete model. This assistance model uses a substitute perception to provide additional information, for example: in VR interfaces, an enhanced video camera view is used to replace the missing information.

B. Virtual Execution

The *Virtual Execution* model is a common component assistance model that provides a pre-prepared test prior to task execution. For example: in the planning process of the telerobotic system scenario, the preparation and test phase provide a simulated outcome that allowed the operators to validate their instructions before they were transmitted to the robot. This form of assistance is known as *Virtual Execution.*

C. Action Generation

This common component of assistance corresponds to Sheridan's [2] concept of supervisory control. In an example of a telerobotics control scenario, the human operator is allowed to specify the target positions. Then the system generates the required actions to move the robot arm to that position without continual human input. This process of assistance is an example of *Action Generation.*

D. Action Reconstruction

An example of this common component assistance model in telerobots control scenario is the usage of a standard keyboard and mouse as input devices. Neither the mouse nor keyboard is an anthropomorphic manipulator, thus preventing the operators from controlling the robot with natural arm movements. However, a substitution action that utilises the mouse and keyboard can be used to reconstruct the missing arm movement and this is known as *Action Reconstruction*. Based on the description above, *Action Reconstruction* is also known as the opposite of *Perception Reconstruction.*

As mentioned above, direct/manual control is still more common compared to supervisory control. In direct/manual control, the operator guides the remote machine directly using the hand-controller. This means that direct/manual control depends totally on real-time human decision control. Meanwhile, in HSC, the remote machine relies on its own intelligence to generate commands and perform the task without continual human involvement.

Related to the types of telerobotics, Fong et al [17] stated that the majority of research in HSC has concentrated on telemanipulation rather than vehicle telerobotics. However, there are many possibilities in the application of supervisory control in vehicle telerobotics. Recently, HSC for vehicle telerobotics has been utilised with a variety of control modes (e.g. coordinated control or individual actuator) and feedback (e.g. visual or haptic). Moreover, HSC is used to address the problem of poor communication which is often found in vehicle telerobotics [17].

As mentioned in subsection 1.1.3, to identify the effectiveness and performance of my telerobot application, I designed all the experiments using the common metrics developed by Steinfeld et al. [24]. These metrics are grouped into two categories: system and operator performance. In this manipulation scenario, the system's effectiveness can be identified by task metrics, such as the percentage of navigation tasks successfully completed. The system efficiency can be measured by using a number of task metrics, such the time to complete the task, or the operator time spent on the task, and the average time to obstacle extraction. Operator performance can be measured with subjective measurement techniques (e.g., Likert scale or open-ended questionnaire). Design of performance effectiveness experiments for the proposed telerobot application is discussed in more detail in the chapters describing the experiments.

2.3.2 Utilising Gaming Concept for Human Supervisory Control

I utilised a number of features commonly used in gaming environments, such as the 'path finding algorithm', 'first person view' concept, and other gaming features to build a HSC concept for the telerobotic interfaces. As well as being suitable for gaming environments, these features are also useful to improve the effectiveness of telerobotic interfaces.

The first utilised feature is a path-finding algorithm. The A-star (A*) algorithm is a common path-finding algorithm in gaming environments [93]. Patel [94] stated that the A-star algorithm was developed in 1968 to combine the best heuristic approach between *Best-First-Search* and *Dijsktra's* algorithm. It is generally used to calculate the shortest and fastest way for an object to move to a defined target position (e.g. Path Finding in the Maze [95]).

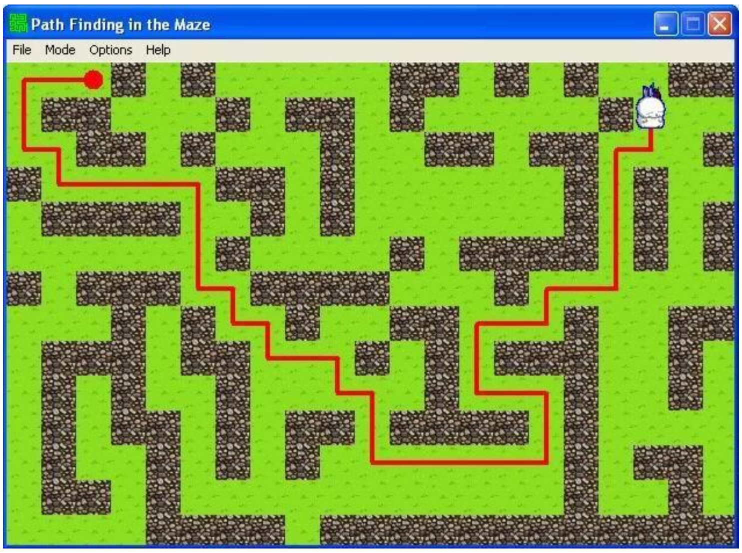


Figure 2.26: An example of path finding implementation for the gaming environment [95]

I applied the A-star algorithm to develop an intelligence function for the HSC concept, which allows the system to possess the knowledge to run select processes by itself. Hence, by applying the A-star algorithm, this telerobotic system will have the ability to generate a number of efficient paths which allow the robot to avoid the obstacles automatically.

Another feature is the ‘game viewpoint’ on virtual camera. In a gaming environment, virtual cameras play an important role in providing information about the VR environment. Users can interact with the virtual object through the ‘remote-person view’ or ‘first person view’ as a basic viewpoint. Sko [96] mentioned that gamer/user performance when playing a game can be improved by better viewpoint control. Hence, I suggest this feature also affects the operator performance for this telerobotic interfaces.

For ‘input device’ features, besides the gamepad (joystick), the mouse and keyboard are the most common input devices for the gamer, especially for PC (personal computer) game types. I argue the mouse device is also suitable to apply HSC in this telerobotic scenario. A number of benefits of using a keyboard and mouse are: (1) commonly used and very compatible for almost all PC applications, (2) cheaper compared to other input devices (e.g. haptic devices and gamepad), (3) easy to use.

Another important feature in a gaming environment is the ability to provide some ‘extra information’. This feature is commonly used to provide additional information needed by gamers (e.g. background and goals of the games). This feature can take the form of a virtual object or text, which is very useful for gamers in completing their gaming tasks. In telerobotic interfaces, providing extra information that is not available in a remote location can be very useful for the operator (e.g. predictive display and visual feedback information). I consider that both predictive displays and visual feedback information as useful in planning, monitoring and performing the task. Besides, it could be argued that this predictive display concept can minimise the effect of time delay to the operator [75].

All the gaming features above are used to build the MR and HSC concept for the proposed telerobotic interfaces. These features can provide comfort in operating the telerobot and improve the efficiency of user performance.

2.3.3 The Model of Response Movement based on Multi-Command Input

In contrast to direct/manual control of manipulators, telerobotics interaction based on HSC allows human operators to plan the movement of the remote machine by entering a series of commands as pre-defined positions. There are two possible kinds of response movements. Firstly, the robot moves towards the newly defined position immediately; or, secondly, the robot moves to achieve the queued series of positions one by one. I grouped the possible kinds of response movements into two models, as follows.

a. Adaptation response model

This response model can respond to the operator’s commands by moving to a new position immediately. The algorithm in the Adaptation model causes the 3D model or the manipulator to cancel the current process, update its target according to the new position specified, and continue the process towards the new target. Thus this model assumes the operator has abandoned their previous plan and formulated a new one. It responds more quickly and achieves the goal in less time compared to the Queue response model which adds a new operator command to the existing queue of commands. The difference between the Adaptation-response model and direct or manual control is that the manipulator works towards achieving a newly defined goal without continuous input from the operator as is required by direct or manual control.

b. Queue response model

This response model adopts the logic of queuing services. Queuing services work by following a FIFO (First-In-First-Out) concept where the system needs to complete servicing one entity before continuing to the next entity. This system is shown in Figure 2.27 where the 3D model or the manipulator moves to reach all the positions sequentially.

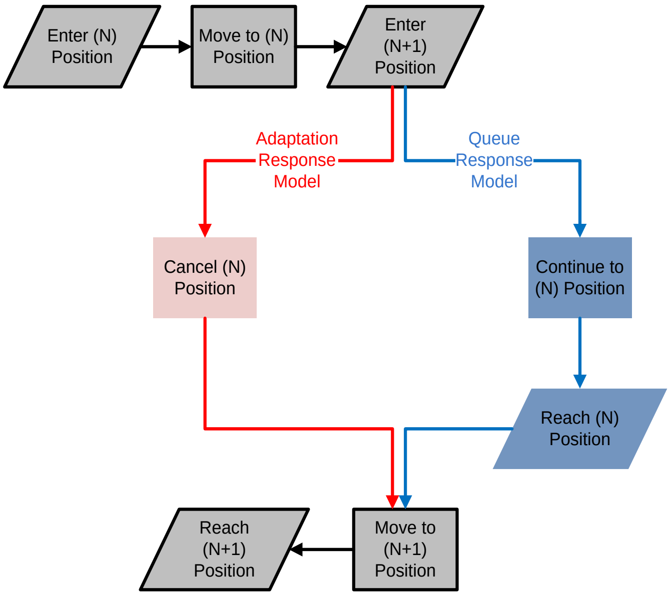


Figure 2.27: Diagram of Adaptation and Queue response model

In comparison to the Queue model, the Adaptation model is closer to direct/manual operation, where a human operator has more control for model movement, rather than in planning a number of positions for the intended target. Hence, the adaptation model is likely to perform faster for conditions that do not require a great deal of planning. However, in a situation where the delay in the response or feedback is large, the operator will feel its effects. In designing the experiment, I addressed this issue by requiring the participants to plan their movements by following a random path arrow. This will be discussed in more detail in the section on experimental design and procedures, section 5.3.3.

To evaluate more information about the telerobotic model and exploring the suitable features of virtual gaming environments, I have begun initial research which is described in the next section.

2.4 Telerobot Communication by Gaming Environment

In applying a virtual gaming environment for telerobotic interfaces, it is necessary to explore and evaluate the game features, especially their ability to deliver information between the operator and telerobot, and vice versa. This is an important step before I start to evaluate application of the MR and HSC concept in the gaming environment. I commenced this research study based on previous work performed by Duff et al [1]. They introduced the development of shared autonomy in control systems and a MR interface of a telerobotic *Rockbreaker* which was used in a mine over 1,000 km from the operator. The system architecture used in the project is shown in Figure 2.28.

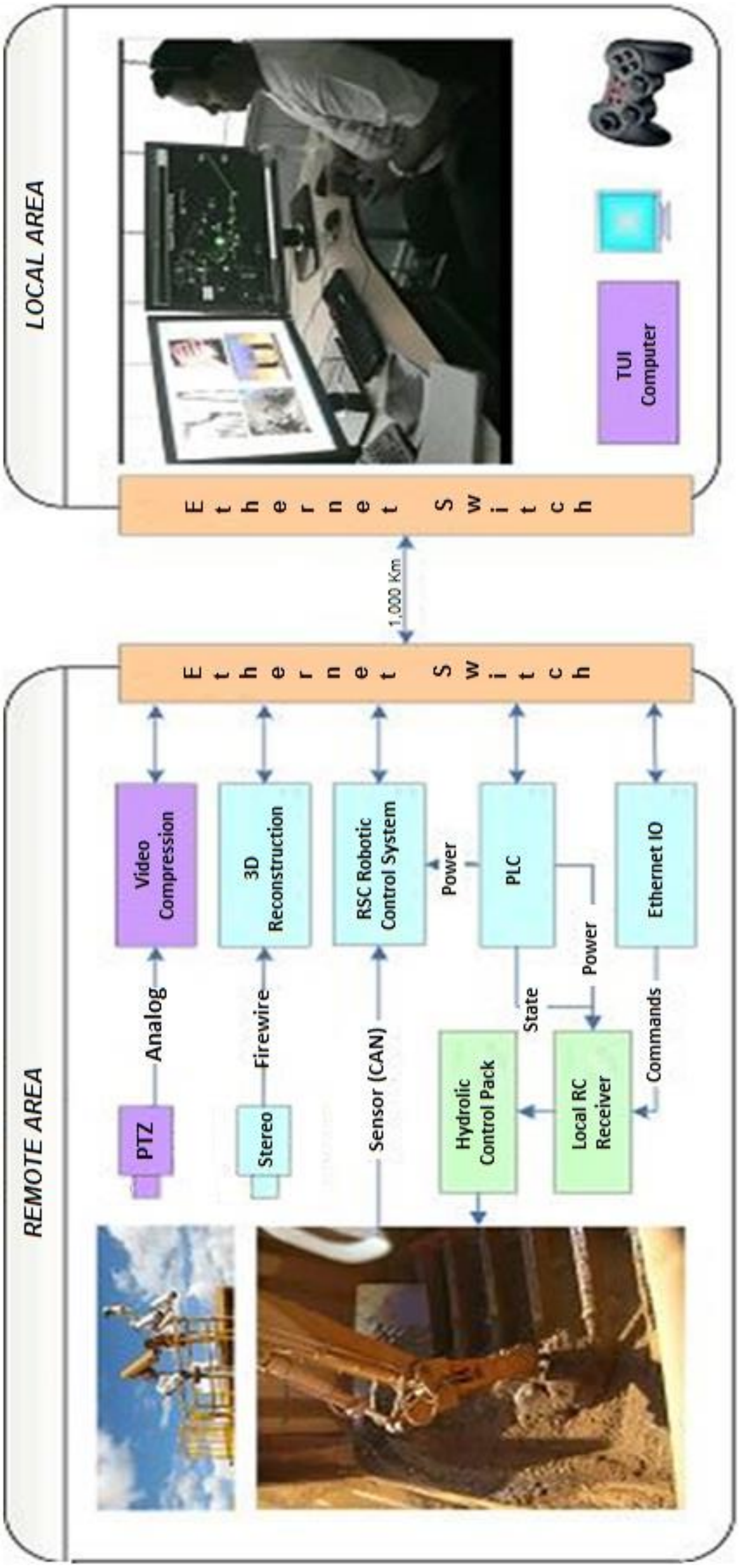


Figure 2.28: The system's architecture of *Rockbreaker* [5]

I investigated Second Life (SL) as the first gaming environment. I built a robot arm *Rockbreaker* model in Figure 2.29(a) as a VR telerobot. This robot arm model consists of four main parts namely the: base, swivel, boom, jib, and hammer. This model has four degrees of freedom (DOF) and all parts are linked together in sequence as shown in Figure 2.29(b).

Initially, I modelled the robot arm by using simple 3D shapes called cube prims (prim or primitive object is a single object inside SL[44, 45]) to represent the base, swivel, boom, jib, and hammer. In addition, I also added a sphere prim as a tip pointer to represent the hammer tip position (shown in Figure 2.29(c)). I located them on one of the private virtual servers inside SL, which prevents unauthorised users/players from accessing the 3D virtual model. A 3D robot arm was made with several 3D shapes.

The interaction between the operator and the 3D model is conducted using the avatar to control the tip pointer (an avatar is a user representative in the SL world with a remote-person viewpoint). The tip pointer could be manipulated to specific positions in 3D coordinates. After a position is defined, it automatically triggers certain functions to move all links of the 3D robot model to match the defined position. This movement works by calculating the inverse kinematics of the arm with its position indicated by the defined tip position. Each link of the 3D model will move one at a time since SL only allows the linked objects to be rotated about its root object, so the base of the arm is rotated first then it is detached from the model, the second link then becomes the root object and the model is rotated to the required angle for the second joint and so on.

In this VR model, the telerobotics scenario is required to deliver and receive information from other servers (e.g. telerobotic server) through the Internet. In order to test the communication between SL and other servers, I utilised a HTTP request protocol as it is one of the limited communication protocols that is allowed in SL. Due to limited access to real mining robots, I considered alternative remote devices for these communication tests. For an alternative telerobotics, I utilised three different telerobotic servers. The first communication test was using a *Rockbreaker* simulator web-based server (see Figure 2.29(e)). The second communication test was using the UWA ABB robot as a telerobot (see Figure 2.29(g)), and the third was using a custom built server that connected to a small robot arm (see Figure 2.29(f)).

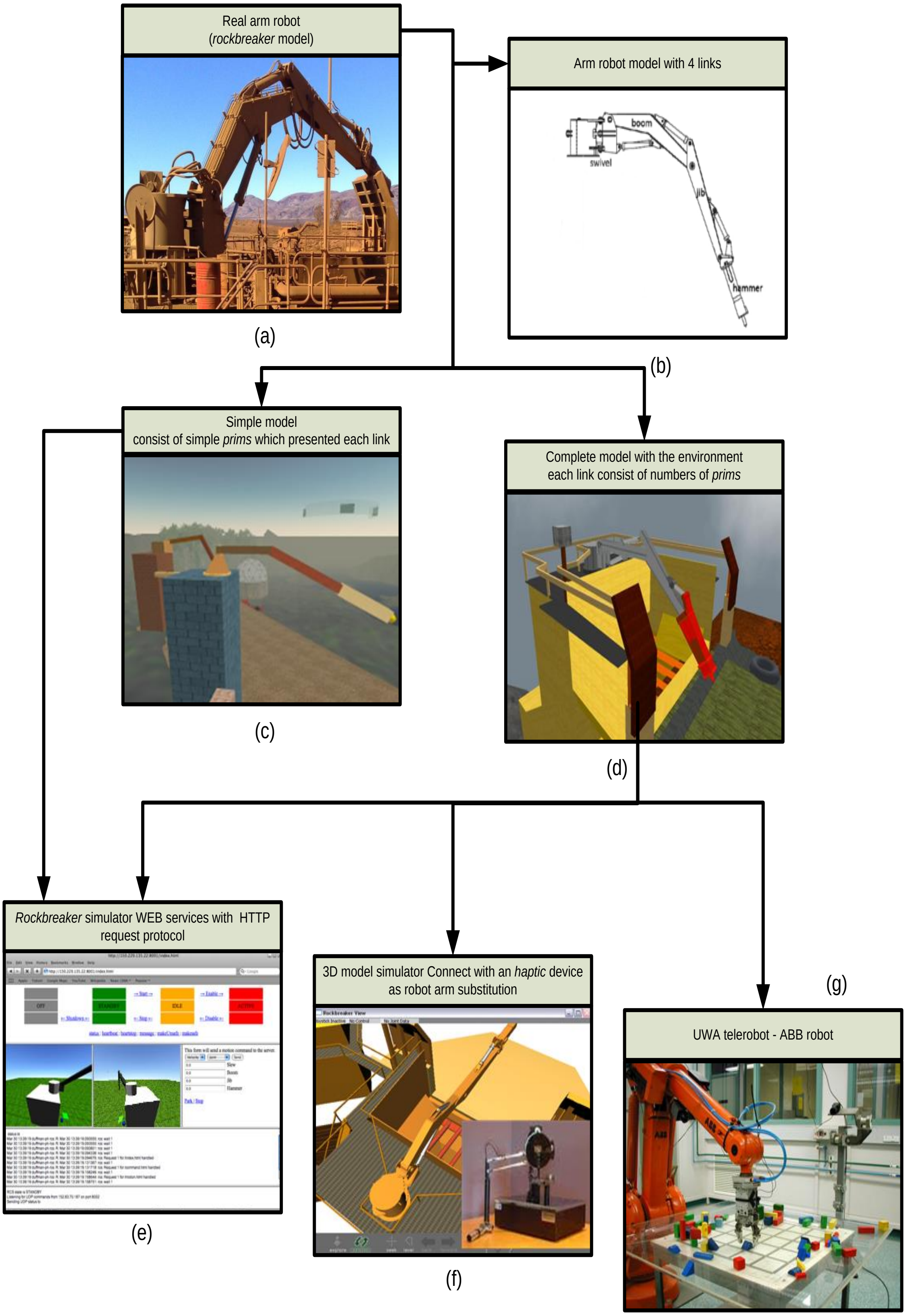


Figure 2.29: First trial overview of telerobotics using the Second Life (SL) environment

2.4.1 Web-based Telerobotics Simulator

The web-based server control system is built based on DDX (Dynamic Data eXchange) which is used as a core platform for building distributed robot controllers for the telerobot *Rockbreaker* project [5]. It aims to simulate the actual *Rockbreaker* arm, and also to trial the communication between their custom built interface and *Rockbreaker*.

DDX refers to software which is packaged from both the application and the controller. It was developed by CSIRO (Commonwealth Scientific and Industrial Research Organisation) over the last ten years under an LGPL open source to assist the rapid development in robotics systems. The advantages of DDX are that it provides a safe mechanism for sharing data between processes, and provides load balancing between different processes from different machines to deal with hardware failure.

The DDX framework provides shared memory access to several clients, and uses UDP (User Datagram Protocol) to copy shared memory content inside one client. The mechanism of DDX uses a communication system to deliver data among processes on the networked computer. It consists of two elements (the store and *catalog*) which can be seen in Figure 2.30. The store is used as a data repository while the *catalog* maintains the contents of each store.

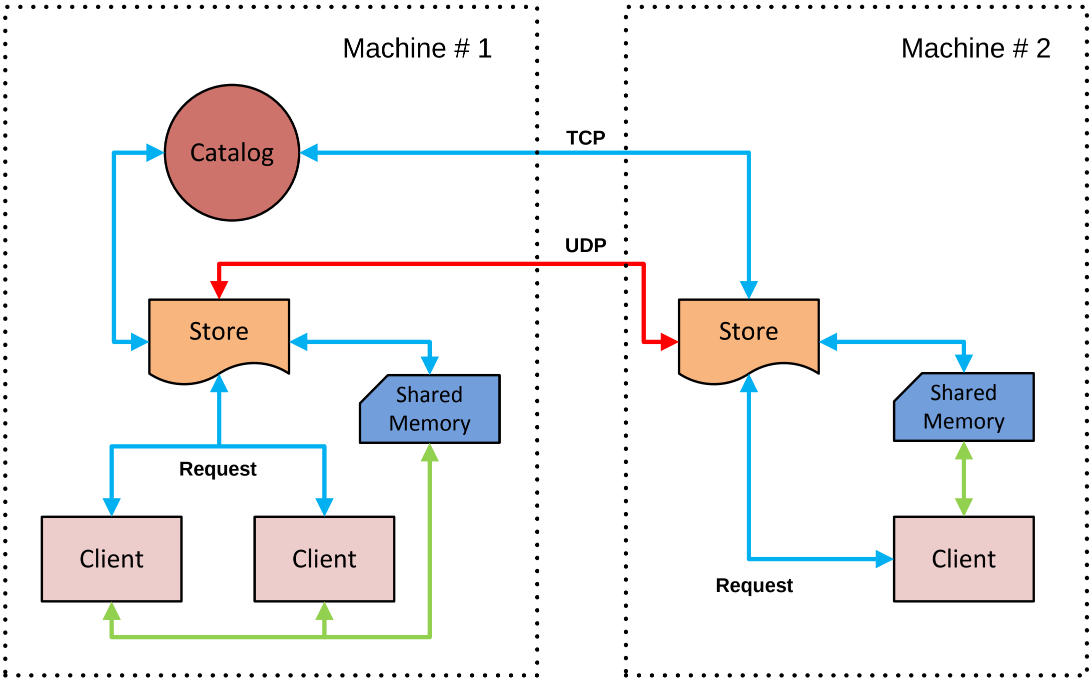


Figure 2.30: DDX framework

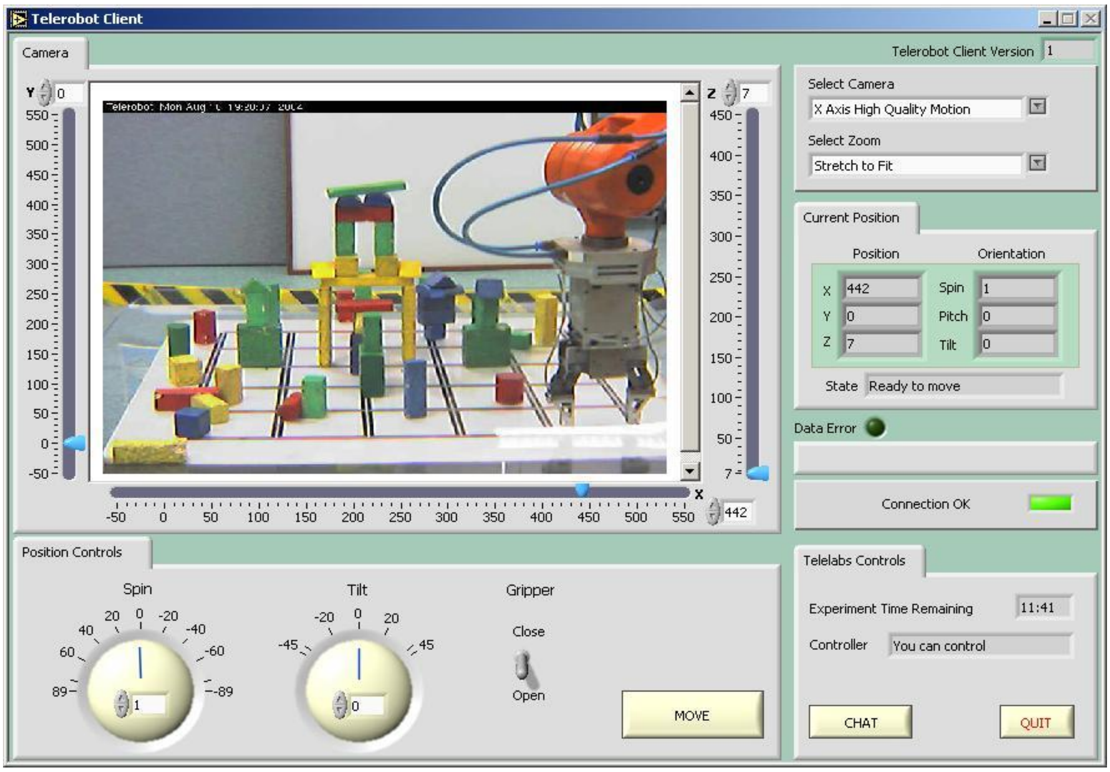
In general, the web-based server works via two-way communication, by receiving a number of arm link positions, and then sending the simulated feedback positions back to the client application. The feedback positions were used to update the 3D model inside SL.

From the first communication test, I discovered that SL enforces a delay of one second to create a link between the prims and 0.2 seconds between rotations of the same object, which was done to ensure the server would have the capacity to keep the world synchronised with all the clients viewing an action. Any multiplayer online gaming has to address the issue of maintaining concurrency and must find a method of limiting the rate of change in the world to achieve this. However, this means a full pose takes nearly four seconds which is too long. Hence a quicker method of displaying the new position was required.

Furthermore, in order to provide reliable information on the telerobot through a virtual model for the user, the 3D arm model and the workspace must also be built to closely represent the real conditions (shown in Figure 3.29(d)). For that reason, I used another method to model the arm. Each link of the arm is made of several prims but rather than joining the links into a single object, they are placed in the right location to look like a linked arm. Then, when the arm is moved the new position is calculated for each link and each link is moved independently. This method reduces the total movement time to 0.4 seconds. However, because each prim moves independently at the same time, it causes the arm to momentarily appear to fly apart and reassemble.

2.4.2 UWA ABB Robot

Since it is not possible to test this gaming environment in actual *Rockbreaker* robot, I used another telerobot, the ABB robot, from the UWA Telerobot (http://telerobot.mech.uwa.edu.au/Telerobot/index.html). Using this ABB robot as the API (Application Programming Interface) of the ABB robot allows modification of the ABB controller to communicate directly to a server, which worked with HTTP requests. Another purpose of this trial was to show that SL could also work with a real machine, not just with the simulator.



Telerobot Client Version 1

Select Camera: X Axis High Quality Motion

Select Zoom: Stretch to Fit

Current Position

Position		Orientation	
X	442	Spin	1
Y	0	Pitch	0
Z	7	Tilt	0

State: Ready to move

Experiment Time Remaining: 11:41

Controller: You can control

Figure 2.31: ABB robot telerobotic client interface [67]

Based on the ABB robot client application, shown in Figure 2.31, the robot can be controlled by sending the three coordinates of the tip position. To adapt to a different shape and the number of links of the robot arm without changing the 3D model, I performed the registration and rescaling of positions between the tip pointer and the ABB robot tip, and only used these tip positions for commands and feedback of communication.

In sending a command to this telerobot, I moved the tip pointer to the small robot arm using the avatar. The small robot arm moved to the position sent by SL as far as possible, and returned the final position it achieved which was used to update the model in SL. Even though the arm was shaped differently I was able to move the ABB robot located more than 1,000 Km from the operator.

2.4.3 Custom Built Server with Arm Robot (a modified haptic device) Attached

For further evaluation, it is important on this research to have a telerobot with full access on it. Hence, I tested this SL game to communicate with a custom built telerobot made by haptic device. The idea was to utilise an X3D application as a simulation telerobot to receive the command from SL. In addition, this application is connected to a haptic device which read the command on X3D application as a force feedback. This enabled the haptic device to act as a telerobot. The X3D is a successor of Virtual Reality Modelling Language (VRML) which is commonly used in presenting 3D computer graphics.

Due to the limitations of X3D API in communicating with the TCP protocol, which was the only way to communicate with the SL server, I utilised an XML file as an alternative mediator between the SL and X3D applications. I created a PHP server and ran a PHP script which could receive the HTTP request from SL, and at the same time update the XML file. On the other side, by merging X3D and AJAX, it allowed the application to read the updated XML file, update the 3D model in X3D application and the haptic device. This X3D application rewrote the XML file with the last position of the haptic device as the feedback. Thus, the PHP script continued to gather feedback from the XML file and send it back to the SL server. I located the XML file on a PHP server machine which could be accessed by the X3D application.

A concept of file lock was applied in order to avoid logic errors when the PHP updating process ran together with the X3D application reading process (Figure 2.32).

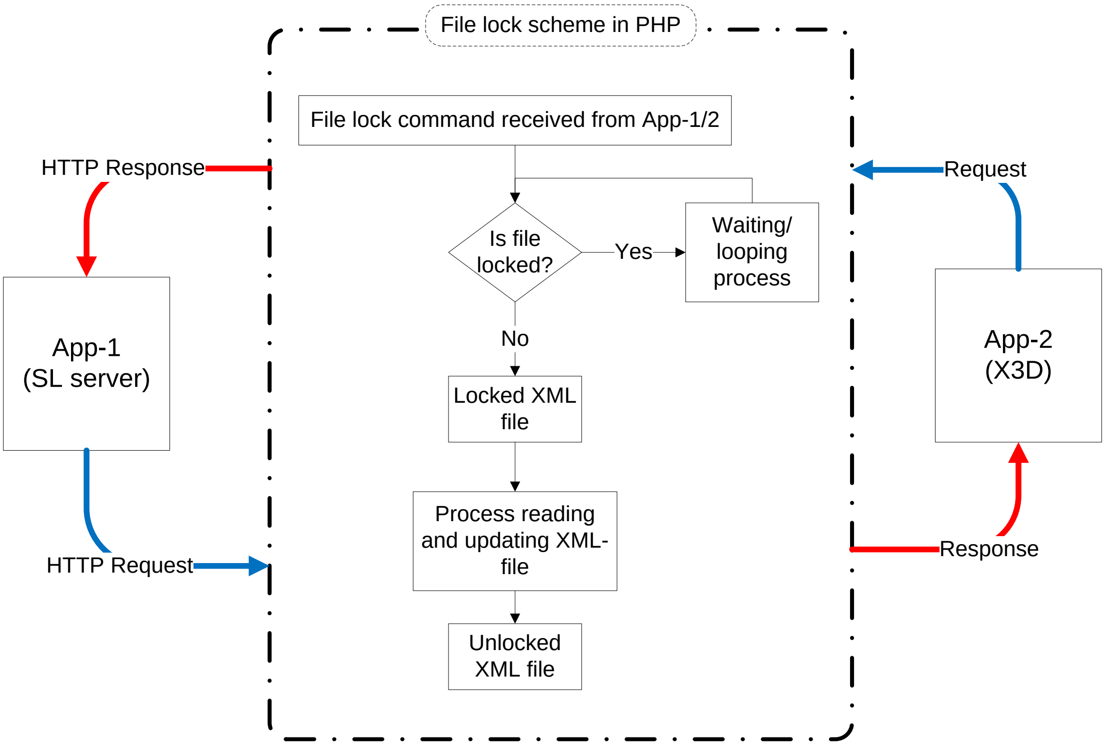


Figure 2.32: File lock concept applied

Based on Figure 2.32, there are two separate closed loops which were running in the system. The locking steps are described below:

1. After receiving the HTTP request from the SL server, the PHP locked the XML file and wrote the request value into the command variable. Then PHP automatically unlocked the file after the writing process was complete.

2. On the other side, while the PHP locked the file, the X3D application did a looping process trying to access and read the XML file. When the file was unlocked, the X3D took over and locked the file, then received the value of the command variable as the request position to move the 3D model and the attached robot. The X3D application kept the XML file locked until it wrote a feedback response into the response variable on the XML file.
3. Meanwhile, during the second step, the PHP continued to try to gain access to read the response variable. When the file was unlocked, the PHP would automatically read the response variable and send the HTTP response back to the SL.

During the communication test, besides the delay in getting feedback information from the HTTP response, the applied file lock concept caused additional time delay in communication. However, the remote simulation server and the robot successfully moved following the request from the SL interface (with 0.3 – 0.5 seconds in a one-way communication – for requests only). Moreover, the 3D model on SL succeeded in implementing the feedback response from the telerobot. For example, when the telerobot gave a different position from the request input because of particular condition, the 3D model would update the position according to the last telerobot position.

Based on this preliminary test, SL has a number of limitations such as: (1) requires up to two seconds in total for receiving the feedback and updating the telerobot model and (2) only allows TCP/IP protocol to communicate with remote devices. However, this gaming environment also provided satisfactory features to continue the research in evaluating the effectiveness of MR interfaces and HSC for a telerobotic based on a gaming environment. To explore the evaluation in more detail, the next chapter discusses the experiment of utilising MR concept in a gaming environment.

Chapter 3

Evaluation of Gaming Environments with MR Concept

This chapter discusses further exploration of the use of gaming engines as telerobotic interfaces. A concept of mixed reality (MR) environment, which combines information from streaming video and 3D computer visualisations inside the gaming environment, was evaluated as an alternative to streaming video interfaces. This chapter discusses user performance from a number of sub-experiments from two gaming engines and the feasibility of using the MR concept in telerobotic interfaces. I demonstrate that the MR concept in a gaming engine can provide an effective telerobotic interface.

3.1 Introduction

In this thesis, I explored the use of gaming environment technology for building telerobotic interfaces. These have previously been viewed as different domains. In my initial stage of research, as described in section 2.4 above, I showed that a virtual gaming environment (Second Life - SL) has similarities features to telerobotic interfaces. According to Richer et al [33], gaming environments have similarity to 3D graphics interfaces but also offer more features, essentially a superset, compared to other 3D applications. They also mentioned that “Unlike most computer applications in which the interface serves as a means of interacting with some underlying functionality, the sole purpose of a video game's interface is for the player to interact with it”. Hence, the gaming environment offers many similar features to telerobotic interfaces, as well as its advantages in comparison to the existing computer 3D applications. Furthermore, a number of existing telerobotic interfaces [1, 11, 21] have successfully used 3D graphics as an alternative to video interfaces. This opens up the possibility of using a virtual-gaming environment to build an interface, as it contains most of the technologies found in existing 3D application interfaces. Besides providing a sophisticated environment for 3D modelling and the freedom to define the actions and behaviour of the 3D model, a gaming environment offers features, such as ease of integration with a variety of sensors and input devices, a wide range of custom-built libraries and functions and an environment that is easy to use [33]. The multiuser features in gaming environments can be used to share information and for collaborative-control scenarios in future telerobotic system.

Video feedback has been used for telerobotics since the 1950s, but streaming video on the Internet only started to become popular at the end of the 1990s [2]. Initially, the main technical limitations of streaming video were its requirement for high CPU load and Internet bandwidth to support the required data transmission rates, especially if the TUI (Telerobotics User Interfaces) was using more than one video stream [6]. With current devices available, the CPU load is not an issue anymore. On the other hand, while high bandwidth is becoming more readily available, it still has practical limitations. Other limitations include the restriction of viewpoints in camera positions, difficulty in conveying non-visual information and the lack of machine-readable information to support automation.

This chapter reports the experiment that was conducted to assess the effectiveness of the MR concept on two gaming environments (Second Life and Simmersion’s Mycosm) as telerobotics user interfaces. Besides, the experiment also tried to assess the effect of the level of user attention on the interface while performing the task. Before further description about the experimental setting, the result and the discussion, the next section describes telerobotics implementation which was used for the experiment.

3.2 Prototype Implementation

Based on the initial communication implementation on Chapter 2, and due to limited access to real mining robots to test the proposed telerobotic interfaces, I built a smaller replica robot arm as a telerobot. This robot has been built to replicate the *Rockbreaker* robot function (manipulation robot arm).

I built the robot by modifying a haptic device. Despite this robot arm having a different shape compared with the real *Rockbreaker* with three rather than four links, I added an engraver as a hammer tip to this haptic device to transform this robot into a miniature *Rockbreaker* robot. Figure 3.1 shows the modified shape of the telerobot model.

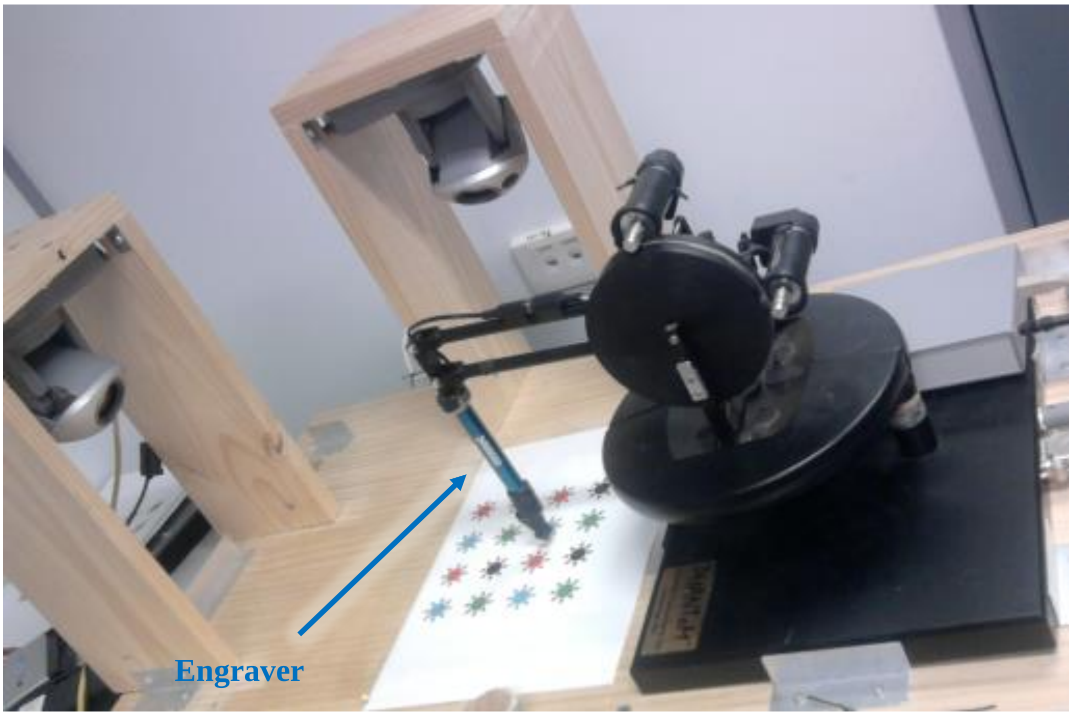


Figure 3.1: Robot arm, workspace and two remote cameras

For the interfaces, a 3D model of the modified robot arm including the workspace was built inside the gaming environments. In order to apply the MR concept, the streaming video from a remote camera was embedded in the virtual environment to show the elements of the scene which were not represented in the model (e.g. people or any undefined modelled objects) and to allow operators to monitor their performance. The streaming video worked by replacing the surface texture of a virtual object inside the virtual world, so it acts as a video window. In addition, the overlaying virtual dot pointer was attached to the video stream to show the position of the robot tip, which was determined by calculating inverse kinematics from the measured joint angles and projecting the three dimensional tip positions onto the plane of the video.

In order to test the possibility of using a gaming environment as a basic platform for telerobotic user interfaces, I applied the MR concept on the two different engines, Second Life (SL) and Simmersion-Mycosm (Sm), as described below.

3.2.1 Utilisation of Second Life as Mixed Reality Telerobotics Interface

The first interface to which the MR concept was applied was Second Life (SL) from Linden Lab. Figure 3.2 shows that the 3D model of the robot arm was built together with the workspace. Based on the experiment scenario, which will be explained in the following section of this chapter, an arena marked with various coloured stars was used as a workspace and also added as a virtual model. Two live videos were included in the virtual environment and they work by presenting the virtual object inside the virtual world. The position of the robot model was represented by the virtual object in the form of two dots that were embedded in the streaming video surface.

As discussed in Section 2.1.2 regarding the SL gaming environment, the limitation of SL is that interaction between the human operator and the model is only available through an avatar. The operator controls the avatar to move the pointer by clicking a desired position or by dragging the model pointer (e.g. the users clicks and holds the tip model and also moves it around). To send a command to the telerobot, a clicking function was also provided on the streaming video. The operator can move the robot arm by clicking on the streaming video surface. The robot will then move in a plane perpendicular to the video camera lens axis. The two cameras are perpendicular to each other to allow movements that are commanded from any direction.

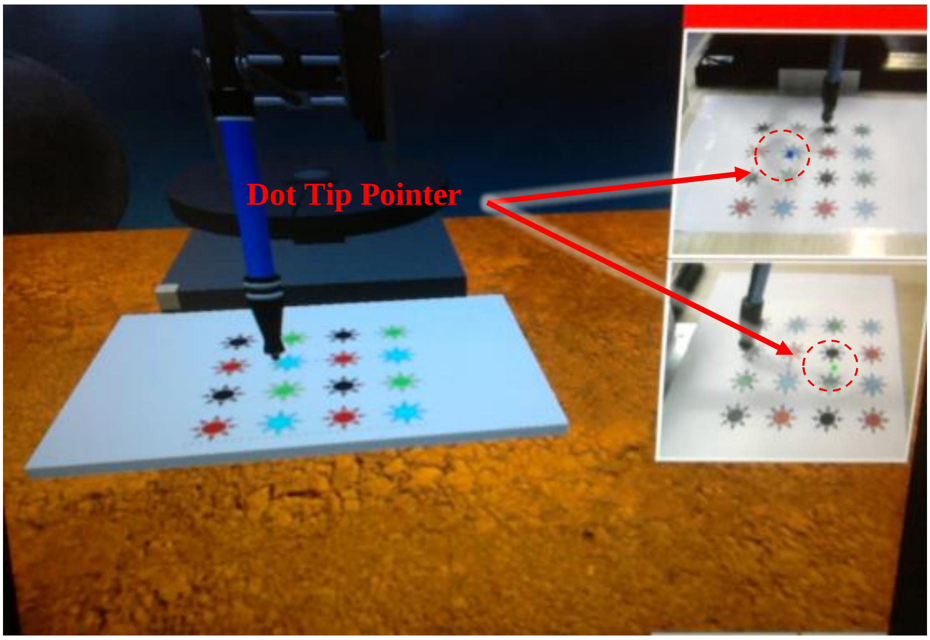


Figure 3.2: MR concept built in Second Life (SL)

Each defined position was sent as a single command to move the telerobot. The SL triggered an event on the script to send a single command each time the users clicked a position on the workspace/screen, or each time they released their finger after dragging the tip model causing the 3D model to move to that position.

3.2.2 Utilisation of Simmersion as a Mixed Reality Telerobotics Interface

Figure 3.3 shows the Simmersion-Mycosm (Sm), another gaming engine that used to apply MR concept for telerobotic interface. The interface was built using the Mycosm library from Simmersion Holdings Pty Limited.

A similar MR concept was applied in this gaming environment. A robot arm model and a workspace were built inside the virtual world including streaming video. In contrast to the streaming videos positions in SL, I placed the videos at various places behind the robot arm model. The front view of the streaming video was set to always facing the users, so the users did not lose any information from the streaming video.

This Sm environment allows the users to give a command to a 3D model without using the avatar (the avatar model could be disabled), which I believe does not greatly affect user performance. This environment also allows the 3D robot model to move together with the user commands, (this feature was limited in the SL environment). Similar to the SL environment, the virtual dot tip pointer was also added to the streaming video surface. The clicking and dragging model input was also applied to this Sm environment, by using a mouse as an input device.

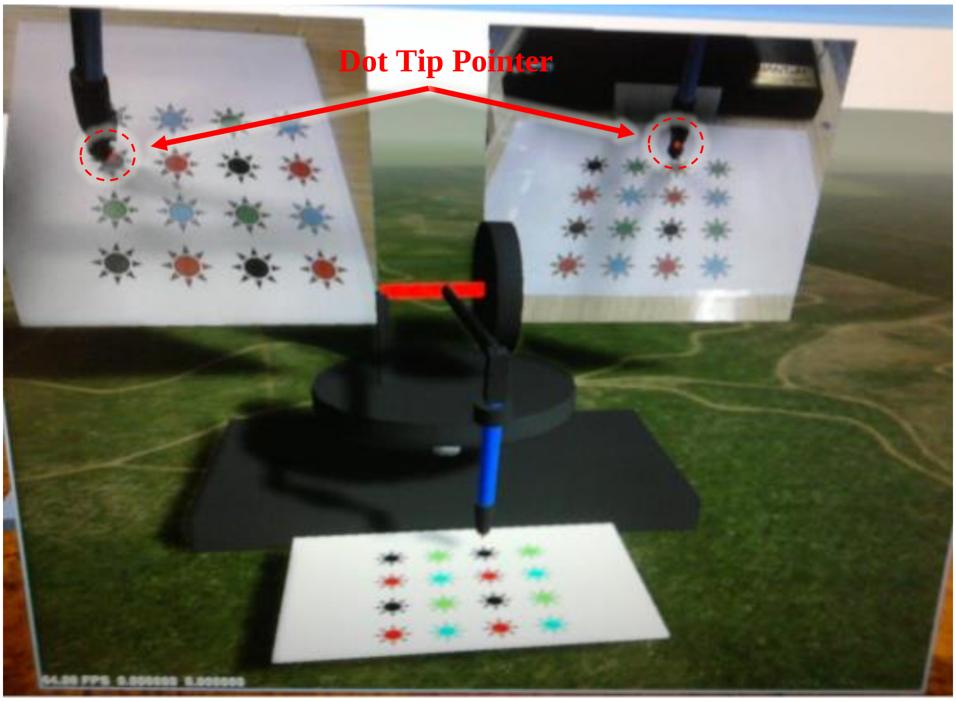


Figure 3.3: MR concept built in Simmersion (Sm)

The pointer movement was in accordance with the tip position on both interfaces. The difference between the Sm and SL environments was that the pointer moves as the model moves in the Sm interface, but in SL the script that moves the pointer can only run on completion of the user action, so the pointer is updated after the new robot position is defined.

As mentioned in previous chapters, the virtual camera enables the operator to see from any direction. However, the view of the real scene from both cameras is fixed, that is a common limitation of remote cameras in a telerobotic application. Most remote cameras in telerobotic applications can only pan and tilt, and for ease of implementation of this experiment the cameras were rarely repositioned.

3.3 User Study

In accordance to one of the aims of this research, which is to evaluate the effectiveness of user performance in gaming environments with MR telerobotic interfaces, I conducted two sub-experiments by using two different gaming engines, SL and Sm. The gaming features available, which are described in Section 3.2.1, were explored to apply a MR interface.

In an implementation of telerobotics to control a large Rockbreaker in an iron-ore mining operation, as reported by Duff et al. [5], the operator was required to dedicate more attention to performing the tasks than when they were performed on site. In this experiment, I evaluated the user performance for two MR gaming interfaces based on the level of attention the operator gave to the interface. A description of how information was collected, and how the level of attention was categorized is given in detail in sub-subsection 3.3.3.

Figure 3.4 illustrates an overview of the experiment’s architecture. The setting was designed to emulate, as closely as possible, the telerobotics setting of the real telerobot machine. In this experiment, the operator used only a standard keyboard and mouse as input devices to move the 3D model and the telerobot.

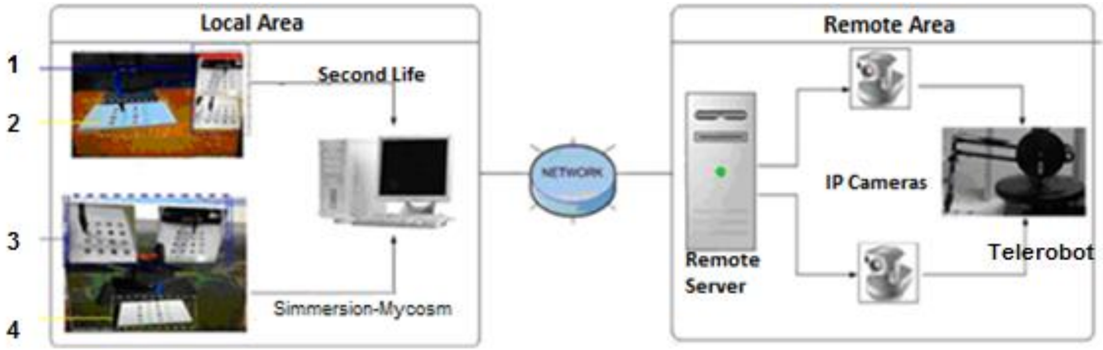


Figure 3.4: An overview of the experiment’s architecture: (1 and 3) streaming video from the camera, (2 and 4) 3D model white board

3.3.1 Apparatus

The two gaming environments with the MR interface applied were run on a desktop PC on the client site, with the following specifications: NVIDIA Quadro FX 1700 for VGA and 2814 MB in memory RAM. The display used a standard 19” monitor with a resolution of 1280 x 1024 pixels to run the interfaces.

In this experiment, a standard keyboard and optical mouse served as the user inputs to the interfaces. Unlike the previous work, conducted by Duff et al. [5] and Hainsworth [6], which used a gamepad, I chose the standard keyboard and optical mouse because they are suitable for use with HSC for clicking and dragging. They are also ergonomic tools, familiar to users and compatible with all computer gaming environments.

Based on a gaming control standard system, I set the four key arrows or ‘A’,’W’,’S’,’D’ as left, up, down, and right respectively; and keys ‘E’,’C’ or ‘Page up’, ‘Page down’ for zoom in/zoom out to control the virtual camera viewpoint. By holding the ‘Alt’ key together with a ‘left-click’ of the mouse will allow the virtual camera to be repositioned. To control the robot arm, ‘left clicking’ the mouse will allow the robot tip to be moved forward, backward, right and left; depressing the ‘Ctrl’ key and ‘left clicking’ the mouse will allow the mouse to control the height of the tip.

The remote location consists of a robot arm with an engraver, which was used as a replica *Rockbreaker* telerobot, and two Canon cameras of type VB-C50iR. One camera was placed 30 cm in front of the centre of the robot’s workspace and 25 cm above the work surface. The other camera was placed 10 cm to the right of the centre of the robot’s workspace and 25 cm above the work surface. Both cameras pointed to the centre of the scene.

I designed a remote workspace to conduct a simple task by using the robot arm to push/move a target object from one position to another. Hence, a white board with 16 symbol stars in four different colours (red, yellow, black, and green) were used as a position target (shown in Figure 3.1), with these specifications, each symbol star of the same colour was placed 10 cm apart.

3.3.2 Participants

A total of 19 volunteers (12 males, seven females) participated in the experiment, all of whom are students in various fields at the university. They range from 18 to 49 years of age (Mean 22.9, SD = 7.8). All participants were regular computer users with no previous experience in this telerobotic scenario system. Nine of them played computer games “often” (more than one hour per day), another six played computer games "occasionally" (less than one hour per day) and the remaining four never played computer games. Since a coloured star was utilised as a target position, no participants were colour blind. A complete list of the characteristics of participants is found in Table 3.1.

Table 3.1: Characteristics of the participants

Characteristics	Percentage (%)
Gender	
• Male	63.15
• Female	36.85
Frequency of playing computer games (habits)	
• Often (> 1 hour/day)	47.37
• Not often (occasionally or never)	52.63
Experienced in Second Life (SL) environment	
• Yes	68.42
• No	31.58
Experienced in Simmersion-Mycosm (Sm) environment	
• Yes	15.79
• No	84.21

3.3.3 Experimental Design and Procedure

The experiment has two task scenarios and participants were asked to use two different interfaces. The two tasks were:

1. Move the robot arm to touch a star of one colour and then to touch another star of the same colour. In total I asked the participants to perform the task four times in both clockwise and counter-clockwise directions within a time limit of two minutes for each direction. The participants received the same information regarding the arm and target positions in both the 3D model and streamed video.

2. Push a rock continuously to four different target positions. Each target position must be reached within two minutes. The participants received the same information regarding the arm and target positions in both the 3D model and streamed video while the rock position was provided by video views only.

At the beginning of the experiment, participants were given a short verbal introduction including a brief description about the interfaces, instruction on how to use the interfaces, and the requirements of the tasks. All participants were asked to confirm their understanding of how both interfaces worked and the tasks. Prior to the experiment, pre-training for each interface was also provided for approximately five minutes. Each participant was randomly assigned to different orders of gaming environments to eliminate any order effect (ten participants had SL first then Sm, and the rest had the opposite). The maximum time for each task was set based on the pre-trial experiment.

As an objective measurement of user performance, I recorded the time taken to reach each target position. The subjective assessment employed a *Likert*-scale based questionnaire to determine the level of attention to the interfaces by grouping the scale into high and low attention. A detailed explanation of the grouping process is given in section 3.4.1. The *Likert-scale* based questionnaire was also used to determine the time taken by each participant to become familiar with the interface, and their estimation of its user friendliness and performance.

3.4 Result

I collected data of two user performance indicators, the task completion time and the total commands sent, on MR telerobotic interfaces built based on both gaming environments. The results on user performance are presenting based on two gaming environment, SL and Sm, following by further discussion in the next section.

3.4.1 User Performance Based on MR Telerobot Interface in SL Environment

In order to evaluate the MR concept in gaming environments, with regard to evaluate the effect of user attention on task performance, I divided the participants into two level attention groups. Based on data collected from the questionnaire regarding the level of attention applied to the interface, the first group consisted of participants who paid a low level of attention to the interface, and the second group consisted of those who paid a high level of attention to the interface.

Based on their level of attention, subjects were grouped by low level of attention and high attention. Next, the t-test method with equal variances was applied to estimate the Mean differences of completion times and number of commands sent between the two groups (Table 3.2 and Table 3.3)

Table 3.2: Mean difference of task completion time between low and high level of attention groups by task, SL environment

Level of attention	**Task completion time (s)**			
	Task 1		**Task 2**	
	Mean	**SD**	**Mean**	**SD**
Low attention	11.96	1.17	68.73	6.90
High attention	22.39	3.75	82.45	11.11
	t = -2.29 **p = 0.03**		t = 1.02 p = 0.32	

Table 3.3: Mean difference of total number of commands sent by participants between low and high attention groups by task, SL environment

Level of attention	**Total commands sent**			
	Task 1		**Task 2**	
	Mean	**SD**	**Mean**	**SD**
Low attention	1.78	0.27	12.9	0.98
High attention	2.94	0.86	11.13	1.28
	t = -1.39 p = 0.18		t = 0.79 p = 0.44	

As shown in Table 3.2, out of all participants who did the first task, those who paid a low level of attention to the interface recorded a significantly lower mean completion time than those who paid a high level of attention to the interface ($p<0.05$). Out of all participants who did the second task, the group with a low level of attention recorded a lower mean completion time, although this difference was not statistically significant, and this could be due to the complexity of the task or having incomplete information.

There is no significant mean difference in the number of commands sent between participants who paid a low level of attention and those who paid a high level of attention to the interface (see Table 3.3). However, the total number of commands sent for those who paid a low level of attention was smaller than that for those who paid a high level of attention in the first task but the opposite was true in the second task.

Hence, based on two user performance indicators in this SL environment, the completion times and the number of commands sent, people who paid low level of attention to the interface perform better compared to people who paid a high level of attention. However, in a situation where the information of rock position was only received from video (task 2), the results show no significant difference between participant who paid low and high levels of attention to the interface.

Also to assess the effect of the level of user attention in the SL environment, a Chi-square method was applied to compare the association between the level of attention spent on the interface and the level of perceived difficulty for both tasks. (Table 3.4 and Table 3.5)

Table 3.4: Proportion of self-perceived difficulty in task 1 by level of attention, SL environment

Level of attention	**Perceived difficulty in task 1 (%)**					**$\chi 2$**	**p**
	Very easy	**Easy**	**Moderate**	**Hard**	**Very hard**		
Low attention	25.0	50.0	25.0	0.0	0.0	8.88	**0.03**
High attention	9.0	9.0	18.0	64.0	0.0		

Table 3.5: Proportion of self-perceived difficulty in task 2 by level of attention, SL environment

Level of attention	**Perceived difficulty in task 2 (%)**					**$\chi 2$**	**p**
	Very easy	**Easy**	**Moderate**	**Hard**	**Very hard**		
Low attention	0.0	40.0	40.0	20.0	0.0	8.23	0.08
High attention	7.0	0.0	22.0	57.0	14.0		

The data showed that for the first task, there is an association between both variables, where those who paid a low level of attention to the interface perceived that the task was easier compared to those who paid a high level of attention ($p = 0.03$). However, for the second task, even though fewer participants who paid a low level of attention to the interface perceived the task as difficult or very difficult (20%) compared with those who paid a high level of attention to the interface (71%), a significant association between both variables was found only at the 90% confidence level.

Based on the questionnaire, all participants paid attention to the information provided by the 3D model (Figure 3.5). When performing the first task, where the 3D model and video provided the same information (task 1), nearly 80% of the participants paid a moderate to higher level of attention to the 3D model. Even in a situation where information on the rock's position was not provided by the 3D model (task 2), 68% of participants still paid the same level of attention to the 3D model.

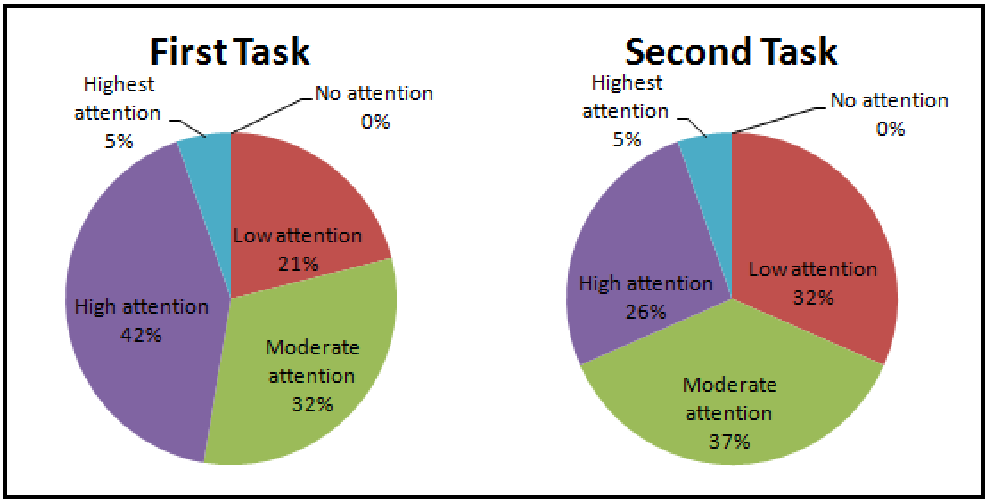


Figure 3.5: Attention level of participants to the 3D model for the first and second tasks using SL environment

Data from the questionnaire also showed that 74% of participants assessed this SL environment with MR interface as user friendly, noting that many did not have prior experience with SL or did not play computer games often.

3.4.2 User Performance Based on MR Telerobot Interface in Sm Environment

In Sm environment, the t-test method with equal variances was also applied to compare the completion times and the number of commands sent between subjects who paid a low level of attention and those who paid a high level of attention to the interface. The analysis results for this Sm environment are presented on Table 3.6 and Table 3.7.

Table 3.6: Mean difference of task completion time between low and high attention groups by task, Sm environment

Level of attention	Task completion time (s)			
	Task 1		Task 2	
	Mean	SD	Mean	SD
Low attention	13.06	5.82	48.40	28.46
High attention	17.27	7.04	54.22	25.95
	t = -1.41 p = 0.17		t = -0.46 p = 0.65	

Table 3.7: Mean difference of total number of commands sent by participants between low and high attention groups by task, Sm environment

Level of attention	Total commands sent			
	Task 1		Task 2	
	Mean	SD	Mean	SD
Low attention	2.04	0.77	11.95	4.7
High attention	2.35	0.51	8.92	2.89
	t = -0.95 p = 0.36		t = 1.67 p = 0.11	

As shown in Table 3.6, the Mean of task completion time for the participants who paid a low level of attention to the interface was also lower than those who paid a high level of attention to the interface. However, this is not statistically significant ($p > 0.05$). For both tasks there was no significant difference in term of the number of commands sent between participants who paid a low level of attention and those who paid a high level of attention to the interface (see Table 3.7).

Similar to the results for the SL environment, the number of commands sent for those with a low level of attention was also smaller than for those with a high level of attention in the first task, but the opposite was true for the second task. Hence, it was indicated that where information of rock position was not modelled or was not available in the virtual environment, paying more attention to the interface was necessary to effectively send commands to complete the task.

In assessing more further about the effect of level of user attention in Sm environment, Table 3.8 and Table 3.9 shows the result of Chi-square analysis for association between level of attention groups and proportion of self-perceived difficulty in task 1 and task 2.

Table 3.8: Proportion of self-perceived difficulty in task 1 by level of attention, Sm environment

Level of attention	Perceived difficulty in task 1(%)					$\chi 2$	p
	Very easy	Easy	Moderate	Hard	Very hard		
Low attention	8.33	66.67	25.0	0.0	0.0	15.78	**0.003**
High attention	0.0	0.0	14.29	71.43	14.29		

Table 3.9: Proportion of self-perceived difficulty in task 2 by level of attention, Sm environment

Level of attention	Perceived difficulty in task 2 (%)					$\chi 2$	p
	Very easy	Easy	Moderate	Hard	Very hard		
Low attention	0.0	50.0	40.0	10.0	0.0	7.10	0.07
High attention	0.0	11.11	22.22	44.44	22.22		

Table 3.8 shows that there is an association between both variables in both tasks. It also shows that those who paid a low level of attention to the interface perceived that the task was easier compared to those who paid a high level of attention (p = 0.003). However, for the second task (see Table 3.9), a significant association between both levels of attention was found only at the 90% confidence level. The similarity of this result with that was found for the SL environment is expected as both environments rely on just one source, for example video to track the rock position (there is little difference whether a user pays low or high attention to one source of information).

According to the participant’s questionnaire responses, in relation to the task where both the 3D model and video provided information (Task 1), nearly 80% of the participants paid a moderate to high level of attention to the 3D model (a similar result to the SL environment).

Where the information on the rock's position was only available via video (Task 2), there were only 27% of participants who paid a low level of attention to the 3D model.

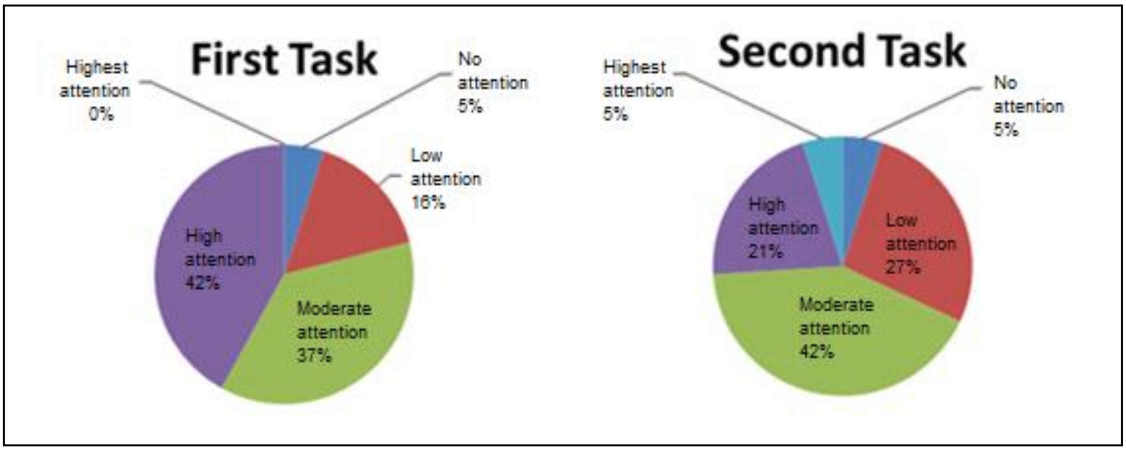


Figure 3.6: Attention level of participants to 3D model for the first and second task using Sm environment

3.4.3 Comparison of Mean Difference Test of User Performance between SL and Sm Environment

In addition to the analysis above, I performed further analysis to investigate whether there was any relationship between the difference of means in user performance between the SL and Sm environments. In order to do a comparison, a t-test with equal variances was applied to compare the average time taken to complete tasks in both environments. A null hypothesis was defined as the time taken to complete the task in the SL interface is not significantly different from that in the Sm interface for each task. In other words, the difference between the Means for the two groups is zero.

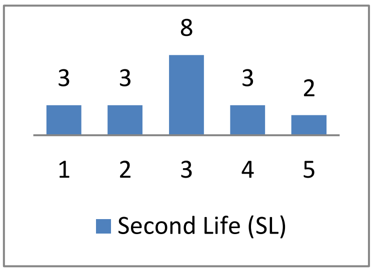
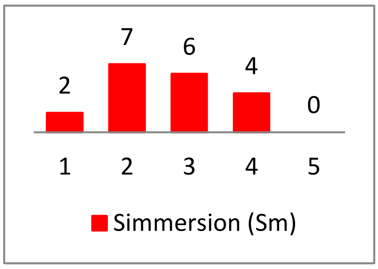
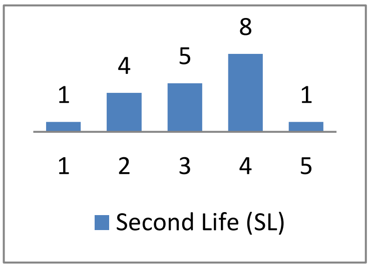
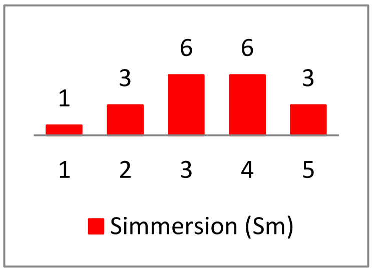
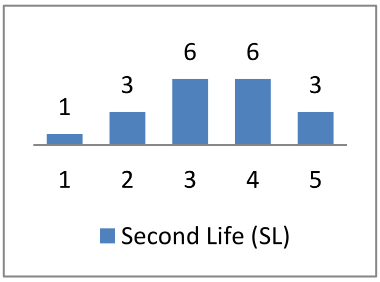
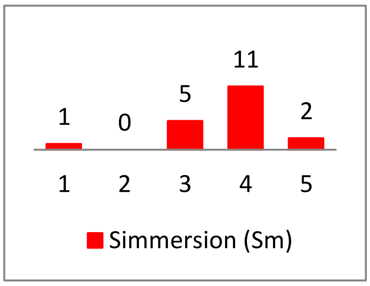
Table 3.10: Average task completion time measurement for each target position in task 1 and task 2

Task completion time in	Task 1	Task 2
Second Life (SL)	Mean = 18.00 s SD = 10.87 s	Mean = 72.34 s SD = 25.73 s
Simmersion-Mycosm (Sm)	Mean = 14.61 s SD = 6.45 s	Mean = 51.16 s SD = 26.71 s
	t = 1.17 p = 0.25	t = 2.49 **p = 0.02**

Table 3.10 showed that at the 95% confidence level, there was no significant difference in completion time for task 1 between participants who used the SL and Sm environments (with p-value more than 0.05). However, it could mean that any difference that may exist is small and would require a more powerful test (e.g. more participants) to detect. In contrast, for task 2, the completion times of participants who used the Sm environment were significantly shorter than those who used the SL environment (Sm: SL = 51.16: 72.34 seconds, $p < 0.05$).

Furthermore, based on the responses to the questionnaire, Table 3.11 shows the impact of a number of factors on user performance. The Sm environment was considered as somewhat easier to learn compared with the SL environment. In terms of user-friendliness, neither gaming environment was obviously preferred over the other. The interface performance for the Sm environment was assessed as better than that for SL. This also led to a few more participants preferring the Sm environment over the SL environment as shown in Figure 3.7.

Table 3.11: Participants' assessment of time needed to become familiar with the environment, user friendliness and general performance on a 5 point scale

	Second Life (SL)	**Simmersion (Sm)**
1. Subjective time needed to become familiar with the interface		
Average (std. d.)	2.895 (0.42)	2.831 (0.44)
		
Info: 1→ very short, 5→ very long		
2. How user friendly is the interfaces?		
Average (std. dev.)	3.211 (0.64)	3.368 (0.49)
		
Info: 1→ very easy, 5→ very hard		
3. Subject perception of the interface performance		
Average (std. dev.)	3.368 (0.49)	3.684 (0.94)
		
Info: 1→ very bad, 5→ very well		

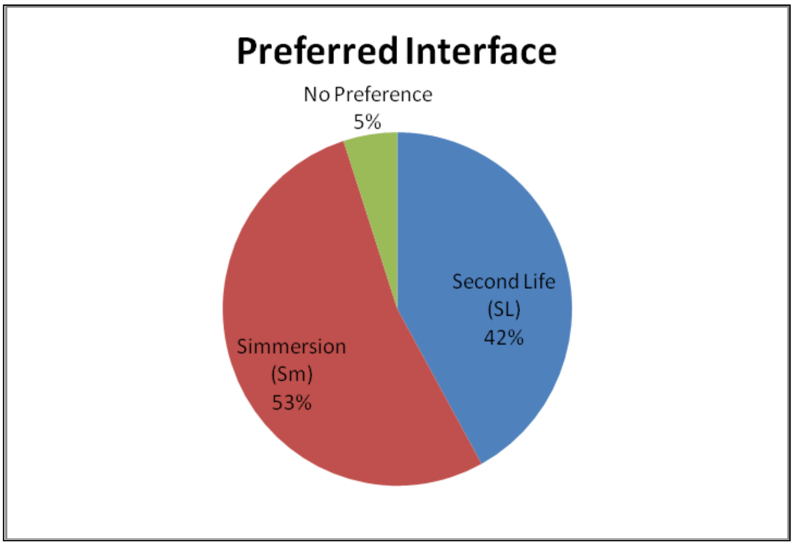


Figure 3.7: Preferred environment based on questionnaire

Based on spoken and written comments, a number of participants mentioned that they experienced difficulty in performing the task when the virtual camera viewpoint was very different from that of the actual camera. Several participants commented that when specifying a location using the video overlay they found it difficult to place the robot tip where they intended in relation to the rock. However, when the operator manipulated the 3D model in the virtual world while at the same time observing the video through the tip pointer overlay, they were able to place the robot where they intended. In addition, given the higher productivity observed in task 2, it was surprising that only 11% more participants preferred the Sm interface over the SL interface.

3.4.4 Dragging versus Clicking

As mentioned in the prototype implementation section in this chapter, MR telerobotic interfaces allowed the participant to give a command using two methods, clicking and dragging. Based on my observations of user behaviour during the experiment, most participants tried both clicking and dragging when giving commands to push the rock from one position to another. However, participants tended to use the clicking method around three times more than they used the dragging method, in terms of the average of proportion of total use (clicking: dragging = 72.03%: 27.97%, with SD = 12.49%).

I did not conduct further analysis to test the effects of both methods on user performance, as the experiment was not designed to test these relationships. However, based on the number of commands sent for each method, I was able to determine that clicking was the favourite method.

I had already assumed the clicking method was preferable to the dragging method since it required less effort in defining the robot's target position.

3.5 Discussion

The experiment was conducted to evaluate the effectiveness of the MR concept on two gaming environments as part of the aims of thesis to develop an application prototype for telerobotics in remote mining equipment scenarios by utilising the features of gaming environments. Here, I determined task completion time, total commands sent and perceived level of difficulty as the outcome variables to indicate the user performance, with level of attention defined as a predictor variable. Analysis was conducted to compare outcome variables between the two groups categorized based on the predictor variable as well as between the interface, Sm and SL.

The results analysis on user performance in subsections 3.4.1 and 3.4.2 shows that paying a low level of attention to the interface and still being able to perform the task well suggests the participant was immersed in the interface and received a sufficient flow of information. This is supported by an argument by Chikszentmihalyi et al. [97], which defined immersion as a state of concentration so focused as to cause an absolute absorption in an activity. The user-friendliness of the interface and the enjoyment gained by the operator when interacting with the interface created a sufficiently immersive experience for the operator to perform the task well.

In task 1 where all required information is provided from both sources of information (3D model and video views), the experiment showed a statistically significant shorter task completion time and a lower perceived difficulty level for participants who paid a low level of attention to the interface. Since in task 1 ensuring that all the information needed to complete the task was sufficiently well modelled in the virtual world and available without referring to the video, the task could be undertaken by only paying attention to the video or to the model. My observations suggest that only occasional reference was made to the video which is in contrast to the real *Rockbreaker* interface [5] where the operator's attention was predominantly directed at the video and the model was mostly unused. This is in line with Adams [98] that mentioned the gaming environment is able to simulate reality inside the user's mind.

In contrast, in the task 2 where information about the rock position was only provided from the video views and not in the 3D model, which is usually the case in most telerobotics scenarios, the experiment did not demonstrate any association between the above variables. This might be due to an inadequate number of participants or other aspects of the gaming [98]. Based on this result, I suggest that other than being an immersive environment, a good interface should provide all required information to the operator. Building models that contain all the necessary information requires an excellent understanding of the task to identify the information that needs to be collected from a large number of measureable indicators and the methods for collecting the required information. This level of knowledge is required to fully automate the task which, if feasible to obtain, obviates the need for telerobotics.

This experiment showed that when users are immersed in the interface, they did not need to pay a high level of attention to the interface, including the display and how to operate the interface. Hence, the operators could be more focused on task accomplishment and thus increase their productivity. This experiment showed that the participants who paid a low level of attention to the interface perceived the task to be easier and were able to complete the task faster than those who paid a high level of attention to the interface.

In comparing user performance in both gaming environments, participants in using Sm environment perform better at the 95% confidence level than the SL environment. The main difference between the two model environments was manipulation of the model during movement was immediately reflected in the video overlay in the Sm environment, but in the SL environment the video overlay was updated only after the new location was specified. This was particularly useful when the viewpoint of the virtual camera was in a different direction to the actual camera, as participants found it difficult to understand how object movements would appear from a different viewing direction.

Another difference is that the participant is represented by an avatar (remote-person viewpoint) in the SL environment but not in the Sm environment. This experiment was not able to identify a significant difference in the task performance times suggesting that a ‘remote-person viewpoint’ or ‘first-person viewpoint’ did not have a large impact on the ease of usage. An avatar is not a hindrance to performance in this situation but is likely to be an advantage to interactions between two operators who must work together on a task. Other experiments have shown that using a three dimensional input device to manipulate a three dimensional model improved task performance, but the improvements will apply equally to either interface tested or even an interface using purely video feedback [65].

Based on the data analysis, I could say that a good interface will make the user feel immersed concentrating on the task flow without having to focus on the interface. This is in line with Fong et al [37] who stated that when an interface is well-designed, it becomes easy to use with minimal effort. On the contrary, when an interface is poorly crafted and difficult to understand, it becomes burdensome, limiting performance and making work tiresome. Hence the value of an interface is largely determined by how easily and effectively it allows the user to perform tasks.

This experiment also demonstrated that information from the 3D model was utilised by all participants to complete both tasks. This disproves my initial speculation that, since the operators were more familiar with the real view, they would tend to ignore the information provided by the 3D model. Supplying the required information from both sources of information (the video and 3D model) in gaming environments also showed that they can be used as telerobotic interfaces with minimal effort, and are enjoyable. This is in line with Jeger's conclusion [99] that understanding the factors that influence a user's enjoyment in an immersive environment allows improved technology such as gaming environments that are immersive.

In addition, the use of a combination of a virtual environment and the overlaying a virtual object (tip pointer) on the video did not show any negative effect on user performance. A prior experience in a gaming environment was not an essential factor for users to perform tasks in these telerobotics scenarios. The briefing and training prior to the tasks were sufficient in providing all the information required to perform the task well. This experiment demonstrated that the MR interface in gaming environments could be used as telerobotics user interfaces. It supported my proposition that using the MR concept in gaming environments was suitable as telerobotics user interface.

3.6 Summary of Chapter

Evaluation of user performance in using gaming environments with a MR concept applied had been conducted. Features available on gaming environments were tested and it was found suitable to provide information for telerobotic interfaces. Avatars and third party servers' features on these two gaming environments tested were not important factors that influence user performance. Manipulating the model using video overlays was a good method of combining video with virtual environments to present information on a telerobotic interface.

The difference features from the two gaming environments, for example: manipulating a model in a virtual environment and seeing the effect on a video overlay was easier to understand and more effective than specifying a location in a video overlay directly. The Sm environment allowed mouse movements to trigger logic that updated the video overlay as objects were dragged, whereas the SL interface only generated events when the dragging of an object was completed and this was a key limitation. Therefore, gaming environments that are to be used for telerobotics should allow logic to be applied during object manipulation.

The results indicate that both gaming environments with a MR concept were suitable for telerobotic interfaces where sufficient information to perform the task could be modelled in the virtual world, and that they only required a low level of attention to perform the task. However, one of the environments turned out to be preferable when completing the task only required information from the video but not modelled in the virtual environment. The preferred environment provided overlays on the video that were updated live as the model was manipulated, whereas the other environment updated video overlays only upon completion of the manipulation.

MR environment by combining two sources of information, virtual model and video, were utilised and were able to work in synergy. The results showed that the virtual environment was useful in providing extra information from the 3D model via tip pointer overlays on video to the participants and assist them to perform their tasks.

Based on this experimental result, I argue that other than providing a sense of immersion, a good interface should also supply complete information. However, as raised by the operator in the Duff et al study [5], multiple sources of information could lead to distraction for the operator which could negatively impact on task performance. Therefore, the challenge is how to identify the required information that is crucial for the operator to perform the task, and at the same time provide a sense of the on-site location so that the operator can be immersed in the task flow. This experiment showed that MR from the gaming environment has potential for facilitating task performance in a restricted type of telemanipulation scenario.

Chapter 4

Telerobotic Gaming Environment with Virtual Camera Control Devices

In chapter 3 showed that a MR environment that uses a virtual model and videos providing identical information resulted in better performance than when using different information. In more complex telerobotic scenarios, it is a challenge to provide virtual models for all physically-remote settings, especially for moving objects with a variety of shapes and sizes (e.g., rocks or blocks that serve as target objects). The virtual model environment also provides a virtual camera that can be used to explore and collect information from the 3D model freely. Hence, this chapter discusses the ability of gaming engines to provide an effective virtual model, where the object adapts to the physical setting and investigates advanced use of the virtual camera. This chapter shows the possibility of integrating various input devices into gaming environments for telerobotic applications. Possible input devices include gamepads and eye-tracking devices, which control virtual-camera movements. This chapter evaluates the effectiveness of these interfaces by closely adhering to the experimental settings of Zhu et al. [39] with telerobotic video-streaming interfaces to enable comparison of results.

4.1 Introduction

To further evaluate the effectiveness of gaming features as telerobotic interfaces, another experiment was conducted. This experiment aims to investigate user performance in gaming environments to deliver updated information from its remote settings. The experiment involves creating a virtual model which accurately represents numerous physical settings. A physical setting contains equipment and a workspace, both of which could be manipulated by an operator. The physical setting that I have used for this experiment is still based on the *Rockbreaker* scenario [5]. The replica robot arm will nudge a target (block/rock) towards a hole.

To maintain the functionality of the virtual model, it is crucial that this experiment takes into account the location of the rock as well as the robot arm. The virtual model will only require simple implementation of physics as the scanner provides information on the positions of the rock/block and arm. Finding the location of the target blocks/rocks and robot arm is quick and precise due to the fact that the other settings remain unchanged.

One of my research goals is to investigate features of gaming environments that can accept input devices from current telerobotic interface. In telerobotic systems, input devices play an important role in delivering information from the operator to the remote machine. Besides delivering operator commands to the telerobot, input devices can also be used to control remote sensors, for example a remote camera sensor. A number of researchers have explored several input devices for machine control such as haptic devices [25, 26, 56] and the Wii control-pad [65]; while others have examined the use of viewpoint control devices such as head tracking, eye tracking or gamepad [39, 70] for streaming video interfaces.

Hence, this chapter describes an experiment to investigate user performance of gaming environments with an improved virtual model using additional input devices for camera control functions. In designing the experimental setting, a design model from the research conducted by Zhu et al [39] was applied. In their experiment, they compared two input devices, namely the gamepad and eye-tracking devices, to control a remote camera for a telerobotic interface with full camera view.

Corresponding to the experimental design of Zhu et al. [39], this used a gamepad and eye-tracking devices for virtual-camera control. In addition to exploring the use of the virtual camera, the experiment made an indirect comparison of user performance between a video interface and using different input devices to control the virtual camera in a gaming environment. To assess user performance, this experiment examined performance differences the two settings. Further details about this experiment are described in later sections.

4.2 Prototype Implementation

4.2.1 The 3D Robot Arm Virtual Model

In previous experiments, the two gaming environments (Second Life - SL and Simmersion - Sm) had been used and tested as telerobotic interfaces. Based on the description from Table 2.3 in Section 2.1.2 regarding features of a gaming environment required to build successful telerobotic interfaces, I investigated available gaming engines and concluded Unity3D [49] fulfils most of the criteria. Hence, I decided to utilise the Unity3D gaming engine for this experiment.

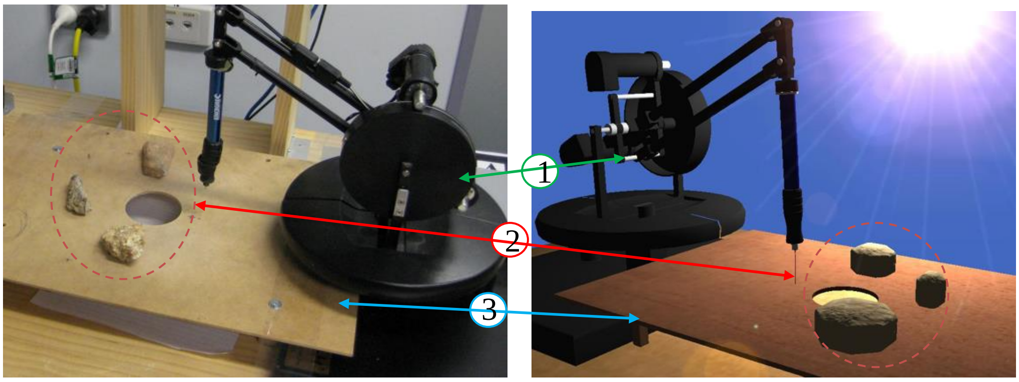


Figure 4.1: Remote settings and 3D model of remote settings based on Unity3D game engine: (1) Robot arm with engraver attached, (2) Rocks – targets objects, (3) Worksite - board with a hole in the middle

As shown in Figure 4.1, the robot arm model was built by using the Unity3D gaming engine. Both the robot arm and the environment models were built to be consistent with the test rig. They were calibrated so that the spatial coordinates of the test rig matched that of the model. The operator controlled the model in the virtual environment, which sent commands to the actual arm to move it to the corresponding position. The position of the arm was represented in the gaming environment by a “ghost” object that typically overlaid the model. The two would separate whenever the arm could not achieve the requested positions, which could be caused by a collision (see Figure 4.2).

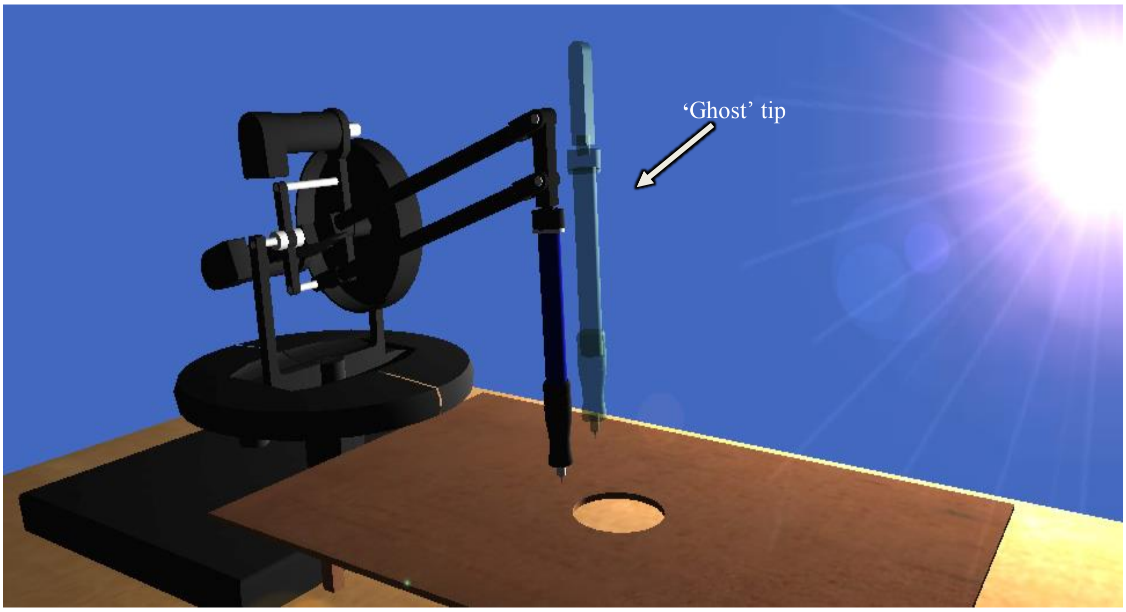


Figure 4.2: The “ghost” tip in transparent green

4.2.2 Rock Models

In order to improve virtual modelling information, an additional model of block/rock models was added to the virtual workspace. As the block/rocks come in a variety of shapes and sizes, and taking into consideration that their positions change constantly, I attempt to overcome this problem by creating a default rock model that could be scaled in two dimensions. I created a scanner application with the OpenCV [100] library and connected it to an IP camera at a remote site to determine the position and size of the rocks (see Figure 4.3). These variables were then automatically relayed to the interface to resize the default rock model and place the rocks in their respective positions in the virtual workspace. The block/rock models were updated at frame rate so the operator could observe movement as it occurred. Figures 4.4 to 4.6 illustrate the process of capturing the video, the rock location with OpenCV and the display of the resulting rock models in Unity3D.

Figure 4.3: Remote IP camera

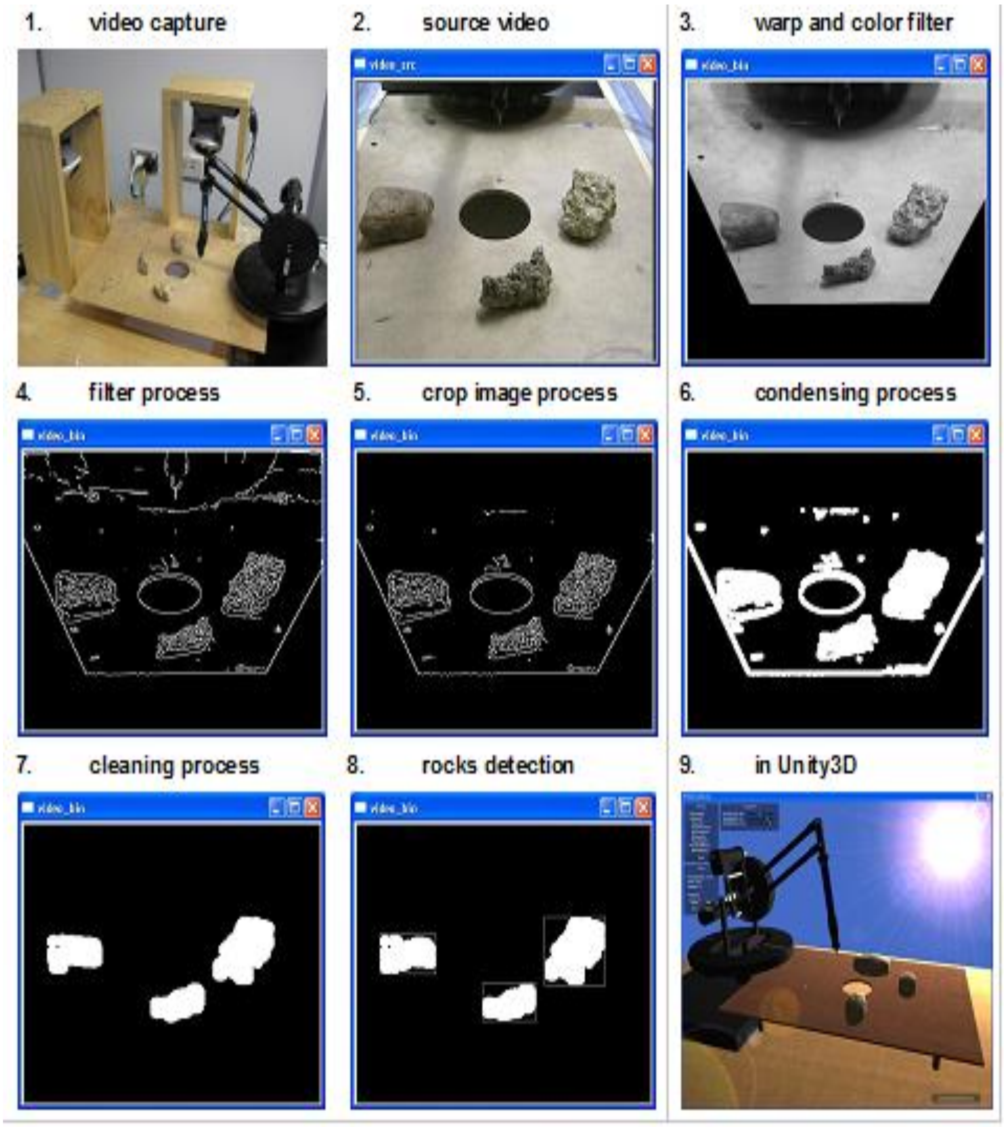


Figure 4.4: Rock tracking steps in OpenCV

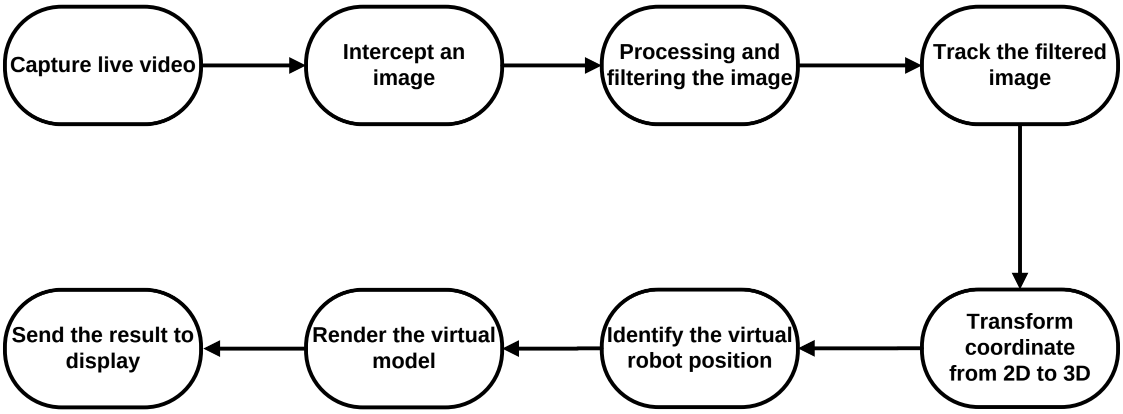
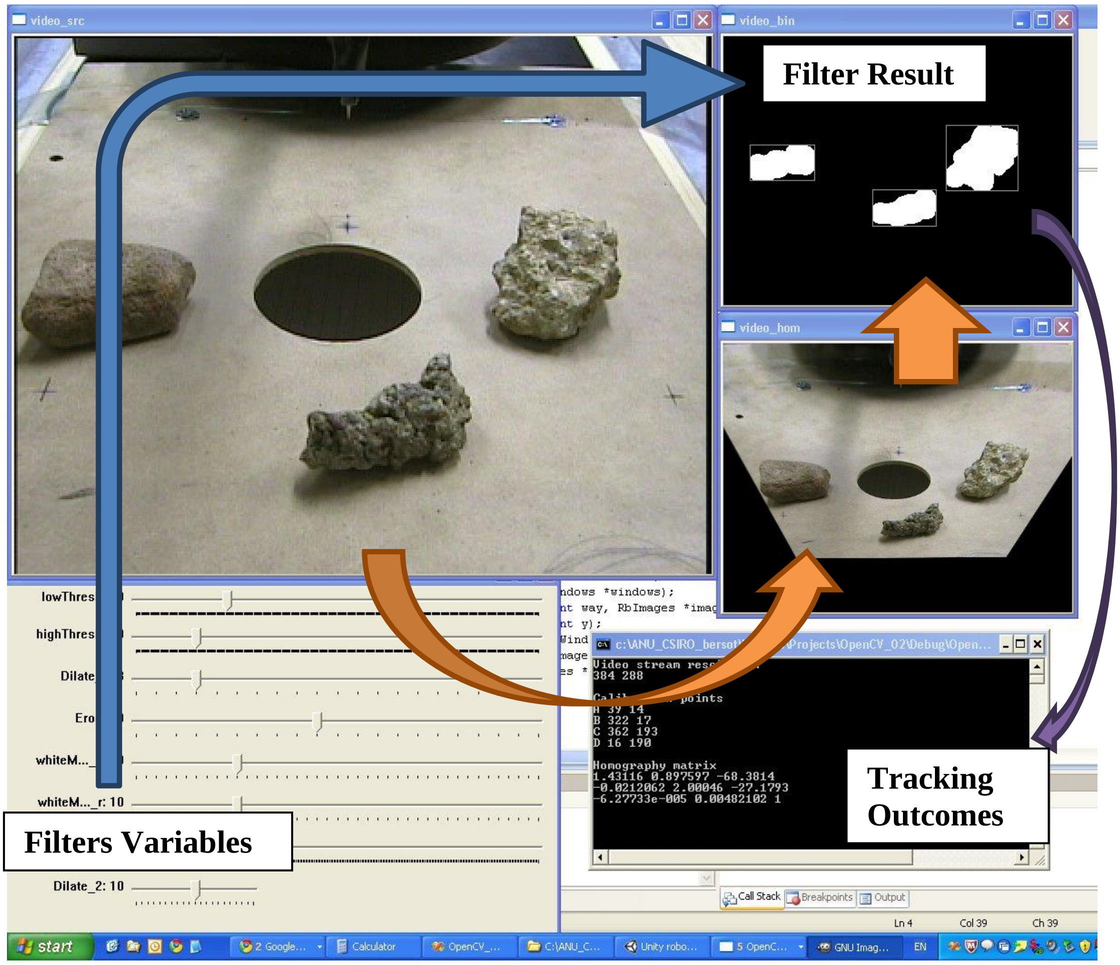


Figure 4.5: Calibration and registering process



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ndows *windows);
nt way, RbImages *imag
nt y);
Wind
mage
es *
```

```
Video stream reso
384 288

Cali      points
A 39 14
B 322 17
C 362 193
D 16 190

Homography matrix
1.43116 0.897597 -68.3814
-0.0212062 2.00046 -27.1793
-6.27733e-005 0.00482102 1
```

Figure 4.6: Application and image processing

4.2.3 Virtual Camera

The drawback of using streaming video in the remote camera is its limited range of viewpoints. However, this limitation does not exist in 3D virtual environments. With the virtual camera (see Figure 4.7), I could explore all aspects of the virtual environment freely as it has the basic functions of a normal camera but works in a virtual environment.

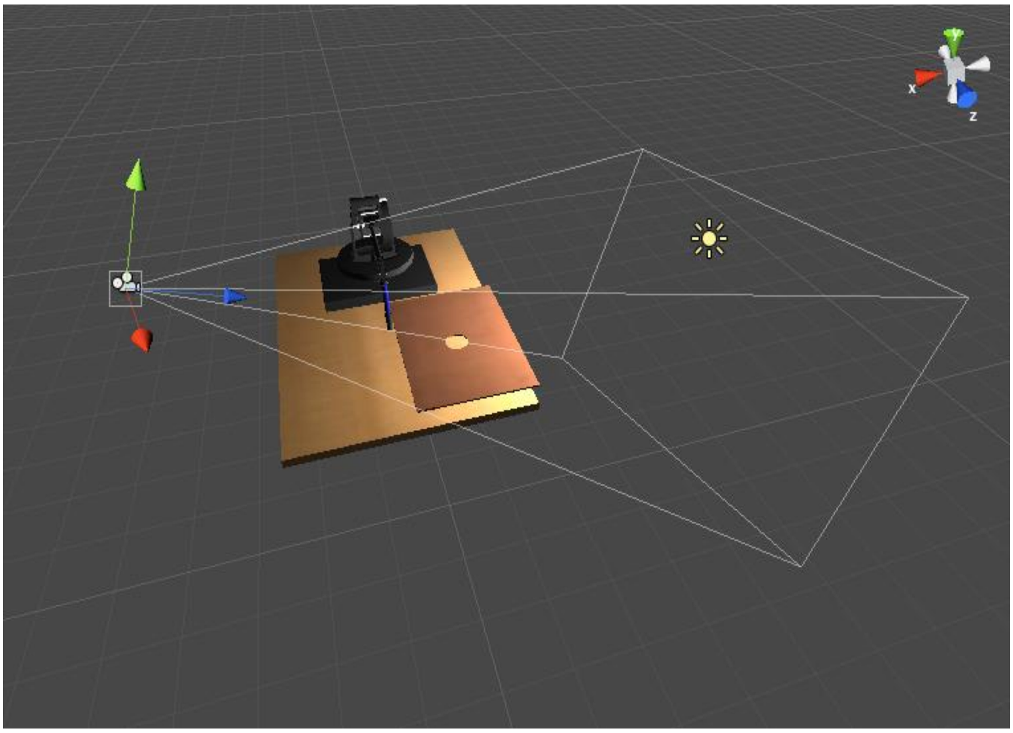
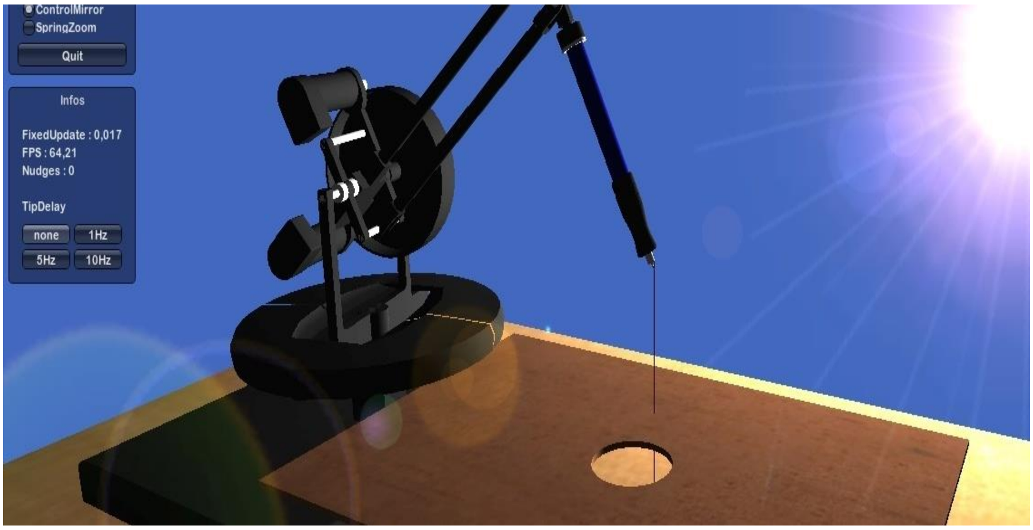


Figure 4.7: The virtual camera in virtual environment can show scenes from any angle

In a virtual gaming environment, a virtual camera can be controlled by moving, rotating, panning and tilting. A virtual camera can be used in a remote-person viewpoint (to the avatar body) or a first-person viewpoint. It can be controlled by using the keyboard and mouse to move around. Furthermore, any input device such as a gamepad (joystick) can also be applied to manipulate the position of the virtual camera. In this chapter, I utilised a gamepad (joystick) and eye-tracking device to control the movement of the virtual camera.

Furthermore while in everyday life it is very natural to use our eyes as a sensor to perceive the depth of three dimensional objects, it is sometimes difficult to perceive the exact height tip position with our eyes from a two-dimensional computer screen. There are two solutions available for use within the virtual environment. The first is using light and shadow to provide information of the tip position in relation to the board. Another solution is to use an additional object as a helping line to allow me to create a vertical line from the tip to the board to measure the height of the target position (see Figure 4.8).



FixedUpdate : 0,017
FPS : 64,21
Nudges : 0

Figure 4.8: The helping line model (vertical line) to show the height tip position

4.3 User Study

As mentioned in Section 4.1, this experiment used the experimental design from previous work [39]. However, the main objectives of both experiments are slightly different. This experiment aims to analyse user performance of all features available from gaming environments including the control device for the virtual camera. On the other hand, Zhu et al's experimental goal is to compare the performance of input devices while controlling a remote camera in the telerobotic scenario. Even though the two experiments have different objectives, the procedure and scenario designed for Zhu et al's experiment is still relevant for this experiment design. It also allowed me to explore whether user satisfaction for telerebotic interfaces that use gaming environments was similar to that for Zhu et al's telerobotic interface which used only full video. The following sub-sections describe in more detail the experimental design.

4.3.1 Apparatus and Implementation

In this telerobotics scenario, two experiment settings were used - the remote setting and the local user setting. In the remote setting environment (see Figure 4.9), as already mentioned in Section 4.2.1, I used a Phantom Premium (V1.5) haptic device [101] as a telerobot. I designed a wooden board with a hole in the middle and some rocks which served as tools for defining the task. Then I used one camera, which always pointed to the board, as a worksite plane. This camera was used to ascertain the rocks' size and position with an OpenCV application as described in Section 4.2.2. All the devices were connected through a server to transmit data to and from the user interface.

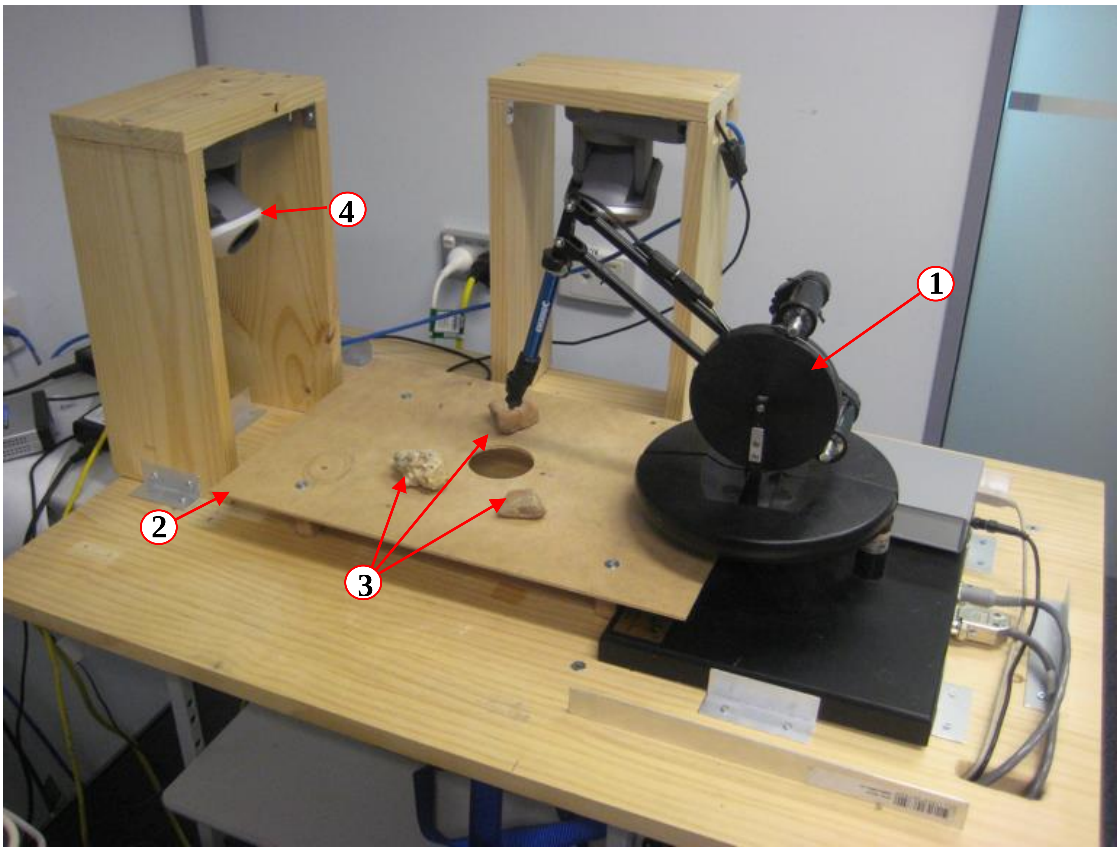


Figure 4.9: Remote setting test rig: (1) Robot arm from *Phantom Premium V.1.5* haptic device, (2) Board with a hole in the middle, (3) Rocks – targets objects, (4) Camera.

For the user setting environment (see Figure 4.10) I used a Dell Precision Work Station with a Windows XP operating system and a standard 19” monitor to execute the gaming environment. I utilised a *FaceLAB* 4.5 eye tracking application as an input device for the viewpoint method. As I did not develop this application myself, only the *FaceLAB* data was available for use in the gaming environment. In addition, some anomalies were found in the application of the data in each frame of the gaming environment. The stereoscopic cameras, as input sensors, were only able to work with a minimum 60Hz frequency. However, it was difficult to apply the large volume of data to each frame. To mitigate this issue I added a function to select a number of frames (i.e. 12 frames) to be treated, and then checked the placement of the eye gaze data on those frames. Subsequently I compared each data point and removed the anomalies, resulting in one data point for every 12 frames. This function assisted in minimising the jumpiness of the viewpoint control. I also used a Logitech Dual Action gamepad as an input device to control the movement of the robot arm model for all participants. The gamepad was utilised as a tip and viewpoint method, as shown in Figure 4.11. It is also robot or camera centric in terms of its direction of movement as shown in Figure 4.12.

Figure 4.10: User setting: (1) Unit PC with situated virtual application running on it, (2) *FaceLAB V.4.5* eye tracker software and sensors, (3) *Logitech Dual Action* gamepad

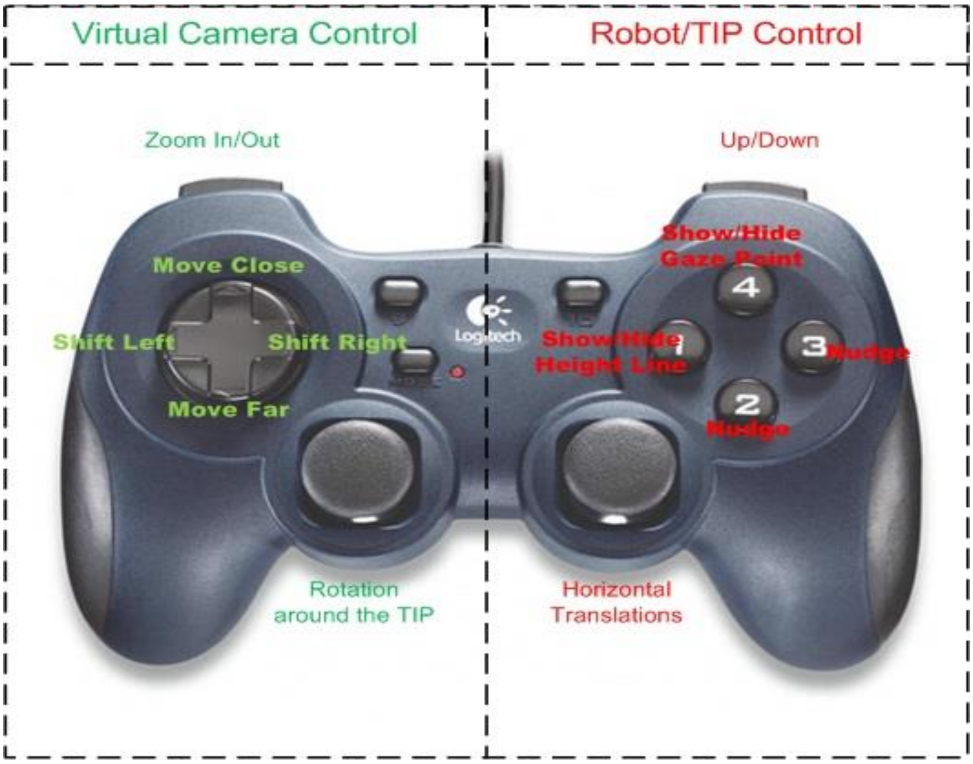


Figure 4.11: Mapping gamepad control: (1) Left – Viewpoint movement, (2) Right - TIP movement

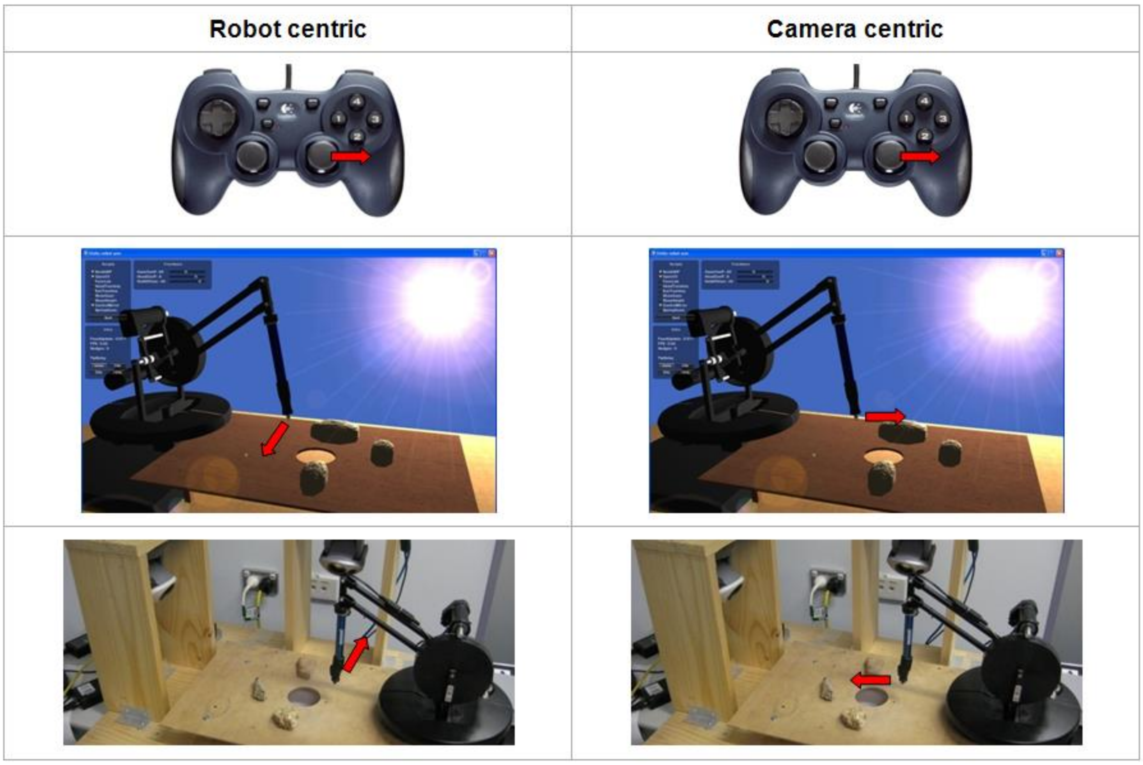


Figure 4.12: Robot or camera centric

Figure 4.13 illustrates the architecture of the whole system. For communication purposes, I set up a LAN to link the remote and user sites. During the initial system development, I applied TCP/IP as a connection protocol but it caused delayed data transmission thus affecting the movement of the remote device. Consequently, I switched to a UDP protocol that functioned well in the system and removed the need to verify receipt of data. Communication was tested between the client and the server as command data and feedback data.

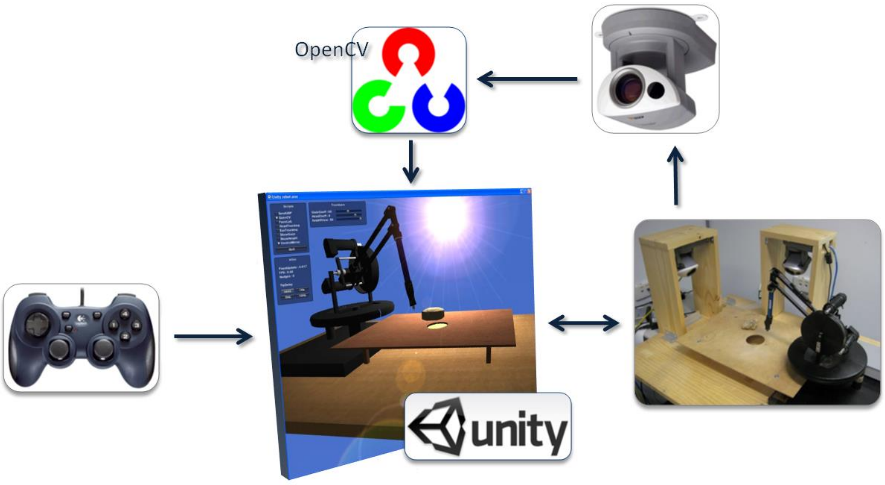


Figure 4.13: Telerobotics system with virtual application interface

4.3.2 Participants

In this experiment, I tested the interface with a total of 12 participants, consisting of eight males and four females. The characteristics of all participants are shown in the table below:

Table 4.1: Characteristics of the participants

Characteristics	Percentage (%)
Gender • Male • Female	 66.7% 33.3%
Range of ages	Range: 21 – 49 years old (Mean = 27.5, SD = 7.09)
Background	University educated
Regular computer users	100%
Experience with gamepad	100%
Experience with eye tracking	25%
Prototype background knowledge	None (0%)

4.3.3 Experimental Design, Task and Procedure

In this experiment, the gamepad (joystick) was used as the primary input device to control the robot's movement, and participants were asked to control the viewpoint using the two input devices (gamepad and head/eye tracking). The primary reasons for testing the interface were: (1) to demonstrate the ability of gaming features in providing an effective virtual model which accurately represents the physical setting, (2) to assess user performance of this gaming environment which is based on the experimental design and scenario of Zhu et al's experiment[39], and (3) to test the feasibility of integrating a gaming environment with two models of input devices for virtual camera control.

In general, the aim of Zhu et al's experiment [39] was to test different methods of camera control for telerobotic interfaces by utilising a streaming video interface. I used a similar set of user performance variables as Zhu et al's experiment. I categorised the gamepad as manual interaction and the eye-tracking device as natural interaction. In order to offset the impact of the order effect, the order at which the two input devices were used by each participant was random.

Prior to the experiment, the participants received a six to ten minute introduction including a brief description of the system, the research objective, and how to perform the task. The main task for the participants was to remotely control the input device through the virtual interface to control both the robot's movement and the camera viewpoint with the aim of sinking the rocks into the hole. In this experiment I also applied a "nudge function" [39] to push the rock into the hole. Each participant had a total of three minutes to perform the task with each input device. Then each three-minute time slot was further divided into three separate (60-second) operation periods in which participants were asked to conduct the same experiment procedure. In addition, a further three to five minutes were required for each participant to recalibrate the eye-tracking input device prior to use.

The initial viewpoint was set to the zoom position to nudge the rock. The participants were asked to use the zoom in/out function on the gamepad or to move their head forward/backward to search for each rock's position. All participants were asked to push the rock with the nudge function, with each nudge and rock sunk recorded as objective data for user performance indicators. If there was no nudge in pushing the rocks, then the rock was not recorded as being sunk. After the participants completed the formal experiment, I sought feedback regarding the performance of the user interface through a questionnaire that used a seven-point *Likert*-scale from one (strongly disagree) to seven (strongly agree), and a short interview. Both five-point and seven-point scales are common scale range in *Likert*-scale. A seven-point *Likert*-scale was used instead of the five-point scale for the rest of experiments to obtain a greater variance in user response.

4.4 Results

To evaluate user performance using a gaming environment with improved virtual modelling and two input devices for virtual camera control, two user performance indicators, the total number of rocks sunk and the total number of nudges, were recorded. The results are presented in two sub-sections based on objective and subjective data analysis. Additional discussion is also presented to determine similarities and differences between this experiment and Zhu et al's experiment [39].

4.4.1 Objective Measurement

The user performance indicators recorded are the total number of rocks sunk and the total number of nudges. Table 4.2 shows the mean user performance in using the gamepad and eye-tracking input devices, for virtual camera control.

Table 4.2: Difference between the 2 input devices for the mean number of rocks sunk and the mean number of nudges

Objective measurement	Input devices for virtual camera control		t	P
	Gamepad Mean (SD)	Eye-tracking Mean (SD)		
Total number sunk	10.67 (4.94)	11.75 (4.99)	-0.534	0.598
Total number of nudges	52.17 (23.73)	58.00 (23.18)	-0.636	0.531

Based on Table 4.2, gaming environments that use eye tracking devices have a larger total average number of rocks sunk and nudges compared to those that used gamepads. However, based on the t-test, there is no significant difference in user performance between the two input devices (rocks sunk: t = -0.534, p = 0.598; nudges: t = -0.636; p = 0.531).

A one-way analysis of variance or ANOVA was also used to test whether the average number of rocks sunk and average number of nudges differ between the two input devices and the participants' characteristics. The results are shown in Tables 4.3 and Table 4.4.

Table 4.3: ANOVA test of the average number of rocks sunk (model) differs between input devices and subject characteristics

Source	Sum of Square	Degree of freedom	Mean square	F	p
Model	496.5	10	49.65	12.07	0.0000
Devices (gamepad & eye-tracking)	7.04	1	7.04	1.71	0.213
Subject Characteristic					
Gender	4.5	1	4.5	1.09	0.314
Age	287.09	6	47.84	11.64	0.0001
Exp. with computer	0	0			
Exp. with gamepad	4.5	1	4.5	1.09	0.1346
Exp. with Eye-tracking	0	0			
Exp. with experimental settings	133.33	1	133.33	32.42	0.0001
Residual	53.458	13	4.11		
Total	549.958	23	23.911		

r-squared = 0.902 Adj r-square = 0.82

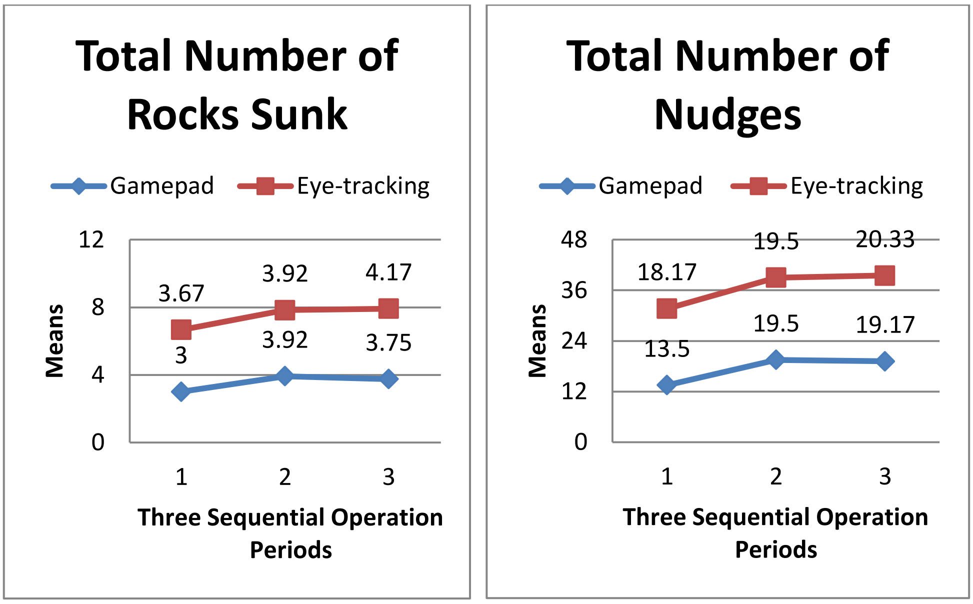
Table 4.4: ANOVA test of average number of nudges (model) differs between input devices and subject characteristics

Source	Sum of Square	Degree of freedom	Mean square	F	p
Model	11280	10	1128	14.61	0.0000
Devices (gamepad & eye-tracking)	222.04	1	222.04	2.88	0.1138
Subject Characteristic					
Gender	480.5	1	480.5	6.22	0.026
Age	7414.02	6	1235.67	16.00	0.0000
Exp. with computer	0	0			
Exp. with gamepad	72	1	72	41.45	0.35.19
Exp. with Eye-tracking	0	0			
Exp. with experimental settings	3201.33	1	3201.33	41.45	0.0000
Residual	1003.958	13	77.227		
Total	12283.95	23	534.08		

r-squared = 0.918 Adj r-square = 0.855

As shown in Table 4.3 and Table 4.4, there is no significant difference in the mean of the dependent/outcome variables (total number of rocks sunk and total number of nudges) between the two input devices, with F(1,13) = 1.71, p = 0.213(r = 0.95) for the total number of rocks sunk and F(1,13) = 2.88 , p = 0.11 (r = 0.95) for the total number of nudges. However, the dependent variables were found to differ significantly among the subject characteristics such as gender, age and experience with the experimental settings ($p < 0.05$).

Further analysis was also conducted to determine the trend between these two performance indicators. I analysed the variables in three sequential operation periods. Figure 4.14 below shows the average number of rocks sunk and average number of nudges for each operation period. An upward trend was observed in both user performance indicators for both input devices over the three operation periods which reflect that user performance increases over time following the start of a new task



(a) (b)

Figure 4.14: Mean number of rocks sunk (a) and number of nudges (b) for each operation period.

4.4.2 Subjective Measurement

The results from a feedback questionnaire regarding user experience of the gaming environments are shown in Figure 4.15.

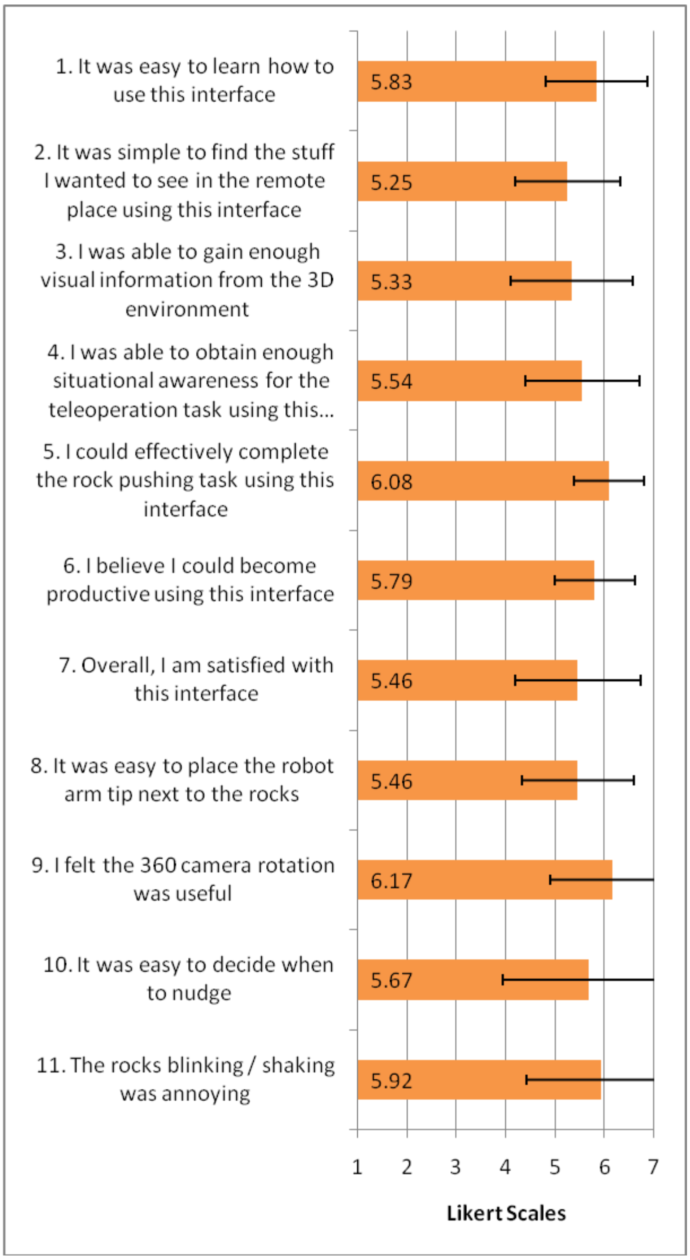


Figure 4.15: Subjective measurement variables

Based on the self-administered questionnaire, most participants gave positive feedback on the interface performance. However, there were some suggestions to improve the virtual interface design in relation to the instability (shaking) of the rock position feedback and the uncomfortable sitting position when using the eye tracking device.

4.4.3 Additional analysis to determine similarities and differences in user performance between this experiment and Zhu et al's experiment [39].

While this experiment has a different research objective compared with Zhu et al's experiment [39], the design and procedure were the same. This section highlights the similarities and differences between the results of these two experiments.

Firstly, the experiments have similar subject characteristics in almost all criteria. Secondly, similarities are also found in the total number of rocks sunk and the total number of nudge variables. Both experiments show that the eye-tracking device resulted in a larger number of rocks sunk and larger number of nudges compared to the gamepad. However, unlike in Zhu et al's experiment result [39], this difference was not statistically significant. Figure 4.16 shows the total number of rocks sunk in both experiments and Figure 4.17 shows the total number of nudges in both experiments.

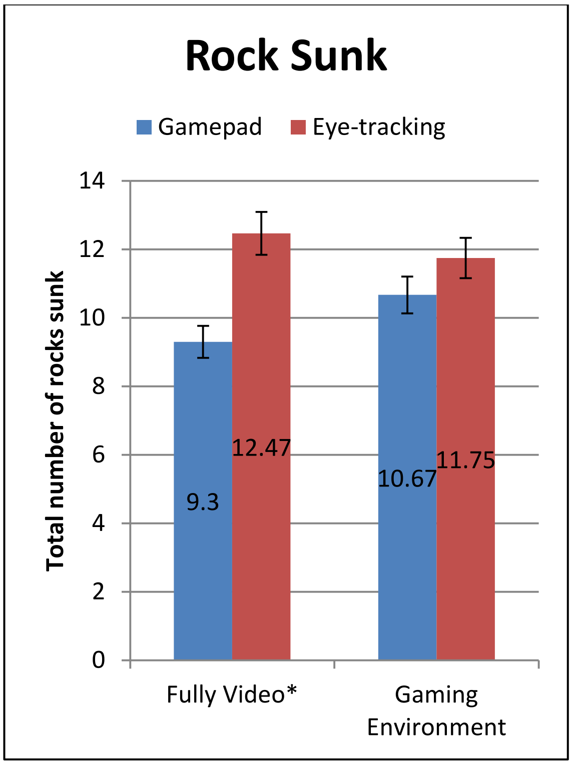


Figure 4.16: Total number of rocks sunk on a full video interface* and a gaming environment interface using two different input devices (*data from [39])

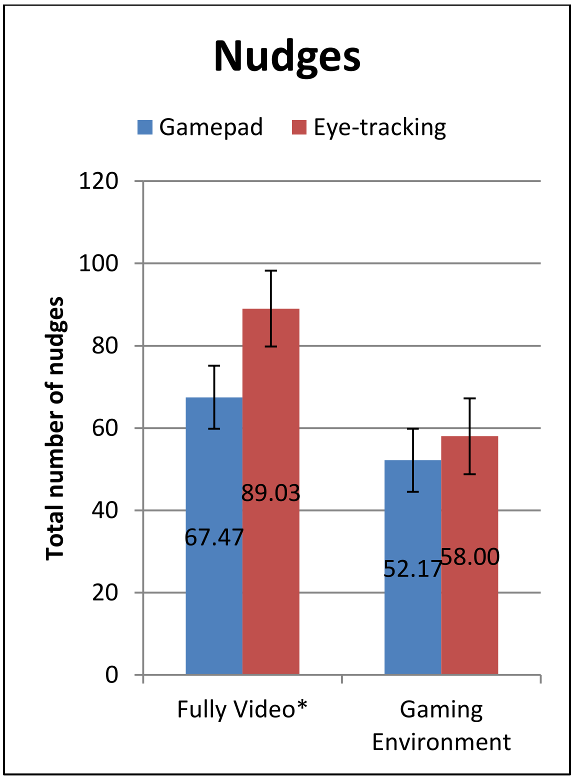


Figure 4.17: Total number of nudges on a full video interface* and a gaming environment interface using two different input devices (*data from [39])

Using a gamepad in gaming environments show a larger average number of rocks sunk compared to that in a full video interface, but the opposite is true for using eye-tracking. However, statistical analysis could not be applied as I do not have access to raw data from Zhu's experiment [39]. However, by simply eyeballing the results shown in Figures 4.16 and 4.17, the gaming environment was able to sink a rock into the hole with an average of five nudges for both input devices, compared with six to seven nudges for the streaming video interface. This suggests that gaming environments probably require less action to achieve the same result compared to the full video interface.

Based on the user performance analysed in three sequential operation periods, both experiments show a similar trend that reflected an increase in user performance over time following the start of a new task.

4.5 Discussion

Based on the results recorded in Table 4.2, two user performance indicators (i.e. the number of rocks sunk and number of nudges) recorded similar means for both the gamepad and eye-tracking input devices. This result is supported by the fact that there was no statistically significant difference between the two devices. Hence I argue that both input devices are suitable in gaming environments in telerobotic scenarios.

Analysis was also conducted to determine the difference in user performance by the subjects' characteristics. Statistically significant differences were observed in gender, age and experience in the experimental settings. Hence it could be concluded that the user performance indicators is affected by the split in gender, variance in participants' age and their knowledge of the experimental settings. However further analysis is needed to understand why these variables influence performance.

Based on user performance data recorded in three sequential operation periods, the participants were seen to show gradual improvement in subsequent operation periods. Hence I suggest that gaming environments and virtual camera control devices are easy learning environments, and through task repetition operators are expected to perform better over time. Moreover, the use of different viewpoint methods did not have a large impact on the performance of the task because the ideal condition was when a fixed camera view was used. I expected that rotation about the tip would be better than panning but this experiment showed that there was no significant difference.

Based on the questionnaire feedback, most participants viewed the interface performance positively, and believed the virtual environment could improve their work efficiency. After the experiment, most participants commented that when using the gaming environment for this telerobotic scenario, the interface proved user friendly, easy-to-learn and fun. Based on Fong [37, 38], interfaces which users find gratifying correlate to improved telerobotic task performance.

4.6 Summary of Chapter

In this experiment, I observed that the gaming environment can be improved by virtual modelling to represent physical settings. I also noted that the gaming environments have features that can be integrated with a number of virtual camera control devices without affecting operator performance.

After evaluating the user performances, I argue that the gaming environment is suitable for applying two input devices for virtual camera control in a telerobotic scenario. These results strengthened my argument that the gaming environment and telerobotic interfaces share many similarities and therefore can be regarded as being in the same domain.

This experiment showed that in contrast to streaming video interfaces only, the gaming environment with MR can model a remote setting effectively, provide real-time feedback of moving objects (robot and rock), have the freedom of viewpoints from the virtual camera, and provide other useful information (i.e., line-helper model, helper text or prediction position). The merits of video views in MR gaming environment plays important role in completing the missing information from the 3D model. However, based on user feedback in the questionnaire, the rock model should be improved to achieve better performance, especially for more complex remote settings.

This experiment has conducted further evaluation of gaming environment features that enhance its suitability as a telerobotic interface. As mentioned in Chapter 1, one of the issues of the telerobotic system is its communication latency. According to Domingues et al research [75], latency in telerobots can be minimised by utilising predictive display modelling in MR or VR environments. Another argument by Fong et al [37] mentioned that supervisory control interfaces are well suited for applications which must work with low bandwidth communication or in the presence of high latency. The next chapter describes an investigation on features of the gaming environment, which can be applied to the human supervisory control (HSC) concept.

Chapter 5

Human Supervisory Control in Gaming Environments

Previous chapters have demonstrated one of the research goals in evaluating user performance using gaming environments with MR interface for a telerobotic scenario. This chapter discusses another goal of this research in improving human machine interaction for telerobotic scenario by utilising the human supervisory control (HSC) concept in gaming environments. In this chapter, HSC is used as an alternative to direct/manual control that aims to reduce human operator involvement and to, implicitly, assist in minimising the latency effect. This chapter investigates components and features of gaming environments, which are suitable to apply HSC for telerobotic interfaces, especially for the HSC planning concept. This chapter also describes an experiment to assess user performance using gaming environments with the HSC concept applied. To provide further evaluation of user performance with the HSC control model, a sub-experiment was also conducted to compare user performance between HSC and direct/manual control.

5.1 Introduction

Human supervisory control (HSC) is designed to reduce operator involvement and may substitute and address the deficiency of direct/manual control [2, 89, 90]. According to the description of HSC in Section 2.3, HSC has five generic functions, namely: planning, monitoring, intervening, teaching, and learning. In undertaking planning, monitoring and intervening processes, an operator is required to have a good understanding of the information provided by interfaces. Hence, the role of MR interface in providing complete information is important to support the functionality of the HSC concept, especially in delivering a combination of feedback, present and predicted future information.

Through a more detailed evaluation of the planning process, I considered that HSC allows the operator to plan the movement by defining a series of commands to the telrobot. As mentioned on Section 2.3.3, there are two possible response movement models based on this series of command processes, entitled Adaptation and Queue response models. Hence, an investigation on gaming features was required to apply these response models.

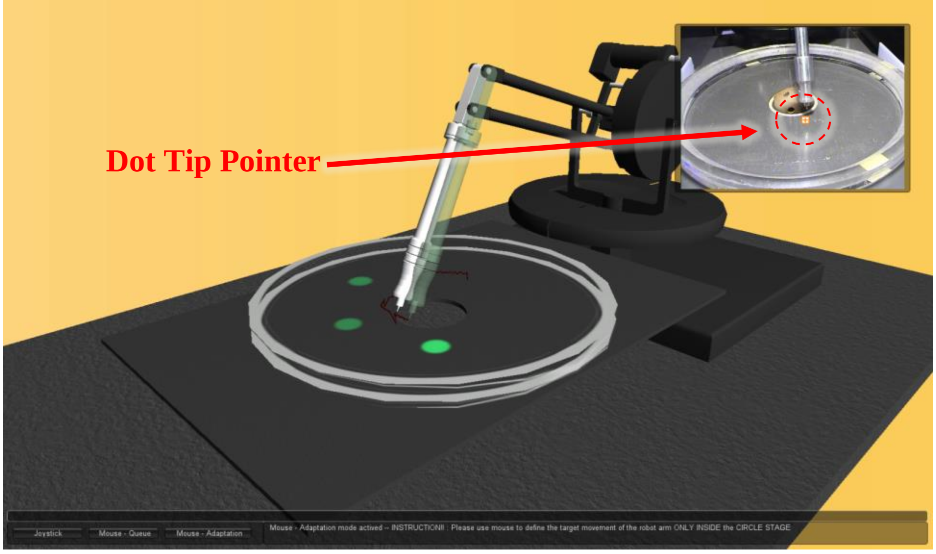
This chapter describes an investigation on gaming features followed by an experiment to evaluate user performance when using HSC response movements from a series of input commands in a gaming environment. The key questions of the experiment were:

- Based on the completion time and success rate, how do the performances of the Adaptation and Queue response movement models compare?
- Could visual planning information improve the operator performance in task completion?
- Would the HSC model be able to replace direct/manual control for this experiment design task?
- How does the use of the virtual camera, stop function, and virtual plan/feedback information affect the user outcomes?

Before I explain the experiment in more detail, the next section describes a number of improvements to prototype implementation based on the previous experiment, including implementation of a number of gaming features to apply the HSC concept.

5.2 Prototype Implementation

In accordance with the previous experiment an interface was developed with a gaming engine called Unity3D. A 3D model of a robot arm was built into this gaming environment to show its position. In applying MR, I embedded streaming video from the IP camera, which was installed at the remote location, inside the 3D model interface. A virtual object, a dot tip pointer, overlaid the surface of the videos to show the predicted position of the tip model on videos. The MR telerobotic interface built on Unity3D can be seen in Figure 5.1. Further information regarding the experimental setup is given in sub-subsection 5.3.1.



Mouse - Adaptation mode actived -- INSTRUCTION!! : Please use mouse to define the target movement of the robot arm ONLY INSIDE the CIRCLE STAGE

Figure 5.1: MR concept built in Unity3D

Based on telerobotics architecture, described in Section 2.1.3, I improved the closed loop client server communication between the operator–interface (as client) and the server/remote machine (as manipulator), which is illustrated in Figure 5.2.

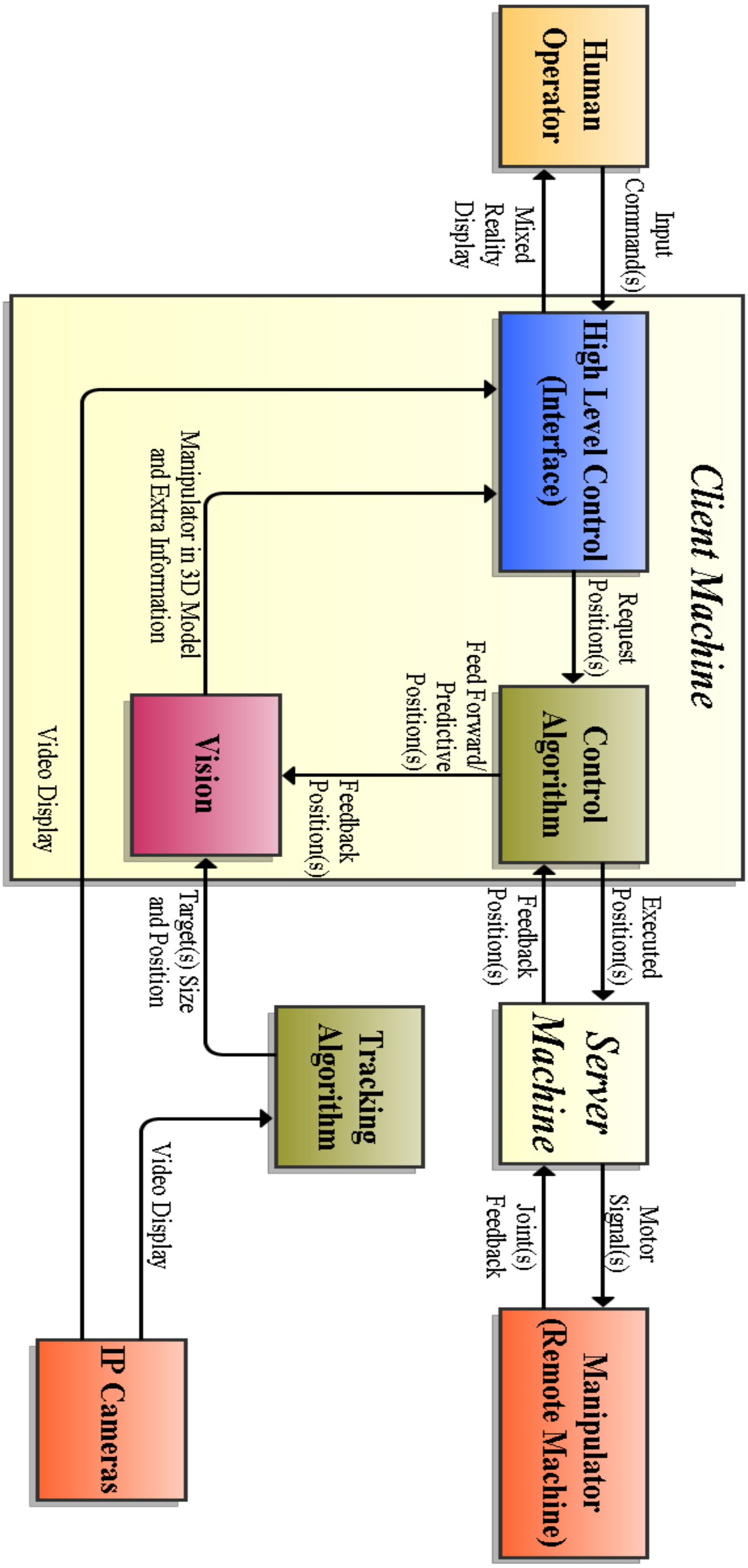


Figure 5.2: Telerobotics system

As shown in Figure 5.2, by applying HSC concept, this telerobotic interface provides: previous information (feedback), current information (monitoring), and future information (planning). In the situation where the tip of robot arm becomes stuck before reaching the target positions, or where the human operator needs to change/cancel the robot’s movement, they can override the process instantly. There are a number of features available through this system to enhance the performance of HSC.

5.2.1 Stop Functions

In emergency situations, the system provides a number of functions that can be used to override the current process and take control of the movement. These functions are temporary stop (TS) and full stop (FS). Firstly, the temporary stop (TS) is a function which works by suspending the predicted model and robot’s movement temporarily by holding a button, and allowing them to continue moving to the target only when the operator releases the button. This function allows the operator to suspend movement while they evaluate the situation. Secondly, the full stop (FS) function works by stopping the robot’s movement and at the same time cancelling all subsequent targets.

5.2.2 A-star Path Tracking

This designed telerobotic interface represents detected blocks as 3D models each of which can be defined as a target block. However, it was designed such that only one block can be selected as a target object at any given time. When a model block was selected as a target, the remaining blocks would serve as obstacles to the manipulator. Accordingly, a path finding algorithm, as already described in Section 2.3.2, in the form of an A-star path finding algorithm function was added into the system to create paths that allow the robot to avoid the obstacles automatically.

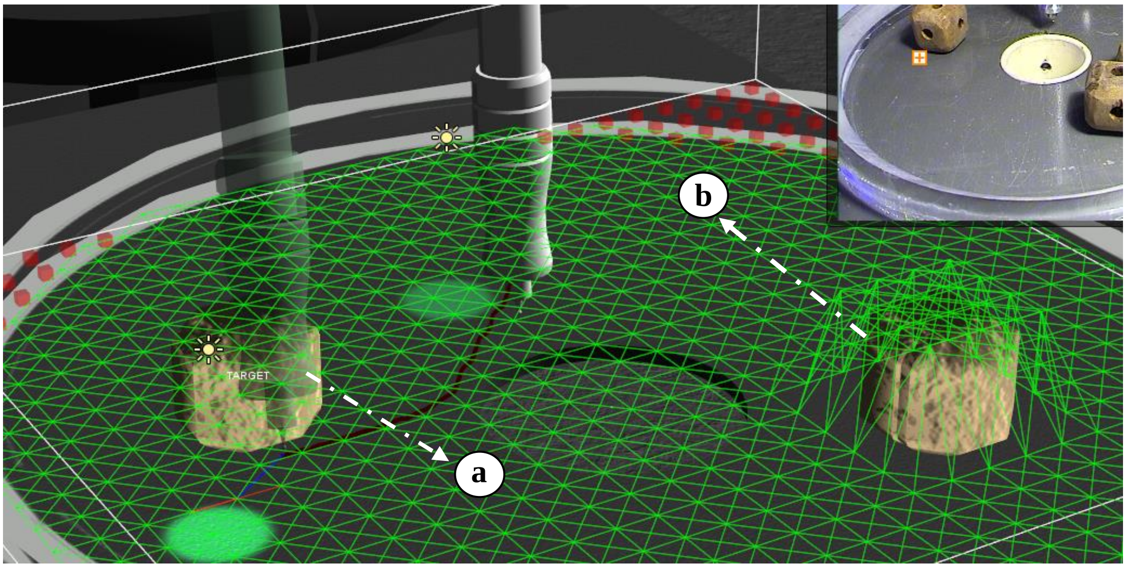


Figure 5.3: Path generated from the A-star algorithm in: (a) selected block, and (b) unselected block model

5.2.3 Virtual Objects for Planning/Feedback Information

The telerobotic interface allows the computer to provide virtual objects for prediction, planning and feedback information (which also known as a predictive display [75]). According to *LiSA* model assistance, described in Section 2.3.1, these virtual objects can be utilised for planning, monitoring and intervening in processes. Below are four examples of the virtual objects which have been used to improve this MR gaming environment for a telerobotic interface (see Figure 5.4). In this interface I reduce a number of video views into one to reduce communication load between the interface and the telerobot. This is also applied to evaluate the usage of these additional virtual object features.

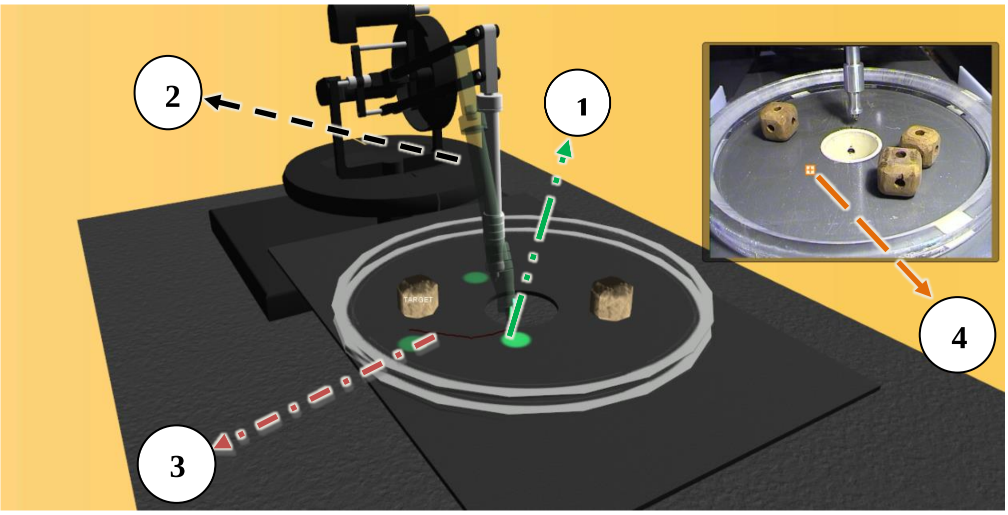


Figure 5.4: Visual information: (1) green circles, (2) shadow of tip, (3) line path, and (4) overlay pointer

A “green circle” object serves as planning information to help the operator by showing a series of target positions. It appears when a target position for the robot is defined. Each green circle had a diameter of 4 mm indicating that the error tolerance for the model/robot to reach the destination target was 0 – 2 mm. Another virtual object that was used was the “shadow of tip”. This gave a prediction of the position of the manipulator model and replicated the shape of the robot arm tip model by using a transparent texture. The “line path” was another virtual object that pointed towards the shadow of the tip object to predict the path of the manipulator model. The last virtual object was the “overlay pointer”. It was presented as a cross symbol and showed the predicted position of the tip on the video display. The overlay pointer applied the concept of AR by enhancing virtual object overlays on the live video. In order to analyse the performance of this visual planning information, each response movement model (Adaptation and Queue) was tested with and without this feature.

5.3 User Study

The objectives of this experiment were: (1) to analyse the performance of two movement response models by using additional virtual information in the planning and monitoring process; and (2) to analyse features that might influence user performance while using the two movement response models of HSC. In order to test the reliability of HSC in substituting the direct/manual control, I also attached a sub-experiment to evaluate user performance as a comparison to the HSC.

5.3.1 Experimental Setup

Based on the results from the previous experiment, I determined that the Unity3D gaming engine offers a sophisticated environment compare to the other two. It allowed me to use more gaming features to build the telerobotic interface with MR and HSC concepts applied. Similar to the setup of the previous experiment, I set this system into local and remote areas.

Figure 5.5: Experimental setup for third experiment

As shown in Figure 5.5, the local area consists of a personal computer connected to a 32" monitor Dell with a resolution of 2560 x 1600 pixels as a display. A standard keyboard and mouse were used as the input devices to deliver the user's commands through the interface. A telerobotic interface with MR environment and HSC was applied in this local machine.

A computer server was located at the remote area; which delivered information between the user machine and the remote manipulator. A 3-DOF (degree of freedom) modified robot arm served as the remote manipulator. The robot arm was located on a stage with a hole representing a dump-bin in the middle of the workspace. Three blocks were provided on the workspace stage as objects targeted for sinking into the hole. Similar to the previous experiment, the IP cameras (external camera) were installed in static positions at the front and side of the telerobot and facing the workspace stage. However, in this experimental scenario, to apply MR and reduce distraction from multiple camera views, only the front camera was utilised and embedded inside the telerobotic interface. In addition to providing streaming video to the interface, the camera also connected to the server to serve as a tracking sensor and provide updates on the position of the target objects through image analysis.

The interface used for the experiment provides information from both the camera view and the 3D model. The embedded camera provides information regarding what is really happening at the remote location before and after giving commands to the telerobot; it provides any additional information if any is missing from the 3D model view (e.g. different number or position of the rocks due to errors of the tracking system). In this experiment, I set the initial view of the virtual camera to that of the external camera and make this the default view for each participant. The participant is expected to be able to perform spatial transformation using this information. The participant can change the view of the virtual camera to see more detail about the remote environment.

Prior to the start of the experiment, all participants were given a brief description of the goals and purpose of the experiment, how to conduct the experiment, and the experimental setting, including information concerning the telerobotic interface and the location of the external camera.

5.3.2 Participants

The experiment was conducted with a total of 24 participants. They were selected by using experiment driven sampling with a snow-ball sampling method. The characteristics of all participants can be seen in the table below:

Table 5.1: Participants characteristics

Characteristics	Percentage (%)
Gender • Male • Female	 79% 21%
Range of ages	Range: 16 – 37 years old (Mean = 22.75, SD = 5.75 years old)
Background	University educated
Computer use • Less than 7 hours/week • Between 7 and 21 hours/week • More than 21 hours/week	 13% 26% 61%
Computer gaming play • Less than 7 hours/week • Between 7 and 21 hours/week • More than 21 hours/week	 50% 25% 25%
Prototype background knowledge	None (0%)

5.3.3 Experimental Design and Procedure

To explore the capabilities of gaming features in implementing HSC and providing continuity with previous experiments, I applied HSC input commands using a ‘click’ function. This function was combined with a virtual object, described in subsection 5.2.3, to help the operator in planning. I refer to these virtual objects as “planning information.”

Based on the model of response movement for multi-command input, described in subsection 2.3.3, I grouped the experiment into: (1) Adaptation model with planning information (Adaptation-info); (2) adaptation model without planning information (Adaptation-non-info); (3) queue model with planning information (Queue-info); and (4) queue model without planning information (Queue-non-info).

For all four, the task was to choose a block and push it into a hole following a path specified by an arrow. The initial robot-arm and block positions were the same for each participant. All participants were asked to select one block by clicking on its model. They were allowed to change their selected block by clicking on another block model which would automatically assign the remaining blocks as obstacles.

The participants were randomly assigned to model-test sequences. Participants were given a 10-15 minutes briefing on the aims of the experiment and the differences between the models. The task scenario was also provided to the participants prior to the experiment. No practice or trial was allowed prior to the experiment.

A maximum time of 180 seconds was allocated to perform the task for each model. During the experiment, the extent to which the user followed the virtual arrow path and whether they sank the block were recorded as the variable outcomes. A successful result was achieved when the participants followed the path assigned and sank a block into the hole during the time allocated. Actual completion times were also recorded when the participant sank the block in the hole before 180 seconds. In addition, the total number of commands given in manipulating the robot arm and virtual camera, and the total usage of stop functions for each model performance were recorded automatically by the system. These variables were noted as user performance indicator in analysing the performance of each model.

After completing the requested task, the participants were also asked to fill in a questionnaire using a seven point *Likert-scale* and answer open-ended questions. These were used as subjective measurements.

5.4 Results

5.4.1 Objective Measurement (Distribution Proportion, Logistic Regression, F1-Score Analysis)

Task completion time was the first user performance indicator recorded in the experiment. The average successful completion time across the four models was 77.35 seconds (SD = 38.41 seconds) with further detail for each model shown in Table 5.2.

Table 5.2: Task completion time for a successful result using each model tested

Model tested	Mean	SD	Min	Max
Adaptation-info	91.49 s	39.61 s	32.6 s	150.7 s
Adaptation-non-info	73.75 s	36.58 s	30.2 s	163.0 s
Queue-info	75.15 s	37.66 s	19.4 s	165.1 s
Queue-non-info	71.41 s	27.55 s	27.8 s	125.4 s

This experiment showed that there was a relationship between the probability of success and the completion time with the coefficient correlation of -0.62. To further study this relationship, I grouped the completion time into three groups, 0-60 seconds, >60-120 seconds, and >120-180 seconds. As shown in Table 5.3, there was a significant relationship (p = 0.000) between completion time and the result of the experiment (fail or succeed).

Table 5.3: The distribution proportion of the results of the experiment by completion time

Task Completion time	Result of experiment		$\chi2$	p
	Fail N (%)	Succeed N (%)		
0 – 60 s	2 (5.88)	32 (94.12)	35.29	0.000
>60 s – 120 s	0 (0.00)	34 (100.00)		
>120 s – 180 s	15 (53.57)	13 (46.43)		

Logistic regression was performed to analyse this relationship in more detail, and the results showed that participants who took longer than 120 seconds to complete the task have a much lower probability of success compared to those who completed the task more quickly (OR = 0.05, p = 0.000). Detailed logistic regressions for each model are shown in Figure 5.6. Based on the shape of the curve for each model tested, the probability of success after 120 seconds has a tendency to decrease, and it can be projected that when the user completes the task with a longer time they will likely fail.

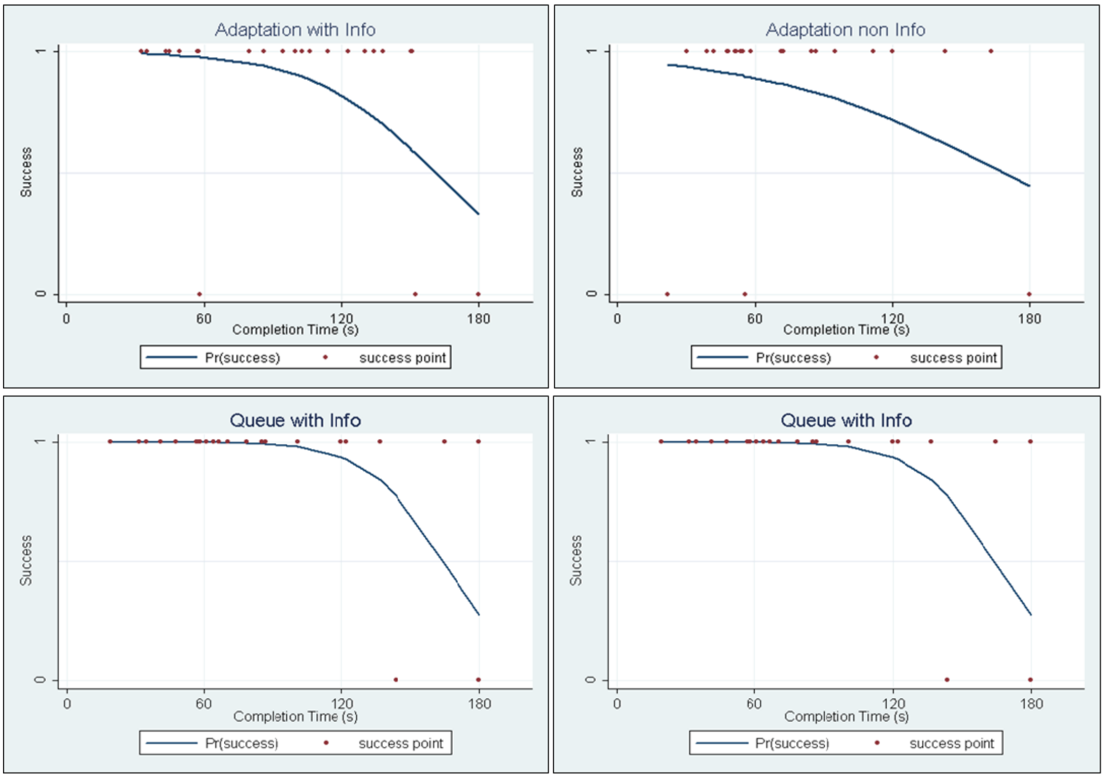


Figure 5.6: *Logistic Regression* showing the relationship between the probability of success and completion time

In this experiment, I recorded two variables, “path” and whether the block was “sinking”, as indicators of result performance. Based on these variables, the result performances were grouped into “both true” which indicated the path and sinking were successful, “true sunk” which indicated the path failed but sinking was successful, “true path” which indicated that the path was successful but the sinking failed, and “both false” which indicated path and sinking both failed. Please see scatter plots in Figure 5.7 for detailed performance results.

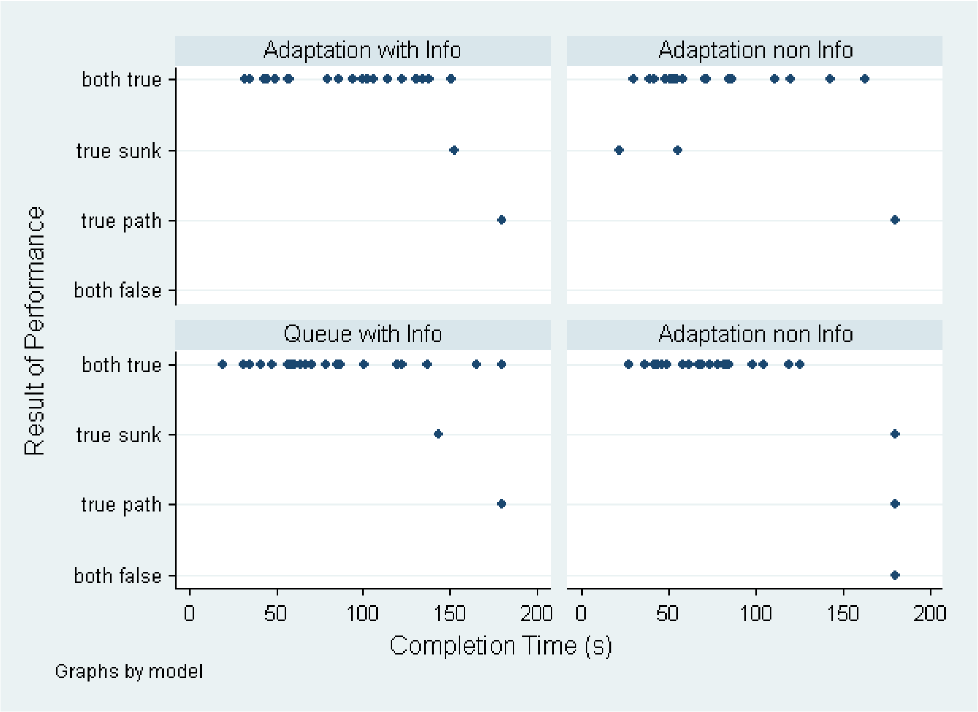


Figure 5.7: Scatter plot – performance and completion time for four supervisory models tested

In order to measure the effectiveness of user performance of each model tested, the F_1-*score* was used to test the harmonic Mean between Position Predictive Value (PPV) and sensitivity variables. The F_1-*score* can be interpreted as a weighted average of these two variables, with the best value at one and worst score at zero. The F_1-*score* is derived from the traditional F_β-*score* equation based on *Rijsbergen's* effectiveness measure (E) [102], which can be seen as follows:

$$E = 1 - \left(\frac{\alpha}{PPV} + \frac{1-\alpha}{Sensitivity}\right)^{-1}$$

Equation (5.1)

Their relationship is $F_\beta\ score = 1 - E$, where $= \frac{1}{1+\beta^2}$, then

$$F_\beta\ score = (1+\beta^2)\frac{PPV\ .Sensitivity}{\beta^2.PPV+Sensitivity}$$

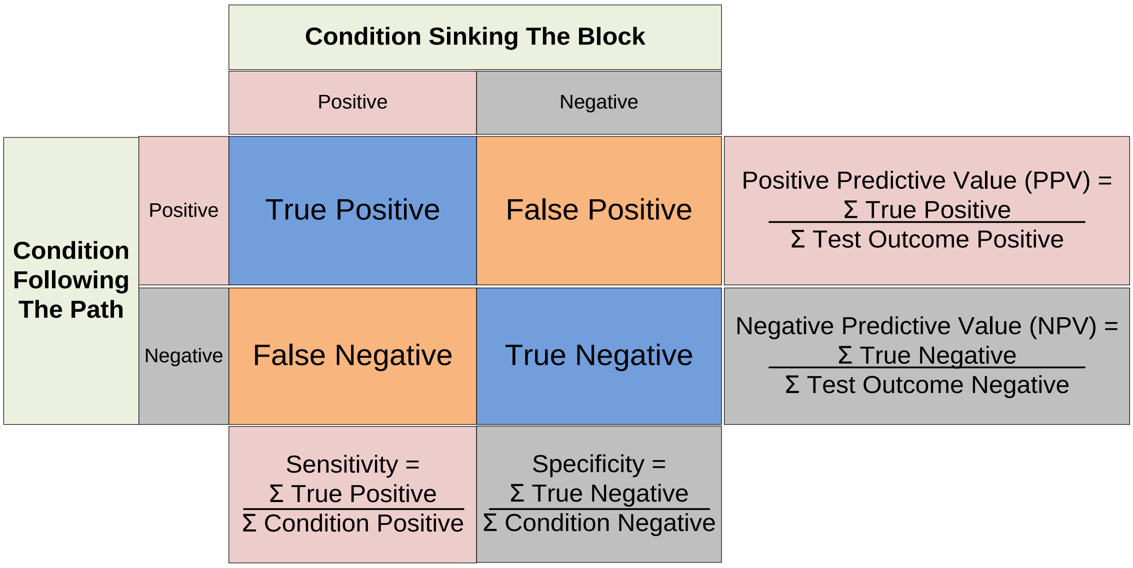
Equation (5.2)

Where $\beta = 1$, the equation becomes:

$$F_1 score = \frac{PPV\ .Sensitivity}{PPV+\ Sensitivity}$$

Equation (5.3)

The F_1-*score* is often used in the field information retrieval and classification task (context) to measure test accuracy. In using the F_1-*score* method, I fitted this model experiment into a classification task (context) model approach. In this model, I tried to measure how the participants could follow the instruction using the interfaces with different model response and information feedback (user performance for each model interface tested). Based on the results of user performance, I categorised the task result to fit into the group classification for the *classification task (context)* model, see Figure 5.8.



		Condition Sinking The Block		
		Positive	Negative	
Condition Following The Path	Positive	True Positive	False Positive	Positive Predictive Value (PPV) = $\frac{\Sigma \text{ True Positive}}{\Sigma \text{ Test Outcome Positive}}$
	Negative	False Negative	True Negative	Negative Predictive Value (NPV) = $\frac{\Sigma \text{ True Negative}}{\Sigma \text{ Test Outcome Negative}}$
		Sensitivity = $\frac{\Sigma \text{ True Positive}}{\Sigma \text{ Condition Positive}}$	Specificity = $\frac{\Sigma \text{ True Negative}}{\Sigma \text{ Condition Negative}}$	

Figure 5.8: The relationship between task results

I categorised the results in the following way: the correct path and a sunk block was regarded as a correct result (true positive); the incorrect path with a sunk block was regarded as an unexpected result (false positive); only the correct path regarded as a missing result (true negative); and if both the path and sinking were incorrect it was regarded as an absence of result (false negative). Using Equation (5.3) and the relationship between task results in Figure 5.8, the F_1*-score* becomes:

$$F_1 score = \frac{2.True\ Positive}{2.True\ Positive + False\ Negative + False\ Positive}$$ ***Equation (5.4)***

Then by using this Equation (5.3) I calculated the value of PPV and the sensitivity for each model and measured the F_1*-score* or Equation (5.4) to measure the F_1*-score* directly (see Table 5.4).

Table 5.4: ***F_1-score*** **for each model tested**

Model tested	***N***	***True(+)***	***False(+)***	***False(-)***	***True(-)***	***PPV***	***Sensitivity***	***F_1-score***
Adaptation-info	24	20	1	3	0	0.95	0.87	0.91
Adaptation-non-info	24	19	2	3	0	0.90	0.86	0.88
Queue-info	**24**	**21**	**1**	**2**	**0**	**0.95**	**0.91**	**0.93**
Queue-non-info	24	19	1	3	1	0.95	0.86	0.90

5.4.2 Evaluation of the impact of features usage in relation to variable outcomes

As the next step in this analysis, the impacts of the features available in this system were evaluated based on each variable outcome (success rate, following path, and sinking the target). I focused on three features in this analysis: the use of a virtual camera, stop function, and additional planning information.

By using X^2 distribution analysis, the use of the virtual camera in this experiment affected one or two variable outcomes with statistical significance on several group models tested.

Referring to Table 5.4, the Mean use of the virtual camera feature is 4.39 usage (SD = 5.46 usage). Then I categorised the use of the virtual camera into three different groups (never → 0 usage, normal → 1 – 10 usage, and over use → more than 10 usage). The range of normal usage was grouped based on the range of the Mean and standard deviation, that is, ten times is the closest integer value to the Mean plus one standard deviation.

The independent variables i.e. the success rate, whether the path was followed, and whether a target was sunk, were used to identify the impact of the use of the virtual camera feature. Two values of “fail” and “succeed” were applied to the analysis. The evaluation was analysed through four different tested combination group models (see Table 5.5).

Table 5.5: Distribution X^2 analysis of the total number of times the virtual camera was used versus the success rate, whether the path was followed and whether the target was sunk for four different combinations of the group models tested

Virtual camera usage groups	Proportion (%) of success rate		X^2	Proportion (%) of following path		X^2	Proportion (%) of sinking target		X^2
	Fail	Succeed		Fail	Succeed		Fail	Succeed	
Adaptation-info									
Never	100	0	5.35**	40	100	0.09	100	0	7.38*
Normal	13.64	86.36		4.55	95.45		9.09	90.91	
Over use	0	100		0	100		0	100	
Adaptationnon-info									
Never	66.67	33.33	4.80**	33.33	66.67	2.91	33.33	66.67	1.65
Normal	16.67	83.33		5.56	94.44		11.11	88.89	
Over use	0	100		0	100		0	100	
Queue-info									
Never	33.33	66.67	1.91	33.33	66.67	6.97*	0	100	1.17
Normal	13.33	86.67		0	100		13.33	86.67	
Over use	0	100		0	100		0	100	
Queue-non-info									
Never	0	100	2.58	0	100	0.56	0	100	2.58
Normal	26.67	73.33		6.67	93.33		26.67	93.33	
Over use	0	100		0	100		0	100	

***P < 0.05, **P < 0.1**

Based on Table 5.5, the use of the virtual camera feature in the Adaptation-info model affected the success of sinking the target at the 5% confidence level and the success rate at the 10% confidence level, whereas, in the Queue-info model, the virtual camera feature only had an effect on the success of following the path. Otherwise, there were no significant effects ($P > 0.05$) on the use of the virtual camera for both the Adaptation-non-info model and the Queue-non-info model.

To show the effect of the use of the virtual camera for the supervisory control model, I combined all existing models to be tested as one group. In addition, I also re-categorised the experiment data into new combination models to show the effect of this feature. First, I combined the Adaptation-info model and the Adaptation-non-info model as the new Adaptation model group, and repeated it for the corresponding Queue models to get the new Queue model group. Then, I combined the Adaptation-info model and the Queue-info model to be used as the new information model group, and repeated it for the respective non-info models to obtain the new non-information model group. Please refer to Table 5.6 for more details.

Table 5.6: Distribution X^2 analysis of the total number of times the virtual camera was used versus the success rate, whether the path was followed and whether the target was sunk for the new combination group models

Virtual camera usage groups	**Proportion (%) of success rate**		**X^2**	**Proportion (%) of following path**		**X^2**	**Proportion (%) of sinking target**		**X^2**
	Fail	**Succeed**		**Fail**	**Succeed**		**Fail**	**Succeed**	
All SC model									
Never	40	60	**6.61***	20	80	**5.22****	20	80	2.66
Normal	17.14	82.86		4.29	95.71		14.29	85.71	
Over use	0	100		0	100		0	100	
Adaptation model									
Never	75	25	**9.60***	25	75	2.77	50	50	**5.94***
Normal	15	85		5	95		10	90	
Over use	0	100		0	100		0	100	
Queue model									
Never	16.67	83.33	2.25	16.67	83.33	2.79	0	100	3.55
Normal	19.35	80.65		3.23	96.77		19.35	80.65	
Over use	9.09	90.91		0	100		0	100	
Model with information (prediction / feedback)									
Never	50	50	**4.99****	25	75	**4.71****	25	75	1.58
Normal	13.51	86.49		2.7	97.3		10.81	89.19	
Over use	0	100		0	100		0	100	
Model without information (No prediction /feedback)									
Never	33.33	66.67	2.76	16.67	83.33	1.61	16.67	83.33	1.69
Normal	21.21	78.79		6.06	93.94		18.18	81.82	
Over use	0	100		0	100		0	100	

***P < 0.05, **P < 0.1**

Table 5.6 shows that the overall use of the virtual camera affected the success rate with a $P - value$ which was less than required for a significance level of 5% (see first three lines of the table content), and it only had an effect on the success of the following paths with a significance level of 10%, hence it is only a minor effect. The “never” category of virtual camera usage showed lower proportions of success in the three variable outcomes compared to “normal” and “over” usage. Moreover, the “normal” category recorded the highest probability of success in less than 60 seconds (never = 9.38%, normal = 78.13%, and over use 12.5%).

Applying a similar method of analysis, the X^2 distribution model for the stop function feature showed that 83% of the participants used the stop function in at least one of the models tested, and the logistic regression model showed those who used the stop functions in the model were 8.4 times more likely to succeed compared with those who did not use these functions ($P = 0.05$). On the contrary, there was no significant relationship between the utilisation of the stop function and the result of the experiments (fail or succeed) in the Queue model ($OR = 0.66, P = 0.6$). This means that the stop function feature works better for Adaptation models as compared to Queue models, even though in this experiment design scenario, the stop function feature did not significantly affect ($P > 0.05$) the success rate, the success of following the path and the success of sinking the target.

For comparison purposes, all 24 participants performed an additional sub-experiment to test the direct/manual control model using the same design task and experiment. I measured the *PPV* value for this model as **0.70** and its *sensitivity* value as **0.94**. Its F_1*-score* was **0.80**, which was smaller than all the supervisory models tested.

5.4.3 Questionnaire

Most participants agreed that all the supervisory models tested were user friendly (the modus score for the four models ranging from five to seven) and had good performance (modus score for the four models ranging from four to six). The Queue model with an extra information model was the most preferred out of the models tested (Mean score = 4.67, modus ranging from five to seven). In addition, participants also agreed that the extra information in the model interface helped them in performing the task.

5.5 Discussion

The experiment was designed to evaluate gaming features in applying HSC to improve human machine interfaces for a telerobotic scenario. This experiment is focused on two models, the Adaptation and the Queue models, as a response to series of commands which is part of the planning process in HSC. In order to evaluate user performance based on key components as mentioned earlier, these two response model were tested with and without additional virtual information.

Here, a successful task result was defined as a participant followed the path assigned and sinking a block into the hole during the time allocated. Based on the result I found there is a moderately strong correlation between these two user performance variables. By splitting the range of completion time into three groups (0-60 seconds, >60-120 seconds, and >120-180 seconds) and applying logistic regression, I found that in both the Adaptation and Queue models, most participants could successfully complete the task (by following the correct arrow and sinking the block) in less than 120 seconds, with the greatest success recorded for the Queue model with visual planning information. I noticed participants who took longer than 120 seconds to complete the task have a much lower probability of success compared to those who completed the task more quickly. So, this means the HSC response model tested with this task scenario allows the participants to successfully complete the task in a short time periods.

In order to evaluate user performance on Adaptation and Queue response model by using two recorded variables, success following the path and success to sink the block, an analysis approach using F_1*-score* was applied. The results showed that user performance for the Queue model is slightly better than the Adaptation model (higher F_1*-score*). In the Queue model, it seemed that the participants had more control in their movement planning. They could intervene by easily altering the path using the stop function. Compared with the Queue model, participants felt that the stop function was more helpful in the Adaptation model since each time this model defined a new target position, the robot moved directly to the new target. In this scenario, the stop function was useful in providing a mechanism for checking or cancelling the planning process.

My first assumption, that the Adaptation model would have faster performance compared to the Queue model, was not correct based on the test results (path and sunk true). The average completion time of the Queue model is lower than the Adaptation model, especially for this experimental design scenario where the participant was focused on pushing a block along a path.

In evaluating the effect of available features on the variable outcomes, the use of the virtual camera for all models showed a significant effect overall for the success rate and success in following the path. The use of the virtual camera feature significantly affects success in sinking the blocks in the Adaptation model and success in following the path in the Queue model, especially for model with planning information. The strong effect of the use of the virtual camera in successfully sinking the target in the Adaptation model was because the process was similar to direct/manual control. The participant did not need to change viewpoints when following the path since the model was always responding to each command given. This feature does not seem to be required in this situation, but worked better to identify where the block position was located form the target hole. Meanwhile, use of the virtual camera in following the path in the Queue model seems to work better as after the participants finished defining the target positions they had more time to observe the model movement when following the path.

The experimental results showed that there is no strong statistical correlation between the use of the stop function feature and the success in following the path, or between the use of the stop function and the success in sinking the block. The results also showed those who used the stop function were eight times more likely to record success in following the path and in sinking of the target compared to those who did not use it. Thus, the models tested with visual planning information performed better than those without it. The planning information is useful in helping the participants to perform the task, especially for the Queue model. In addition, I assume the stop function was not widely used since I only tested the system with a low level HSC design. In a real task scenario, especially in mining telemanipulation, there are a number of situations which require this function, one of the example is when the robot arm nearly hit the wall because incorrect command which can possibly damage the robot.

Comparing the performance between the best HSC response model (Queue with info model) and direct/manual control, participants who used the supervisory model did better in following the path and sinking the block than those who used direct/manual model. The movement planning function appeared to be an important feature which should be provided in telerobotics especially for the supervisory control model.

In addition to the objective measurements collected, I also asked the participants with several open-ended questions about interface performance. Participants were asked which features they were most attracted to and their suggestions for improving the interface performance. Some participants said that the interface was enjoyable and gratify, I therefore argue that the gaming environment has played a significant role in creating a sense of immersion contributing to the participants' satisfaction. When asked about the features of the interface, most mentioned that they liked the functionality of the interface in providing information. As mentioned by one participant, "The mixture of 3D and video interfaces was useful for me because I can cross-check between the interfaces.” This showed that the combination of 3D virtual and video views had assisted in performing the task well.

Moreover, three participants mentioned that they liked all features of the interface. Based on participant comments, the viewpoint control, graphic display and additional information provided (e.g. green circle and lines), made this interface likeable. Furthermore, 17.6% of the participants emphasised that the most interesting feature for them was being able to use or control the interface easily, as expressed by the following response, “…the use of the gaming keypad setting helped me to better control the robot arm and manage the 3D interface …”

5.6 Summary of Chapter

In this chapter I evaluated user performance using a gaming environment with the HSC response model, the Queue and Adaptation model. In order to assess the effectiveness of these two response models with planning information and without it, I grouped the interface into four categories. I evaluated user performance by using logistic regression to establish the relationship between the probability of success and completion time.

All four classifications of HSC response models showed better performance than direct/manual control. User performance using the Queue response model with visual planning information performed best. However, visual planning information did not have a large impact on the performance of the Adaptation model probably because the participants did not plan very far ahead.

In contrast to the visual planning/feedback information and stop functions features, the use of the virtual camera had a significant effect on the outcomes of the experiment, especially on the success rate. This feature seems to work better in the process of sinking the target into the hole for the Adaptation model, and in following the path as part of the supervisory planning process for the Queue model.

Even though the models tested showed good performance and received positive responses from the participants, a number of suggestions for improvements in several aspects of the interface were provided. Most of the participants focused their comments on the 3D virtual views performance. When they tried to operate the interface, they found several weaknesses in the 3D model, such as the precision and the stability of the 3D graphic. Due to these problems, in some circumstances, a number of participants had to rely more on the video camera than they otherwise would have: “…there were situations when I could see the robot arm touch the object on the video … but this could not be seen in the 3D model”. This emphasises the need for MR in interfaces to provide a mechanism that allows human interpretation to be applied where inaccurate sensing has introduced model errors.

In this chapter, I have tested the latest prototype of telerobotic interfaces with MR and HSC concepts applied. As mentioned above, I have only applied low level task HSC for performing a task in real telerobotic scenarios, thus the latency issue is not perfectly addressed. Based on the experiment results, the built system successfully performs when used by participants with a specific background, such as university students. Therefore, there is no evidence to suggest that the system will be user friendly for everyone. In order to test the user satisfaction on this telerobotic interfaces, the next chapter will describe an experiment whereby participants (from diverse background) tested the latest prototype telerobotic interfaces. In the next chapter, a *Weibull* distribution is also used to analyse the distribution data of user performance.

Chapter 6

The Utilisation of *Weibull* Distribution for User Performance Analysis

This chapter presents the analysis using the *Weibull* distribution to evaluate the user performance of the latest prototype telerobotics user interface. I deployed this telerobotic interfaces for public testing at an exhibition in the CSIRO Discovery Centre, Canberra, Australia, and conducted the experiment over three months (May to July 2012). I recorded 6139 total user sessions. The *Weibull* distribution was applied to analyse the reliability of the user performance data based on two response models, Adaptation and Queue response models. In addition, I also recorded the user performance for direct/manual control and conducted the same analysis as a comparison.

6.1 Introduction

Mathematical models are mostly used to explain actual problems for many different applications. Murthy [103] suggested two approaches to building suitable mathematical models: a theory-based model (physics-based model) and an empirical model (data-dependent model). He also mentioned that the theory-based model is an approach built based on theories that are relevant to the problems, while the empirical model is an approach that used the available data as the basis for model building without requiring prior understanding of the underlying mechanism involved.

The empirical approach is commonly used in experimental studies as most experimental results exhibit a high degree of variability [103]. This experimental data needs to be modelled with a suitable distribution model, so it can be viewed as observed outcomes of random variables from the distribution. In this case, a mathematical model is used to evaluate and compare the user performance data to assess the suitability of the response models as telerobotics user interfaces. A distribution model is a common way to interpret information in the evaluation process. When the data is found to follow a similar pattern as represented in a known distribution model, the data can be summarised easily.

The *Weibull* distribution is one of many popular distribution models that have been applied in many fields such as: engineering, material science and finance. The literature on *Weibull* distribution is substantial and scattered across many different journals [103]. It is commonly used distribution in reliability engineering to model time to fail, time to repair and material strength [104]. This model has been utilised not only to model the reliability of a product, but also to study other issues in different stages of the product life cycle, including quality control. Johnson [105] also stated that the *Weibull* distribution is a distribution that has been used in many scenarios.

The advantage of the *Weibull* distribution is it can easily be transformed into different kinds of distribution behaviours, which makes it very convenient as a lifetime model [105]. Research conducted by Taylor [106] in 1999 utilised the *Weibull* distribution to model the requests scenario in his web telerobotic interfaces. In his scenario, the operators may stop for any one of many reasons and each of these reasons has a probability of occurring at any particular time. He found that besides describing the model of user’s request to interfaces, this *Weibull* distribution can be used to compare data captured from telerobotic interfaces during normal use without conducting controlled experiments and is likely to be applicable to other classes of interfaces.

An experiment with the “in the wild” method, that uses a visitor of the exhibition as the participant, was applied to gather observation data. This method reduces the bias from conducting controlled experiments. The variance of the participants can more accurately represent a cross section of population. Studying user behaviour from this sample of the population means I can analyse how my telerobotic interface will be used in a more general way and use this as a basis for developing interfaces for evaluation with skilled operators.

By adopting the approach model applied by Taylor [106], in this chapter, I analyse the experiment outcomes based on two response models: Adaptation and Queue. Even though these telerobotic interfaces have different properties from Taylor’s web telerobotic interfaces, I successfully tested whether the *Weibull* distribution is also suitable for modelling and describing the distribution of user behaviour/performance in my telerobotic interface. Hence, before I describe the experiment, the results and the analysis, the next section describes the *Weibull* parameters which are used for the main analysis.

6.2 Prototype Implementation

It is not uncommon to find varying user behaviour when utilising telerobotic interfaces. In order to evaluate the effectiveness of the designed telerobotic interface, an experiment was conducted. The evaluation was focused on the user behaviour using this telerobotic interface with two different response models for human supervisory control (HSC), the Adaptation and Queue response models. The data was gathered over a period of three months using this two response models, which had been applied in previous experiments.

In applying the *Weibull* model to the experiment result, it is necessary to understand the two different properties known as the *probability density function* (*pdf*) and the *cumulative distribution function* (*cdf*). According to Johnson [105], in the set of all possible values of x, which is an interval or union of two or more non-overlapping intervals known as *continuous random variables* (*crv*), the *pdf* can be defined as any real valued function $f(x)$ that satisfies $f(x) \geq 0$ for all x, and $\int f(x)dx = 1$. While the *cdf* of a random variable X is defined by $F(x) = P(X \leq x) = \int f(t)dt$ for all x. Both *Weibull pdf* and *cdf* have three parameters, as shown in the formula below:

$$\textbf{\textit{pdf}} \rightarrow f_{(x)} = f_{(x;\beta,\theta,\delta)} = \begin{cases} \frac{\beta}{\theta}\left(\frac{x-\delta}{\theta}\right)^{\beta-1} e^{-(x-\delta/\theta)^{\beta}} & , x > \delta \\ \delta & , x \leq \delta \end{cases} \qquad \textbf{\textit{Equation (6.1)}}$$

$$\textbf{\textit{cdf}} \rightarrow F_{(x)} = F_{(x;\beta,\theta,\delta)} = 1 - e^{-(x-\delta/\theta)^{\beta}} \qquad \textbf{\textit{Equation (6.2)}}$$

where β (beta) is the shape parameter, θ (theta) is the scale parameter and δ (delta) is the location parameter, which describe more detail below:

a. *Shape* Parameter or β (beta)

The shape parameter provides the flexibility of a *Weibull* distribution. Different values of this parameter produce variant forms of distribution [103, 104, 107], for example: $\beta = 1$ is identical to the exponential distribution; $\beta = 2$ is identical in the Rayleigh distribution; and $\beta = 3$ is identical to the normal distribution. Figure 6.1 below shows the $\boldsymbol{pdf}$ and $\boldsymbol{cdf}$ of a *Weibull* distribution for selected values of the shape parameter.

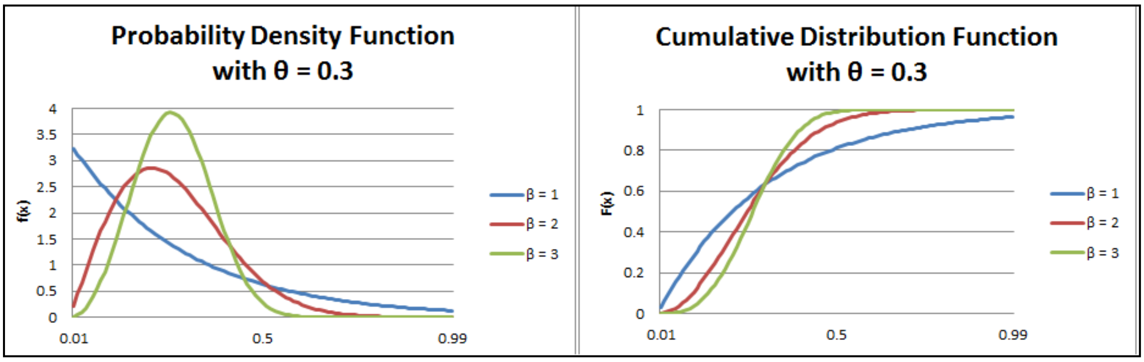


Figure 6.1: *Probability Density Function* (*pdf*) and *Cumulative Distribution Function* (*cdf*) with selected values of the shape parameter

As an example in reliability engineering, where *x* is equated to time (*t*) which means a “*hazard rate*” or “*failure rate*”, and the *Weibull* distribution provides a distribution where the failure rate is proportional to the power of time, the shape parameter is the power plus one which can be interpreted as follows: (1) if $\beta < 1$ then the failure rate decreases over time; (2) if $\beta = 1$, it means the failure rate is constant over time; and (3) if $\beta > 1$, it means the failure rate increases with time.

b. *Scale* Parameter or θ (theta)

This parameter determines the range of the distribution. Engineered Software [108] states that the scale parameter is also known as *characteristic life* when the location parameter is equal to zero. The examples of variant $\boldsymbol{pdf}$ and $\boldsymbol{cdf}$ with selected values of the scale parameter are shown in Figure 6.2.

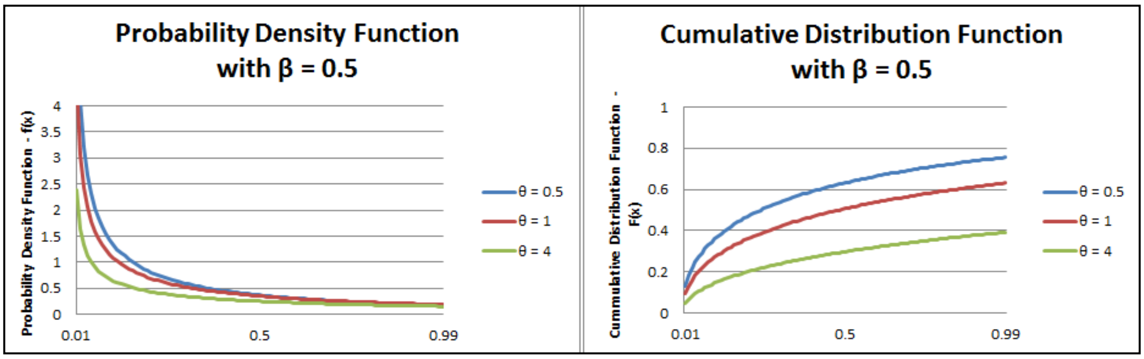


Figure 6.2: Probability Density Function (pdf) and Cumulative Distribution Function (cdf) with variant of scale parameter

c. *Location* Parameter or δ (delta)

In most cases, the location parameter is assumed to be zero. This parameter is normally used in defining a failure-free zone. The probability of failure when the variable *x* is less than the location parameter is zero. The location parameter has been assumed to be greater than zero, so that no failure can occur before the test starts. An example of the effect of the location parameter is shown in Figure 6.3.

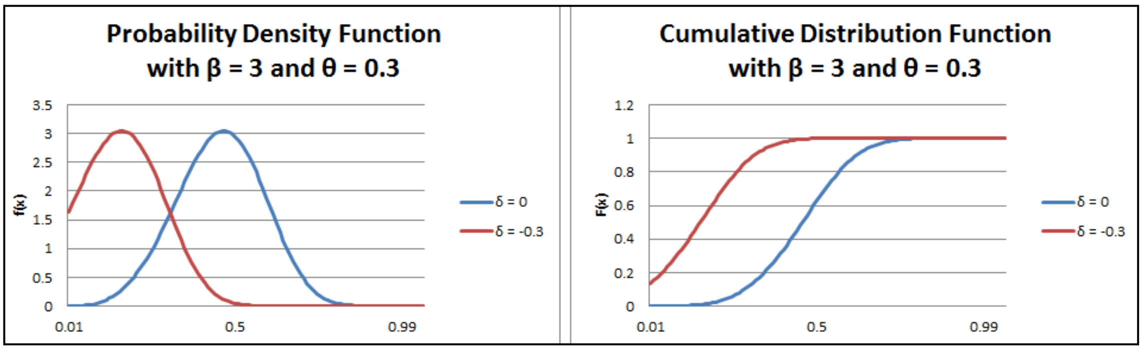


Figure 6.3: The effect of location parameter in Probability Density Function (pdf) and Cumulative Distribution Function (cdf)

Where δ = -0.3 this means the curve is shifted 0.3 points to the left. A negative value in the location parameter means the curve is shifted to the left while a positive value means the curve is shifted to the right.

In order to modelling user behaviour/performance in my telerobotic system, the variable x in *Weibull* distribution is equated to two different random variables, which are the *number of requests made by the operator to the telerobot in a session (r)* and *the length of time the device was operated in a session (t)*. Hence, by using Equations (6.1) and (6.2), the *pdf* and *cdf* in the *Weibull* distribution gives the relationship:

$$\boldsymbol{pdf_{request}} \rightarrow f_{(r)} = \frac{\beta}{\theta}\left(\frac{r-\delta}{\theta}\right)^{\beta-1} e^{-(r-\delta/\theta)^{\beta}}$$ ***Equation (6.3)***

$$\boldsymbol{cdf_{request}} \rightarrow F_{(r)} = 1 - e^{-(r-\delta/\theta)^{\beta}}$$ ***Equation (6.4)***

$$\boldsymbol{pdf_{time}} \rightarrow f_{(t)} = \frac{\beta}{\theta}\left(\frac{t-\delta}{\theta}\right)^{\beta-1} e^{-(r-\delta/\theta)^{\beta}}$$ ***Equation (6.5)***

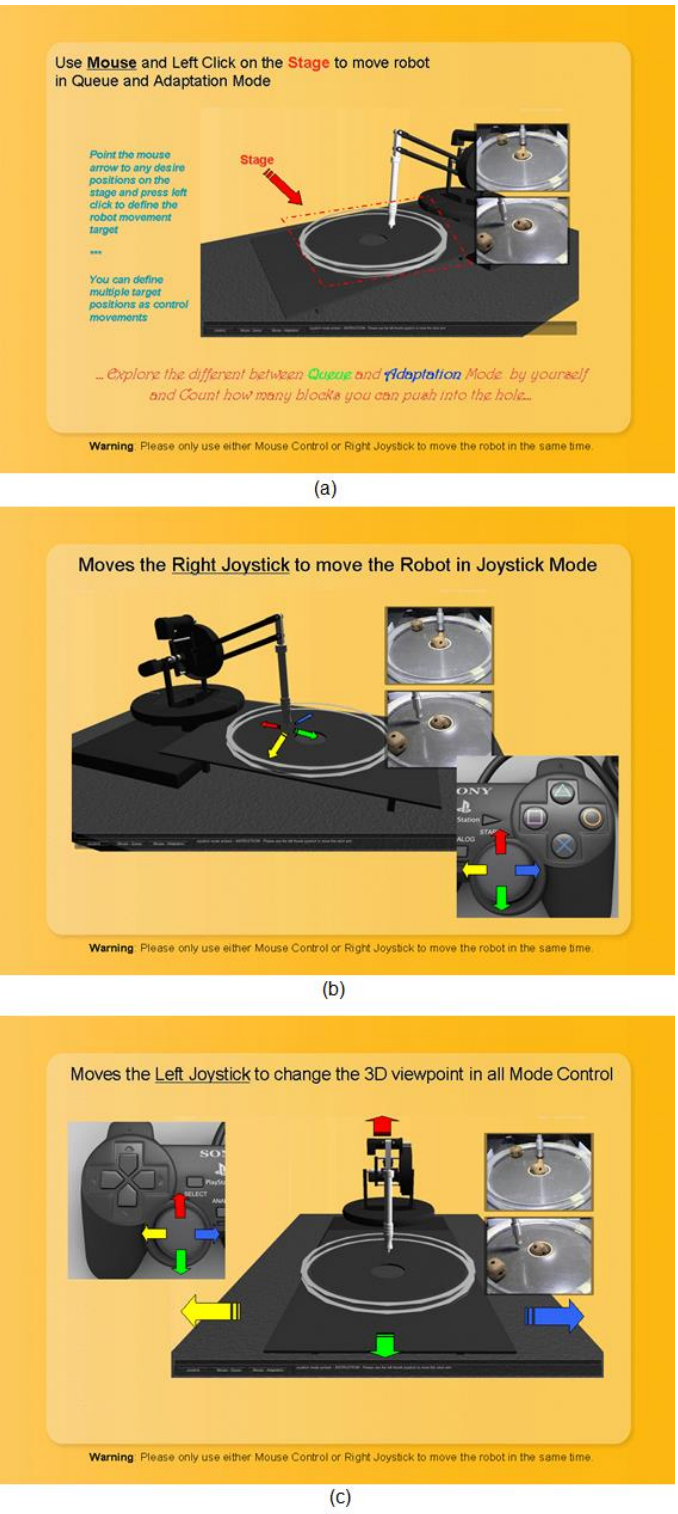
$$\boldsymbol{cdf_{time}} \rightarrow F_{(t)} = 1 - e^{-(t-\delta/\theta)^{\beta}}$$ ***Equation (6.6)***

When deploying the telerobotic interfaces for the exhibition, there were several factors that needed to be considered. Firstly, safety issues for both the visitors and the system should be prioritised, as the system was publicly accessible to all exhibition visitors including some who are malicious. Most of the components of the telerobotics system, except the input device (joystick and mouse), were placed inside a display protected with glass.

Secondly, this telerobotic system ran unsupervised for eight to twelve hours per day (based on the opening hours of the exhibition). Hence, in order to maintain the reliability of the system, a regular restart process was applied to the machine and the system (telerobot and 3D model) was reset to its default position if no one was using it.

Thirdly, since no guide would be present to assist in explaining how the system works, sufficient information should be displayed for visitors. This information should be simple, interesting and informative. So I used six screens in total which showed information including: (1) information of the name of the exhibition; (2) slide presentation about how to use available functions in the system and the control device; (3) video about the background of this system; (4) information about the technology which was applied in the system; (5) the task required; and

(6) that the telerobotic user interface applied the mixed reality (MR) environment and human supervisory control (HSC) concepts. A number of information screens for the telerobotic interfaces can be seen in Figure 6.4.



Use **Mouse** and Left Click on the Stage to move robot
in Queue and Adaptation Mode

Point the mouse arrow to any desire positions on the stage and press left click to define the robot movement target

...

You can define multiple target positions as control movements

... Explore the different between Queue and Adaptation Mode by yourself and Count how many blocks you can push into the hole...

Warning: Please only use either Mouse Control or Right Joystick to move the robot in the same time.

(a)

Moves the Right Joystick to move the Robot in Joystick Mode

Warning: Please only use either Mouse Control or Right Joystick to move the robot in the same time.

(b)

Moves the Left Joystick to change the 3D viewpoint in all Mode Control

Warning: Please only use either Mouse Control or Right Joystick to move the robot in the same time.

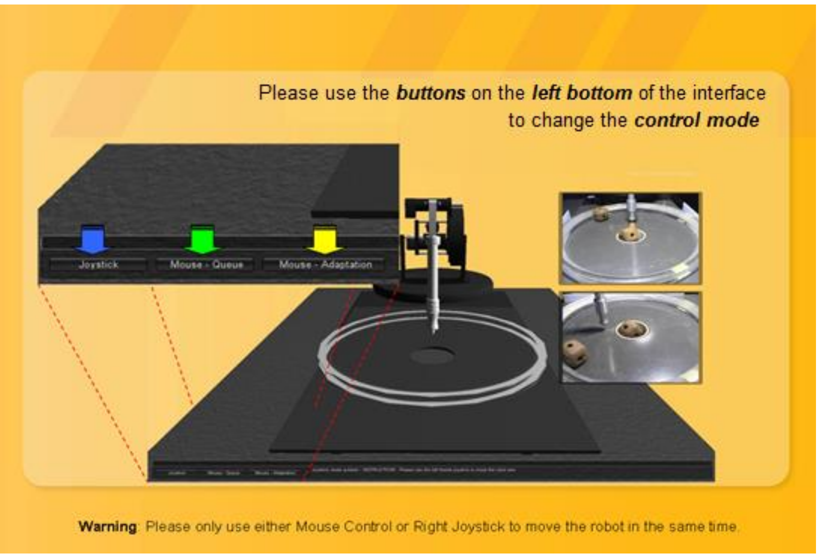
(c)

Figure 6.4: Preview of information screens for the telerobotic interfaces

In relation to the type of control model used by the participants, functions were built into the system such that each participant could choose their preferred control model for the task or be automatically assigned one of the control models. These functions also explained how a session, in which request and time variables are recorded, is created.

a. Assign the model control manually

In order to choose the control model manually, the participants were required to use the mouse and click one of three menu buttons (see Figure 6.5) on the screen based on their control model preference. The user could view information representing each control model on menu buttons: the mouse-Adaptation button and the mouse-Queue button for HSC and joystick button for direct/manual control. There was a message box beside the menu buttons that displayed information about the active model control, including which input device needed to be used. This information was also provided on another screen as part of the instructions.



Please use the ***buttons*** on the ***left bottom*** of the interface
to change the ***control mode***

Warning: Please only use either Mouse Control or Right Joystick to move the robot in the same time.

Figure 6.5: Menu buttons representing each model control tested

The system starts a new session every time the participants click a button. They are allowed to change their preference model control during their playing time, and at this time it will automatically terminate the previous active session and start a new one. A session is automatically terminated when no command is given to the system for more than ten seconds. It also puts the telerobot in an idle condition which resets the robot to its default position.

b. Assign the model control automatically

The system automatically assigns one of the control models when participants do not make a selection. The HSC model is assigned automatically when the participants use the mouse and click on the 3D model workspace area (virtual object inside the circle, please see Figure 6.4(a) for reference). Both Adaptation and Queue response models will be assigned randomly. On the other hand, when participants use with the right joystick/button of the gamepad, the system will automatically assign the direct/manual control model. A session then activates automatically in the system.

In addition, a virtual camera can also be controlled by the left joystick (see Figure 6.4(c)) in all control models, Queue, Adaptation or manual models. However, when the participants press this left joystick before they complete the two methods, assigning the models control manually or automatically, it will not create the session. The session is only created based on these two methods explained above. The complete joystick mapping can be found in Figure 4.11 in Section 4.3.1.

6.3 User Study

In conducting the experiment, I deployed the latest prototype of the telerobotic interfaces on one of the exhibition stages at the CSIRO Discovery Centre. In order to conduct a user study to measure operator satisfaction based on the response model of this telerobotic user interface, the visitors who were the experiment participants, were allowed to control and manipulate the telerobot through the system interface directly. For the purposes of the exhibition, two types of control model were applied, the direct/manual and HSC. In addition, for continuity of the research experiment, two response models of HSC, the Queue and Adaptation response models from previous experiments ware also applied to the system.

6.3.1 Apparatus and Implementation of the Telerobotics System

On the exhibition stage, the local-remote environment was built to apply the concept of telerobotics. A wall was placed between the local and remote areas to block the operator’s direct view of the telerobot (See Figure 6.6 for more detail).

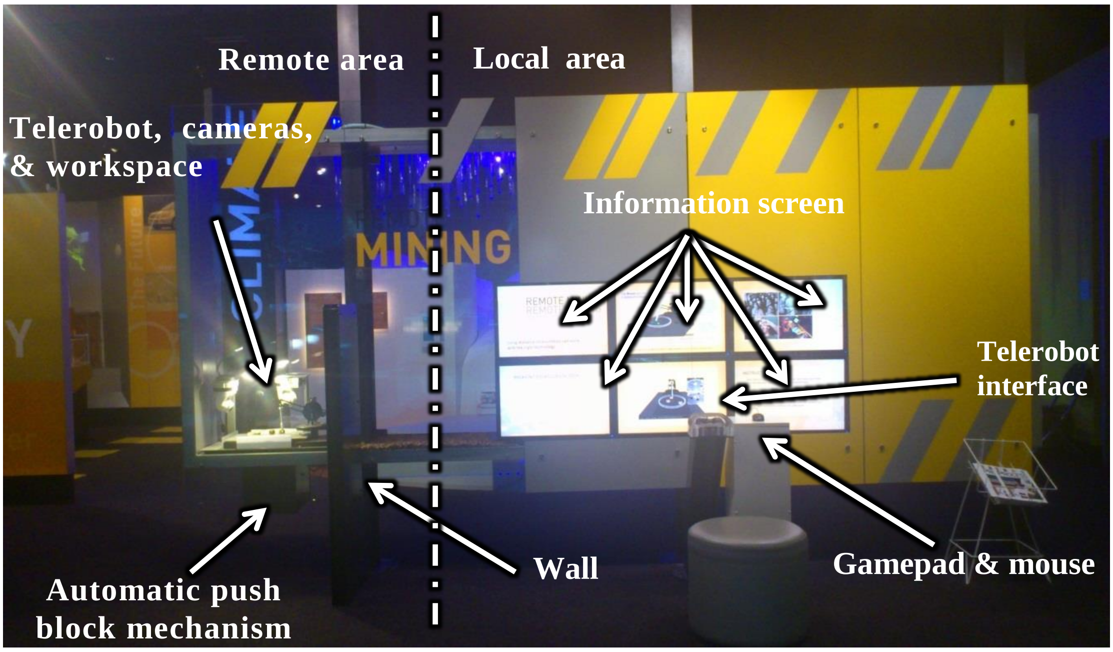


Figure 6.6: Overview of the exhibition

The local area consisted of six flat-screen Dell monitors (type 3008WFP), each with a resolution of 2560 x 1600 pixels. These were connected to a PC running the client application for the telerobotic interface. A standard gamepad and mouse were also located in front of the screen as the main control devices. The mouse was used as an input device to give input HSC commands; while for direct/manual control, the operator used the gamepad (the right button/joystick of the gamepad, see Figure 6.4(b)). In order to change the viewpoint of the virtual camera, the operator used the left button/joystick of the gamepad; this virtual control camera was used in both direct/manual and HSC models (see Figure 6.4(c)).

In the remote area, a robot arm was placed on the stage (workspace). This robot was connected to the robot controller system linked to a PC which acted as a server. There were two IP cameras installed in front of and beside the robot workplace. These cameras were connected directly to the Internet. The telerobotic scenario was to push the blocks into the hole, following which a mechanism installed under the workspace was activated to detect and push the block back automatically to the top of the workspace.

6.3.2 Participants (Sessions)

As mentioned above, the aim of the experiment was to evaluate users' satisfaction of this telerobotic system interface based on two proposed response models – the Queue and Adaptation models. All visitors to the exhibition who played/tried the telerobotic interfaces were assigned as random participants. For the variable performance, I recorded the total number of commands sent to the telerobot and the total playing time of each participant in a session. A session means the time taken for a series of movement commands to be sent to the robot.

The data collection was conducted over three months (May to July 2012). Based on the recorded data, I collected a total of 6139 sessions, which is divided into three groups as follows:

Table 6.1: The number of sessions per model interface tested

Model interface tested	Sessions
HSC with an Adaptation response model	2218
HSC with a Queue response model	1593
Direct/manual model	2328

6.3.3 Experimental Design and Procedure

This experiment was designed to be similar to my previous experiment. The main differences are in the process of recruiting participants and the length of time they were playing. The participants were all the visitors who played with the interface to manipulate the telerobot. However, unlike previous experiments, I did not direct participants to play with the telerobotic interfaces in particular way.

As mentioned above in Section 6.3.1 on apparatus and implementation of the telerobotic interfaces, all the required information to play with the system was provided on the information screens, and the system automatically recorded the number of requests sent to the telerobot and the length of the session for each model as measures of user interest.

The provided scenario was controlling the robot arm to push the blocks into a hole. The participants were required to use one of the provided interface models to operate a robot arm and they were free to play as long as they liked. I did not analyse the user performance based on how many blocks they could push into the hole, but I analysed the probability of participants in making one more request/command to the robot.

In this experiment I did not collect any personal information from the participants, their preferred control model, or any feedback using a questionnaire or informal interview. The collected data was aimed at collating information about the performance of the general public when using this telerobotic interface. It was by far the study with the largest number of participants as the effort required to acquire data from each participant was low.

6.4 Results

I used the *Weibull* model to fit the experimental result for the total number of requests sent to the telerobot (r) and the length of time played in a session (t) with the observed data. I analysed how well the *Weibull* model could reflect the data or how well the expected distribution under the model fitted could explain the observed data. In addressing these questions, I applied two methods by calculating the value of *Chi-square goodness fit test* (X^2) and the *Coefficient of Determination* (R^2) from the fitted *Weibull* curve on the observed sampling data.

A *Chi-square goodness of fit test* is normally utilised to test the association between two variables, the observed and expected variables. Based on Walpole and Myers [109], the *Chi-square goodness fit test* can be expressed as:

$$X^2 = \sum_{i=1}^{k} \frac{(o_i - e_i)^2}{e_i}, v = k - 1 \qquad \textbf{\textit{Equation (6.7)}}$$

where X^2 is the value of random data where the sampling distribution has approximated closely to the *Chi-squared* distribution with the *degree of freedom*, $v = k - 1$. The symbol o_i and e_i represent the observed and expected variables respectively for each *i*-th cell with a maximum of *k* cells.

Walpole and Myers [109] also mentioned that when the observed data is close to the corresponding expected data, the value of X^2 will be small, indicating that the observed data model is a good fit for the expected distribution model. On the contrary, when the value of X^2 is large, the fit between the observed and expected data is poor. A good fit leads to the acceptance of the hypothesis which is indicated by the significant value (α) not being greater than 0.05 $(\alpha \leq 0.05)$. The opposite is indicated by the value of the *Chi-squared goodness fit test* (X^2) being less than the value of *critical value* (X_α^2) for the significant level of 0.05 ($X^2 \leq X_{0.05}^2$).

In this case, four variables, which are the random sampling variables (the *request* (r) or the *length of playing time* (t)) and the three *Weibull* parameters $(\beta, \theta$ and $\delta)$, are derived from the *Weibull* model. The value of the *degrees of freedom (v)* was obtained by reducing the total number of cells (k) by 4, $v = k - 4$. This v value was used to calculate the critical value (X_α^2) mentioned previously.

In terms of decision-making criteria using the *Chi-square goodness fit test*, Walpole and Mayer [109] suggested that the value of each expected data should be at least 5. To satisfy this rule, the adjacent cell where the expected data was less than 5 were combined, and were assigned as $f_{(r)} \geq 5$ for the request variable and $f_{(t)} \geq 5$ for the time variable. By applying the Equations (6.3) as $\boldsymbol{pdf_{request}}$ and (6.5) as $\boldsymbol{pdf_{time}}$, the satisfaction of all the requirements above and the Equation (6.7) gives:

$$X^2_{request} = \sum_{i=1}^{k} \frac{\left(o_i - f_{(r)}\right)^2}{f_{(r)}}, f_{(r)} \geq 5, v = k - 4, \beta > 0, \theta > 0$$ ***Equation (6.8)***

$$X^2_{time} = \sum_{i=1}^{k} \frac{\left(o_i - f_{(t)}\right)^2}{f_{(t)}}, f_{(t)} \geq 5, v = k - 4, \beta > 0, \theta > 0$$ ***Equation (6.9)***

The *Coefficient of Determination* (R^2) is normally used to describe how well the curve of a statistical model fits with the observed data set. The value of R^2 is perceived as a number between 0 and 1, where a value close to 1 indicates that the curve fits the sampling data set very well, on the other hand, when the value is close to 0, the curve does not fit the sampling data set. The use of the R^2 value in fitting with various distribution models had been reported by Ricci [110].

The *Coefficient of Determination* (R^2) is the quotient between the total sum of squares (SS_{total}) and the regression of squares $(SS_{regression})$, where:

$$SS_{total} = \sum_i (e_i - \bar{o})^2$$ ***Equation (6.10)***

$$SS_{regression} = \sum_i (o_i - \bar{o})^2$$ ***Equation (6.11)***

the e_i and o_i are the expected and observed data, and $\bar{o}$ is the mean of the observed data, $\bar{o} = \frac{1}{n}\sum_{i=1}^{n} o_i$. Thus, the *Coefficient of Determination* (R^2) can be formed as:

$$R^2 = \frac{\sum_i (e_i - \bar{o})^2}{\sum_i (o_i - \bar{o})^2}$$ ***Equation (6.12)***

The analysis of the two variables, the number of requests and time taken on each model control tested, are as follows:

6.4.1 HSC with Adaptation Response Model

a. Request variable (r) in Adaptation response model

Based on the observed data set in 2218 sessions for the Adaptation response model, which was fitted by the *Weibull* curve, 50.8% of these sessions were unsuccessful in sending any requests to the telerobot. This could be due to a number of reasons such as the participants lost interest or the robot stuck. However, the remaining observed data still showed sufficient information that could be analysed, where the most number of requests in a single session was 188, and there were 35 sessions with at least 50 requests per session. By excluding the first four requests from data analysis ($r > 4$), I found the *Weibull* curve fitted the observed data with the estimated variables:

$\beta = 0.32$

$\theta = 2.45$

$\delta = 0.72$

$k = 34$

$X^2_{Request-Adaptation} = 43.772$, where $r > 4$

$\alpha_{Request-Adaptation} = 0.019$

$X^2_{0.05} = 39.841$, where $v = 30$

A plot of the observed and estimated data for the number of requests sent to the telerobot (1 to 80) using HSC with the Adaptation response model is shown in Figure 6.7.

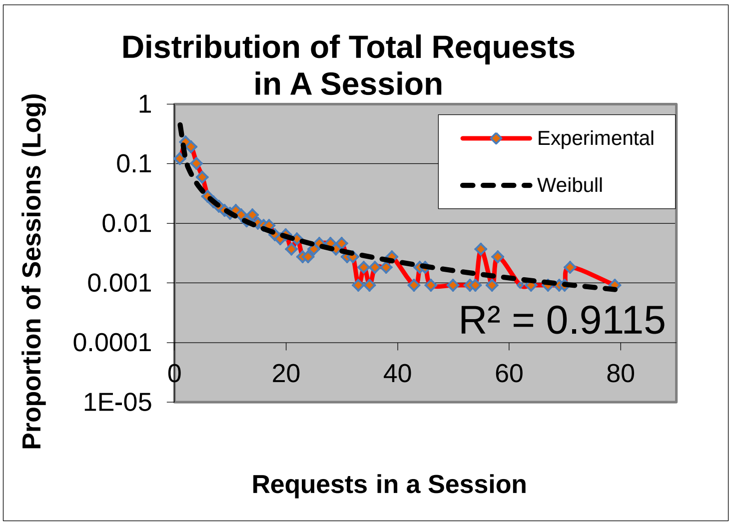


Figure 6.7: The comparison between the *Weibull* curve and observed data in HSC with the Adaptation response model, from a sample of 2218 sessions, which is showing the range between 1 – 80 requests to the telerobotic interface

The significance value, $\alpha_{Request-Adaptation} = 0.019$ and the $X^2_{Request-Adaptation} < X^2_{0.05}$ indicated that the hypothesis of the observed data for the number of user requests per session using the Adaptation response model fitted with the *Weibull* curve is acceptable, even though there was little variance in the observed sampling data for sessions with at least 80 requests. The *Weibull* curve was found to be a statistically significant good fit with the experimental data using the first 1090 sessions.

The specific range of the plot curve in Figure 6.7 shows the large random sampling error observed which suggests that data with a large number of observations may not be accurately represented by random sampling. Thus, the simple *Weibull* curve may not completely explain the whole sampling population. However, the high *Coefficient of Determination* (R^2) of 0.9115 suggests that the *Weibull* curve is acceptable and fits well with the observed data.

Taylor [106] mentioned that it is possible in telerobotic scenarios to have a mixture of distributions for the “number of requests” population. In his telerobotics experimental scenario, it was possible for the telerobot to be out of action or not respond to the request made by the operator. This was also possible in this experiment when the telerobot was faulty or when all the blocks were stuck in the hole. Hence, a mixed event population was produced between the sessions with a faulty telerobot and with a functioning telerobot. The contribution of the *Chi-square goodness fit* test from this Adaptation response for each $bin(i)$ is shown in Figure 6.8.

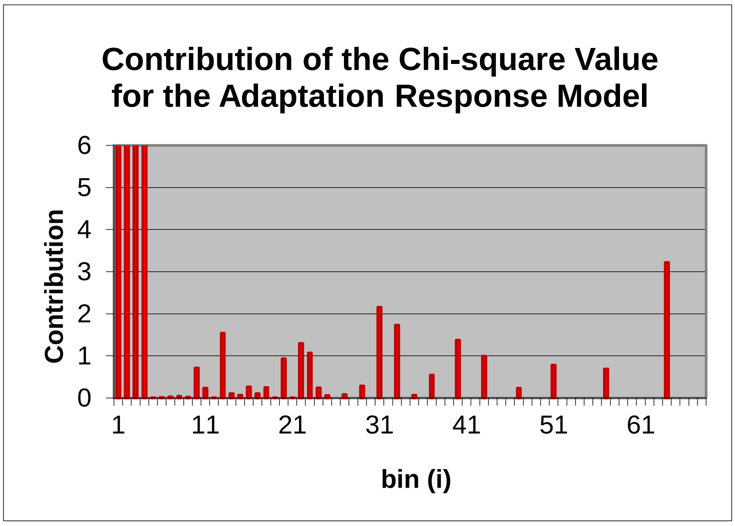


Figure 6.8: The contribution of the X^2 value from each of the bins for a simple *Weibull* model fit as per Equation 6.6 for the full range of observed data of the number of request recorded for HSC with an Adaptation response model

The block diagram shows that the largest contribution occurred mainly in the bins which represented a low number of requests, with total contributions over 80 sessions. As mentioned above, by excluding the first four requests, the *Weibull* distribution showed a good fit with acceptable X^2 and R^2 values.

In accordance to the example in reliability engineering [104], when the shape parameter β is sufficiently less than 1, the instantaneous drop off rate decreases quickly as the number of requests to the telerobotic interfaces increases. Hence, the probability of the user making at least one more request to the telerobot increases rapidly as more requests are made. By comparing the number of sessions between each consecutive bin, for example: $bin(i)\ /\ bin(i-1)$, Figure 6.9 illustrates the probability of the user making at least one more request for this HSC using the Adaptation response model. This number can be used to quantify user preference for one response model to another.

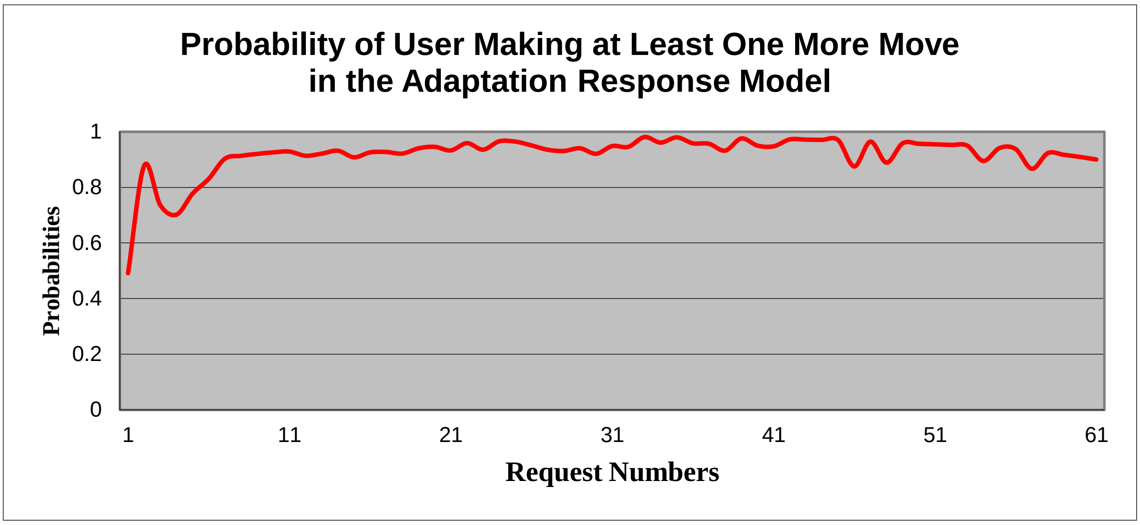


Figure 6.9: The probability of the user making an additional request in HSC with an Adaptation response model

Based on Figure 6.9, 74% of users who successfully made their first request made at least one more request, and 90-99% of users who made at least seven requests made at least one more request.

b. Time variable (t) in the Adaptation response model

The length of playing time in a session (t) is the variable that provides information on how long the user will stay to play with the telerobotic system. I noted that the longest playing time in a session was 600 seconds (10 minutes), and there were 60 sessions when the interface was played for at least 60 seconds. Based on the data analysis with the *Weibull* distribution, I noticed that the curve was better fitted with the observed data if the length of the playing time was greater than two seconds$(t > 2)$, and these give:

$\beta = 0.3$

$\theta = 2.5$

$\delta = 0.701$

$k = 42$

$X^2_{Time-Adaptation} = 47.279$, where $t > 2$

With $\alpha_{Time-Adaptation} = 0.022$

$X^2_{0.05} = 53.383$, where $v = 38$

A model distribution of the length of playing time data using HSC in Adaptation response model is shown in Figure 6.10.

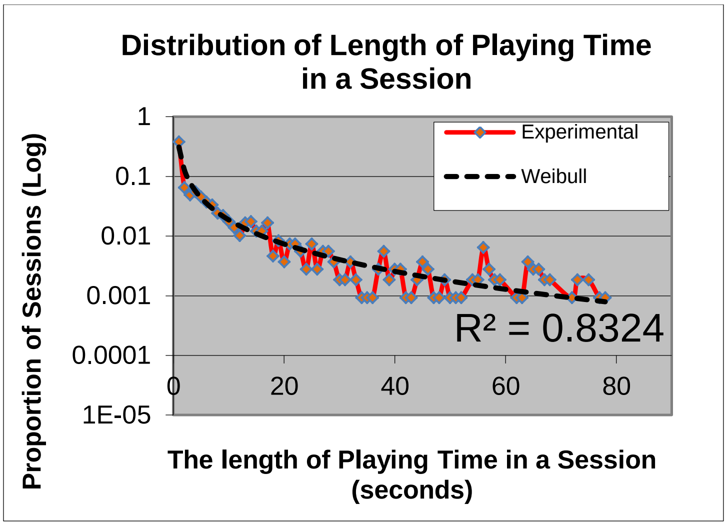


Figure 6.10: The comparison between the fitted *Weibull* Curve and the length of time for HSC with an Adaptation response model from a sample of 2218 sessions

Compared with the curve fitted for the "number of requests" variable above, the plot curve in Figure 6.10 also shows a large random sampling error. However the R^2 value for the fitted trend line equals to 0.8324, which is also close to 1, indicating that the curve from the sampling data can be used to represent the entire population.

6.4.2 HSC with Queue Response Model

a. Request variable (r) in Queue response model

In this Queue response model, 56.3% of sessions failed to send any requests to the telerobot. However, a trend line could still be fitted for the number of user requests in this response model. The most number of requests recorded in a single session was 150 and there were only five sessions which had at least 50 requests per session. Based on the range from 1 to 80 for the number of requests in the observed data set for 1593 sessions, I found the *Weibull* curve with the observed data, where:

$$\beta = 0.35$$

$$\theta = 4.197$$

$$\delta = 0.78$$

$$k = 23$$

$$X^2_{Request-Queue} = 12.849$$

$$\alpha_{Request-Queue} = 0.049$$

$$X^2_{0.05} = 30.143 \text{ , where } v = 19$$

Figure 6.11 showed the plot for the observed and estimated number of requests sent to the telerobot using HSC in the Queue response model.

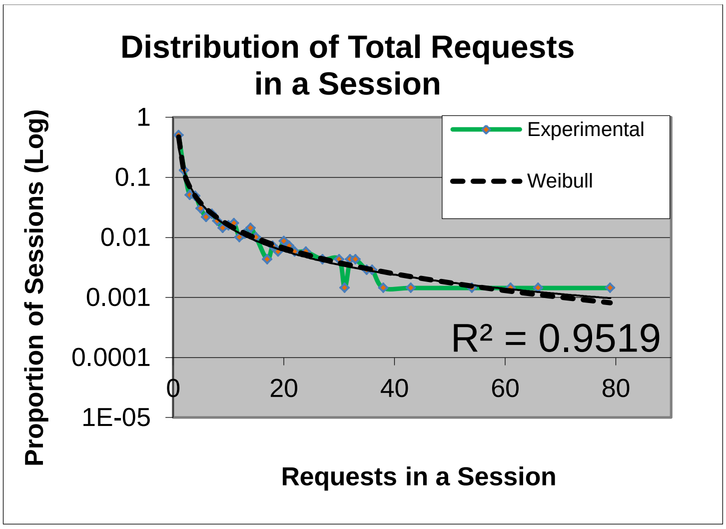


Figure 6.11: The comparison between the fitted *Weibull* curve and observed data using HSC with a Queue response model, from a sample of 1593 sessions which recorded 1 – 80 requests sent to the telerobotic interface

In this Queue response model, the *Weibull* model was also fitted for the observed data, as shown by the value of X^2 being less than the critical value ($x^2_{0.05}$) for all observed data in the selected range. Moreover, this value of X^2 for the number of user requests using this Queue response model interface was shown to be statistically significant with $\alpha < 0.05$.

The small number of observed data in this specific range accurately represents the population with $R^2 = 0.9519$. This suggests that the fitted curve for the number of user requests using the Queue response model is slightly better compared to that using the Adaptation response model. This is also demonstrated by the curve which was fitted with the full observed data set (without restricting the range of the number of requests sent.)

Figure 6.12 showed the contribution of X^2 for each *bin* in the Queue response model. There is no significant difference among the bins, although the contributions are still represented by a low number of requests sent to the telerobot.

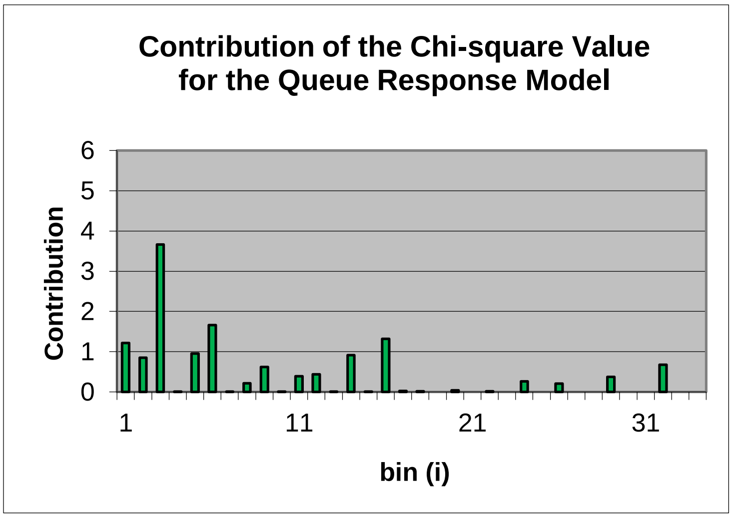


Figure 6.12: The contribution of the X^2 value from each bin for a simple *Weibull* model fit as per Equation 6.6 for the full range of the observed data of the number of request recorded for HSC with a Queue response model

Almost half (49.78%) of the users who successfully made their first request made at least one more request, and 86.27% of those who made at least three requests made at least one more.

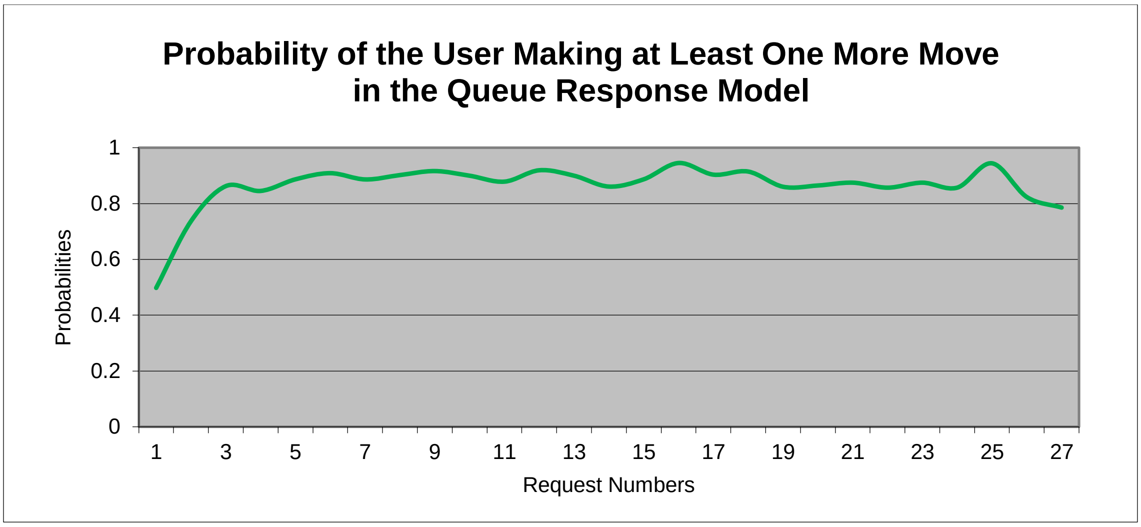


Figure 6.13: The probability of the user making an additional request in HSC with a Queue response model

b. Time variable (t) in Adaptation response model

In contrast to the “number of requests” variable analysis which included all sampling data in the range, for the length of playing time in a session (t) in HSC with the Queue response model, the *Weibull* curve was fitted with the observed sampling data where the length of playing time was greater than two seconds. The results, as shown in Figure 6.14, give the following:

$\beta = 0.32$

$\theta = 4.2$

$\delta = 0.701$

$k = 28$

$X^2_{Time-Queue} = 33.276$, where $t > 2$

With $\alpha_{Time-Queue} = 0.02$

$X^2_{0.05} = 36.415$, where $v = 24$

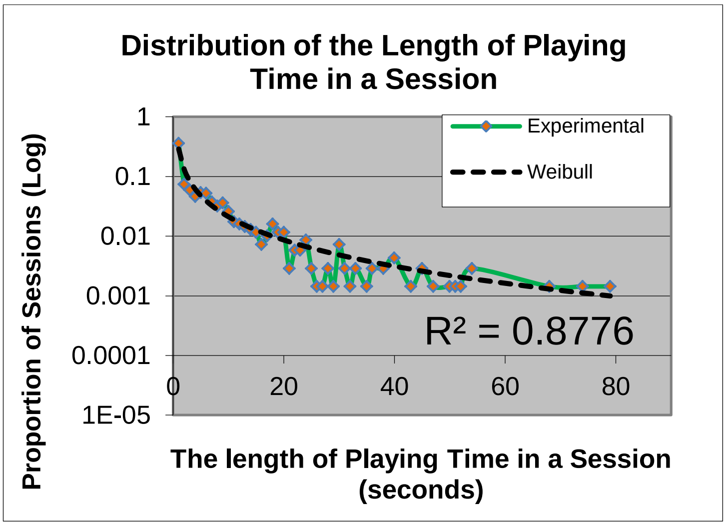


Figure 6.14: The comparison between the fitted *Weibull* curve and the length of playing time using HSC with a Queue response model from a sample of 1593 sessions

The comparison value of X^2 is still less than the critical value ($x^2_{0.05}$) for all observed data in the range with a significance value of α < 0.05. A number of sampling errors were still evident, but the R^2 value from the fitted *Weibull* curve was 0.8776 which indicated that the trend line of the curve has a good fit with the observed data.

I noted that the longest user playing time in this Queue response model was 510 seconds (8 minutes 30 seconds), and 18 sessions recorded a playing time of at least 60 seconds. Note that just 695 sessions recorded playing times of 0-80 seconds, which was much lower than the 2218 sessions included in the Adaptation model.

6.4.3 Direct/Manual Model

Unfortunately for the manual model it is difficult to determine the total number of requests sent to move the robot, since the robot movement process depends on how long the operator pushes the joystick button.

The time variable in this manual model showed a better fitted *Weibull* curve model compared to the HSC interface. I noted that the fitted curve was obtained without excluding any length of playing time in a session. I also noted that the longest time a user spent using the manual model was 2469 seconds (41 minutes 9 seconds), and there were 374 sessions that recorded a playing time of at least 60 seconds. When fitting the *Weibull* curve to the observed data I found:

$\beta = 0.34$

$\theta = 34.2$

$\delta = 0.699$

$k = 96$

$X^2_{time-Manual} = 96.034$

$\alpha_{time-Manual} = 0.026$

$X^2_{0.05} = 115.389$, where $v = 92$

Figure 6.15 shows the distribution of the observed data and the fitted *Weibull* curve with $R^2 = 0.8762$, indicating a good fit for the data.

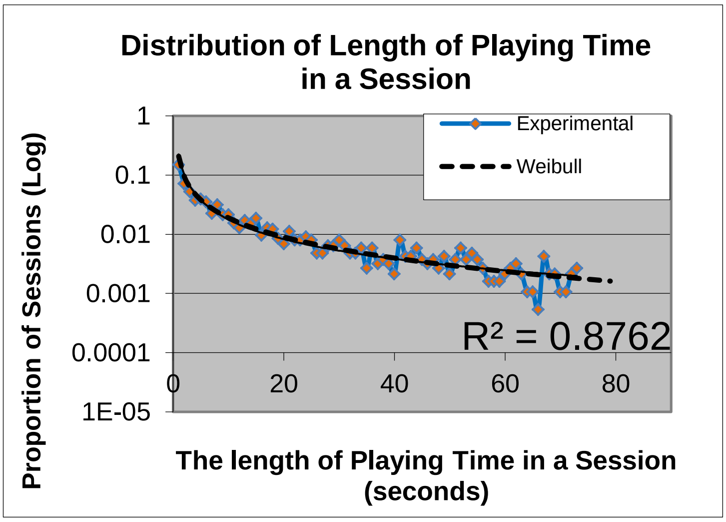


Figure 6.15: The comparison between the fitted *Weibull* curve and the length of playing time by using direct/manual model from a sample of 2328 sessions

In addition, the fitted trend line for this manual model can be easily seen as a well fitted curve. This curve model recorded a large *Chi-square goodness of fit* value since it was supported by sufficient sampling data which closely represents the number in the population. The *Coefficient of Determination* also supports the suitability of the fitted curve on the full range of the time variable for the sampling data.

All the results above are presented in a single table as seen in Table 6.2.

Table 6.2: Estimated parameters for the three models tested

Models tested	β	θ	δ	X^2	α	$X^2_{0.05}$	R^2	r/t
Estimated parameters for request in a session								
Adaptation	0.32	2.45	0.72	39.841	0.019	43.772	0.9115	4
Queue	0.35	4.197	0.78	12.849	0.049	30.143	0.9519	0
Estimated parameters for length of time playing in a session								
Adaptation	0.3	2.5	0.701	47.279	0.022	53.383	0.8324	2
Queue	0.32	4.2	0.701	33.276	0.020	36.415	0.8776	2
Manual	0.34	34.2	0.699	96.034	0.026	115.389	0.8762	0

Figures 6.16 and 6.17 show the comparison of the number of requests (r) and the length of playing time (t) per session for each model tested. These two figures show a similarity of a shape curve among the three models. In both response models HSC shows a very similar

dispersion of sampling data, especially for the comparison of the "number of requests" variables, even though the data for each model was based on a different total number of sessions.

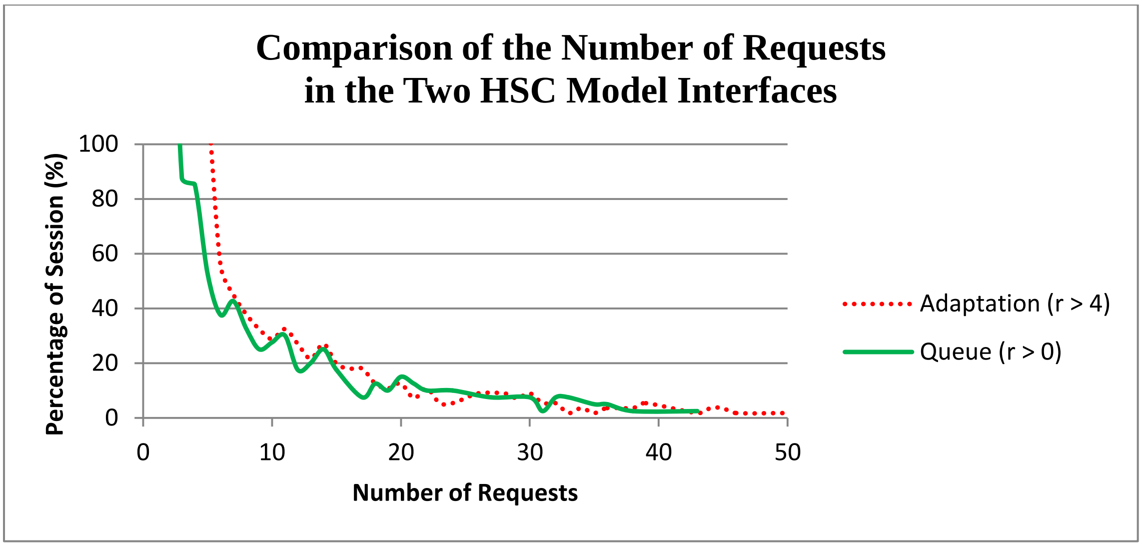


Figure 6.16: Comparison of the number of requests between the two HSC models tested

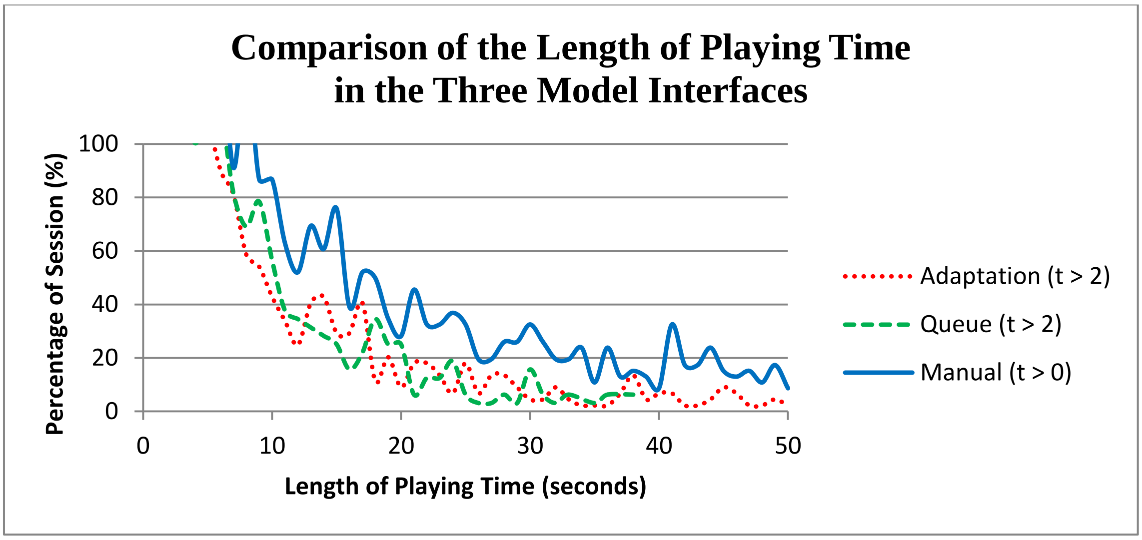


Figure 6.17: Comparison of time variables between the three models tested

6.5 Discussion

The number of requests (r) and the length of playing time (t) per session for all models tested fit the *Weibull* distribution. However, based on the request variable in both response models, a number of sessions failed to request any robot movements. I noted that the failure's event in this telerobotic scenario is the termination of the session due to one or many possible reasons, for example failed communication, user lost interest, and robot arm or target blocks stuck inside the hole.

In assessing user behaviour/performance, the sampling data from these two response models also showed a difference between the observed and expected distributions which were accounted for by a random sampling error to a satisfactory significance level. The distribution model enables the sampling data to be characterised by three parameters (β, θ and δ). In this analysis, I found that by manipulating the value of the location (δ) parameter, the fitted curve can be improved.

According to Table 6.2 for both r or t variables, even each model showed α value < 0.05, the models with a bigger α value resulted a smaller X^2 and an R^2 value close to 1 compared to models with a smaller α value. Based on this result I could say that by using the *Weibull* distribution and *Chi-square goodness of fit test* in analysing the number of requests and the length of playing time in a session for the telerobotic interface, a higher α value is better than a lower α value.

Similar to the result from Taylor's telerobotic interface [106], I found that the value of the *Shape* (β) and *Location* (δ) parameters were similar among the three model data sets from Table 6.2. Once this is known, I could estimate the *Scale* (θ) parameters from a set of model interfaces without estimating their *Shape* (β) and *Location* (δ) parameters. This can be done by rescaling and overlying the data from one model interface on the others and adjusting the scaling factor until the best fit is observed. This method is useful to compare user behaviour/performance for this telerobotic user interfaces.

The different value of the *Scale* (θ) parameter shows a different user performance in these two response models tested. The higher of scale parameter indicates that the higher chance of the request made by the operator to be succeeds. For length of playing time variable, the higher scale parameter also indicates longer of playing time on the interface. In order to compare the *Scale* (θ) parameter between the model interfaces tested, Based on a similar approach proposed by Taylor [106], I used the Queue model as a benchmark since it has a better fitted *Weibull* curve compared to the other model tested, and in matching the request variable in the Adaptation data set to the Queue data set, I get:

$$f_{(r,\beta_{both},\theta_{Queue},\delta_{both})} \cong w f_{(wr,\beta_{both},\theta_{Adaptation},\delta_{both})} \qquad \textbf{\textit{Equation (6.13)}}$$

where $r_{Queue} > 0$, $r_{Adaptation} > 4$, $\beta_{both} = \beta_{Queue}$ and $\delta_{both} = \delta_{Queue}$

the w means scaling factor used in rescaling the data set. Figures 6.18 shows the comparison result between the Adaptation and Queue response models tested based on Equation 6.13.

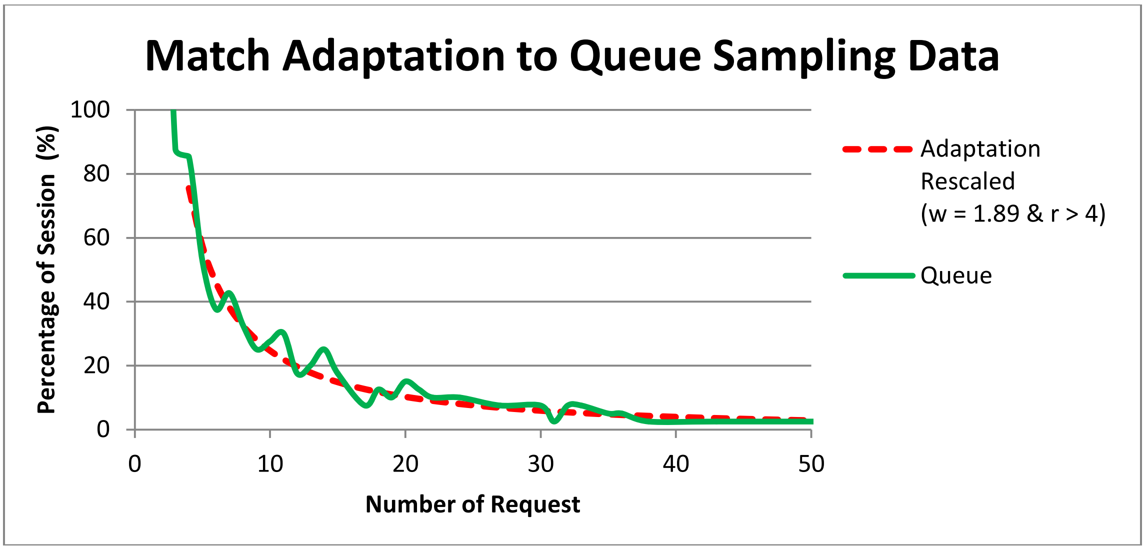


Figure 6.18: Rescaling the Adaptation sampling data according to Equation 6.13 with a value of w = 1.89 and overlaying it on the Queue sampling data shows similarity between the sampling data with correlation = 0.9749

This method can also be applied when analysing the length of the playing time variable for each model tested. By using Equation 6.5 for the time variable gives:

a) To match the time variable in the Adaptation data set to the Queue data set.

$$f_{(t,\beta_{both},\theta_{Queue},\delta_{both})} \cong wf_{(wt,\beta_{both},\theta_{Adaptation},\delta_{both})} \qquad \textbf{\textit{Equation (6.14)}}$$

where $t_{Queue} > 0,\ t_{Adaptation} > 2\ ,\beta_{both} = \beta_{Queue}$ and $\delta_{both} = \delta_{Queue}$

b) To match the time variable in the Manual data set to the Queue data set.

$$f_{(t,\beta_{both},\theta_{Queue},\delta_{both})} \cong wf_{(wt,\beta_{both},\theta_{Manual},\delta_{both})} \qquad \textbf{\textit{Equation (6.15)}}$$

where $t_{Queue} > 0,\ t_{Manual} > 2\ ,\beta_{both} = \beta_{Queue}$ and $\delta_{both} = \delta_{Queue}$

by applying the same steps to rescale the sampling data for the time variable, I derived the scaling factor (w) of 1.13 for the Adaptation model with a correlation of 0.98891, and for the Manual model, I received a value of w = 1.64 with correlation = 0.988402.

This approach enables me to minimise the comparisons process between the sampling data by using only scale parameters. As the comparison result on the number of request variable from the two HSC response model, the Queue response model is preferable compared to the Adaptation response model. It also showed the same result in the comparison between lengths of playing time variable from this two HSC response models. In the end, these comparisons showed operators preferred the Queue response model over the Adaptation response model and the HSC model over the direct/manual model.

In addition, Table 6.2 showed the Queue response model has a 40% higher *Scale* parameter value on both variables tested compared to the Adaptation response model. Since both r or t variables in both response models tested have a similar scale ratio, I considered that the distribution data on the number of requests made by the operator can be used to estimate the trend curve on how long the operator used the interface and vice versa. The scale ratio also does not change when I stretched or shrunk the x-axis of r or t variables.

I successfully followed the technique developed by Taylor [106], and found this technique was applicable to my telerobotic interface, which is very different teleroboics scenario than was tested by Taylor. The technique used for choosing the scaling factor was arbitrary as requires choosing a shape parameter for each data set and then estimating a scale parameter from that. In this technique approach, if the two data sets are compared directly, there is no need to estimate *Shape* (β) and *Location* (δ) parameters, but there is an assumption it is the same. The comparison can be done by rescaling and overlaying one data set on the other and adjusting the scaling factor until the best fit is observed. This telerobotic interface and situation were quite different to those tested by Taylor and I provided evidence that human response to a wide variety of interfaces can be characterised by a *Weibull* distribution.

Walpole [109] stated that the correlation coefficient is a number which attempts to measure the strength of the relationship between two variables. In this case, the correlation coefficient is used to determine the relationship between the sampling data and the estimated scaling factor (w). Here, the random error from the sampling data was measured in comparison with the *Weibull* curve benchmark, and to satisfy the assumption that the test model has the same *Shape* (β) and *Location* (δ) parameters. A correlation that is close to 1 indicates a strong relationship between the scaling factor and the sampling data, while a value that is less than 0.5 implies no relationship between the variables.

In this experiment, the total number of sessions in the sample data did not have a large impact on the distribution of the curve shape. The variance of the random error variables from the sampling data is negligible as proven by the value of the *Chi-square goodness fit test* and the *Coefficient of Determination* from the *Weibull* model. However, to achieve a good fit for the *Weibull* curve on the ‘number of requests’ variable for the Adaptation response model (HSC) and the manual model, I need to exclude the first four to five requests that were sent to the telerobot per session. This is due to a number of operators starting their sessions under specific circumstances such as when the telerobot was unresponsive or when the block is stuck inside the hole or out of reach of the telerobot. Indow [111] stated that it is possible to have a mixed distribution in the event population, which gives more complex results and depends on the nature of the discrete distribution. This describes this telerobotic system, which also experienced cases when the telerobot was out of action or not responding to requests.

6.6 Summary of Chapter

In the last phase of this research, I tested the prototype of a telorobot system interface in a telemanipulation scenario for general usage with participants of diverse backgrounds. This experiment demonstrated that the system is reliable and user friendly for any level of background operator. The recorded data of user performance over a three-month period were classified into three categories: Adaptation, Queue, and direct/manual model. An empirical model which adopts the *Weibull* distribution has been successfully used to describe user performance on these model interfaces.

There are two variables recorded from this event: (1) the request variable which represented the total number of requests sent by the user to the telerobot in a session for each model interface; and (2) the time variable, which represented the length of playing time taken by the user in a session. Based on the two variables above, I used the *Weibull* parameters to explain the observed data. The hypotheses test, with a *Chi-square goodness of fit test*, was also used to measure if the data model was suitable to represent the observed data. These tests had been used in other works [106] to compare telerobotic interfaces. In addition, I also calculated the *Coefficient of Determination* from the developed curve to support the suitability of the curve model in representing this population data.

The results for user behaviour and user performance based on the two variables recorded, show congruence between observed and expected data. The Queue- and the Adaptation-response models have demonstrated potential for use in telerobotic interface applications. In this experiment, the Queue-response model exhibited better user performance, in terms of having a higher probability that a request made by the user would be successful and in terms of length of playing time. For comparison to manual control, user performance can only be analysed using time variables. Both the Queue- and Adaptation-response models reduced the playing time, compared to the manual model. However, this comparison does not prove the manual model yields superior user performance as it relies on different input devices (joystick and gamepad).

In this analysis, the value of the shape and location parameters proved similar among the sampling data for each interface tested. Following the approach applied by Taylor [106], I used only a scale parameter for comparing the sample data of different models, although my telerobotic interfaces, have very different scenarios compared with Taylor's. This technique is likely to be applicable to other models for interfaces with different properties.

In general, this chapter has supported the idea that applying MR and HSC concepts in gaming environments for use as telerobotic interface is effective. The next chapter will summarize my work, including the results and limitations I have identified

Chapter 7

Conclusions and Recommendations for Future Work

7.1 Conclusions

This thesis demonstrated that gaming environments are potentially useful platforms in evaluating the effectiveness of the concepts of mixed reality (MR) and human supervisory control (HSC) for telerobotic interfaces.

In this thesis, I categorised the research framework into three main areas: the gaming environments, the MR interfaces, and HSC. I completed four experiments, which covered the three categories of the research framework above, to evaluate user performance and effectiveness of various telerobotic interfaces, which has been published in a number of international conferences and a Journal as mentioned in the Declaration section, (e.g. APCHI-2010, ICRA2011, WMC2011, ICIRA2012 and an Australian Journal of Intelligent Information Processing Systems).

This research addresses a number of gaps in existing research in telerobotics [5, 6], using a simulated mining scenario. These gaps include: (1) Whether multiple sources of information increase an operator's cognitive fatigue and their level of attention to the interface, leading to performance reduction; (2) how to improve the effectiveness and user friendliness of telerobotic interfaces; and (3) how to reduce safety concerns associated with unintended actions and implicitly remove, or at least decrease, the decline in operator performance caused by latency in telerobotic scenarios.

Starting from the idea that telerobotic interfaces and gaming environments are similar domains, would allow us to use sophisticated gaming environments for building telerobotic interfaces. Although they have been seen as unrelated, I successfully evaluated a number of features in gaming environments that are required for a telerobotic interface. These include: (1) the ability to build client-server communications to transfer information between the operator and the telerobot; (2) the sophistication of the gaming environment in manipulating a 3D model and a virtual environment for applying MR and HSC to the interface; and (3) other features that are necessary and useful for telerobotic interfaces, such as suitable input devices and sensors, additional virtual information and camera views, and path-finding algorithms to improve telerobot automation. I have shown these gaming features prove useful for telerobotic interface design. This enables telerobotic interfaces to be developed from powerful existing tools rather than being developed as bespoke designs.

Virtual-reality software or traditional 3D simulation tools (e.g., WorldToolKit and VRML) have been used to develop telerobotic interfaces. . Gaming environments offer a superset of the functionality of these tools but being more specific are less flexible. They have also become widespread and are now powerful enough to serve as telerobotic interfaces. For example, from the developer perspective: (1) gaming environments offer an integrated development environment with a range of predefined and customized software libraries and functions which are easy to implement; (2) gaming environments provide integrated and powerful tools in building 3D virtual modelling; (3) gaming environments provide the technologies for communications and data transfer inside and outside of the gaming environments; and (4) gaming environments simplify the integration of a variety of input devices and external sensors.

From the user's perspective: (1) gaming environments provide an interface that is easy to learn and understand, and is user friendly; (2) gaming environments are designed to make people feel comfortable while used over long periods; and (3) gaming environments have a primary aim of achieving user immersion, which is an also an important factor for effective telerobotics interfaces. Gaming environments are thus seen as a suitable platform for applying and evaluating MR and HSC in telerobotic scenarios.

In order to demonstrate the predominance of gaming environments for telerobotics scenario, I conducted the first experiment to test the effectiveness of user performance in using MR interfaces in gaming environments. The combination of overlaying video with a virtual model in the gaming environments showed that MR interface was able to provide sufficient information to the operator to perform the experimental tasks. When incomplete information from the remote environment was provided to the operator in this experiment, they were still able to access the missing virtual information from overlaid video. This showed that the concept of combining information by overlaying virtual information on the streaming video, works well in substituting the missing information. This result explains that when the minimum information required by the operator is fulfilled; the operation task is possible to be completed. This technology might be useful to improve operator performance in telerobotic for mining scenarios or other telerobot scenarios, where there are variance conditions found in remote workspace.

In addition, in this first experiment, I also assessed the effect of the level of user attention on the interface while performing the task. As the assessment result, the usage of a combination of information on a single screen did not show any indications of distraction for user performance. Thus, based on the experiment, I can conclude that MR concept for telerobotic interfaces cause no, or minimal, distraction to the operator.

I designated the ‘mouse’ as the main input device for delivering commands from the operator to the interface since it is very commonly used by computer users and computer-based games. Besides, I chose this input device in order to be used as a main input device for applying HSC concept for the following experiments. In this first experiment, I tested the use of clicking and dragging functions of the mouse as input commands, and concluded that the clicking command was preferred over the dragging command. This is perhaps due to the clicking command being simpler and is effortless compared to the dragging command.

If it was possible to accurately model a physical environment, videos would not convey extra information to the operator. In this case it was possible to improve the model in the gaming environment by applying additional sensors to detect the block/rock position. In order to investigate whether virtual information is sufficient in providing minimum information required by the operator to perform the task, I tested a virtual reality interface with enhanced virtual information for the second experiment. In this experiment, I also tested a potential of gaming features in term of ease of integration between gaming interfaces and a variety of input devices. In actualising the investigation of this gaming features, I used an experimental design and scenario from a previous experiment by Zhu et al [39], that only utilises streaming video for operator feedback. Corresponding to their experimental design, my experiment utilises a gamepad and eye-tracking devices to control the virtual camera view to assess user performance in gaming environment.

The experimental result for the second experiment showed that the gaming environment is suitable for applying two input devices for virtual camera control in a telerobotic scenario. Comparable results of user performance indicators derived from two input devices showed similar performance of participants in completing the task. The trend of user performance on three sequential operation periods also shows gradual improvement, which indicates that this gaming environment is an easy learning environment and capable of being understood within a short period of time. These results strengthened my argument about how gaming environment and telerobotic interfaces share many similarities and therefore make it possible for them to be regarded as being in the same domain.

Further experiment in this research, third experiment, I reported the use of the HSC concept as an alternative to direct/manual control. I applied the principle of HSC into the MR telerobotic interfaces. The planning process in HSC allowed the operator to define a series of target positions as input commands to the telerobotic interface. The process gives two models in response to the operator’s commands, which I modelled as the Adaptation and Queue response models. I applied these two HSC response models for the third experiment and compared user performance operating a robot arm with these two response models. I also applied virtual objects as additional predictive information to compare the user performance in these two HSC response models. I tested four different models (Adaptation with predictive information, Adaptation no-predictive information, Queue with predictive information, and Queue no-predictive information). In addition, I also tested the direct/manual control as a sub experiment. I found that user performance in the Queue response model with predictive information performed best in terms of task completion compared to the other three models. When compared with the direct/manual control model, the user performance for HSC (both the Queue and Adaptation response models) was improved.

In this third experiment, I was also concerned about the effect of the use of virtual camera control and stop functions on user performance. Hence, I conducted analysis on performance of both functions in relation to the success rate. By categorising the usage of virtual viewpoint camera control function into three groups (never, normal, and over use), I found that this function affected user performance in completing the task. This was statistically significant, especially for the Adaptation response model with predictive information. In general, this function also affected all response models with predictive information. In contrast with virtual viewpoint control, I did not find a statistically significant relationship between the use of the stop function and the success rate for all HSC models tested. This might be due to the experiment only testing low level HSC commands rather than more sophisticated commands like “remove that block to here”. Although I realised that the stop function was important in emergency situations or when operator involvement was required, this experiment was not able to prove conclusively the need for it in the scenario tested.

In the Human Supervisory Control (HSC) model, the operator is not required to continually control each movement. This means instability, the major problem caused by latency does not occur. With HSC latency slows the rate an operator can issue commands as it increases the time they must wait for feedback from previous commands but it does not affect their ability to carry out the task. For this reason latency is less of an issue in telerobotic interfaces that make use of the Human Supervisory Control (HSC) model and is why experiments were not conducted with variable latency. In the open ended questionnaire responses a few participants commented on latency issues in completing the experimental task. The combination of MR and HSC in creating predictive information seemed sufficient to divert most participants’ attention from the effects of latency. This result conforms to the arguments from a number of other researchers [37 , 74, 75].

As mentioned earlier, it is not possible for me to test my telerobotic interfaces in actual mining situations, due to access restrictions, time limitations and the inevitability of disrupting production. Hence, in the first three experiments, I conducted the experiments with volunteers who had known demographics, as operators. In my last experiment, fourth experiment, I had a large number of novice users who were visiting the exhibition, of unknown demographics. I deployed a simulation of a mining telemanipulation scenario in this exhibition for a period of three months, and recorded the endeavours of exhibition visitors playing with a robot arm. The goal is to push blocks into a hole by using one of the two HSC response models or direct/manual model. As the public users were generally novice operators, if the prototype telerobotic interface is easy to use it will also be easy for trained operators in mining and other industries.

To analyse the results of the fourth experiment, I followed a technique developed by Taylor [106]. The three model interfaces tested (Adaptation-, Queue- and Manual-model interface) were different to those tested by Taylor. The recorded variables in the Adaptation- and Queue-response models, the number of requests per operator and length of time the device was operated, demonstrated congruence between observed and expected data. These two model interfaces also showed potential for being used as telerobotic interfaces. However, the Queue-response model afforded better user performance, in terms of providing a higher chance of success in completing the requested task and longer playing time on the interface

Further analyses revealed almost identical estimations of shape and location parameters in the variables recorded by the model interfaces tested. This result is similar to the model analysis done by Taylor [106]. Thus, this method proved to be applicable to my substantially different interface designs. This allows estimation of the scale parameters from a data set without estimating shape or location parameters and reducing the required sample size. This can be achieved by rescaling and overlying the data set from one interface onto the other and adjusting the scaling factor until the best fit is observed. With this method I also found the scale parameter for the Queue model was higher than for the Adaptation model. Based on the assumption people will play longer with an interface they like it suggests the Queue model showed higher user acceptance as well as superior task performance.

In a comparison of the HSC response model and the direct/manual model, for the variable of length of time the device was operated, the operator preferred direct/manual model over the

HSC response model. The sessions created using the direct/manual model were twice as long as sessions created on HSC response models. However, this comparison does not prove manual model having superior user performance compare the other two since only one variable was compared. I assume this might be due to a gamepad device being more interesting compared to a mouse device. Moreover, in my experiences, having full control of a robot arm in short periods of playing time, it feels more attractive. It is probably similar experiences felt by other participants.

As well as objective measurements, in my experiments, I collected participant feedback on my interfaces. Using subjective rating scales (i.e., the *Likert* scale and open question questionnaires), I showed that users considered my interface to be relatively easy to use. Interfaces which users find gratifying correlate to improved telerobotic task performance according to Fong [37, 38].

Based on the goal of this research, which is to improve human machine interfaces for telerobotics scenarios with current immersive technologies, the gaming environments. In this research I have successfully demonstrated that:

- gaming environments have potential environment to build telerobotics interfaces
- gaming environments are also suitable platform to apply and to explore MR and HSC concept to improve telerobotics interfaces.
- many features of gaming environments can be utilised to build good interfaces, especially in providing minimum information required for telemanipulation scenario.
- gaming environment are possibly regarded as a same domain with telerobotics interfaces.

Moreover in this study I also successfully addressed a number of issues, including:

- the potential of operator distraction due to multiple sources of information in s single display;
- the user friendliness of the interface which is enhanced by the utilisation of the gaming environment; and
- the effect of latency which has been indirectly addressed by the use of predictive display and feedback as a combination of technologies from the MR and HSC concepts.

This research shows great potential of gaming environments as a tool for building telerobotic interfaces with MR and HSC concepts in specific telemanipulation scenario. It also shows that gaming environment is available as an interaction medium between human and the machines.

7.2 Future Work

The research was designed in an academic setting to build a prototype of telerobotic interfaces which could serve as a potential model to build a real application in mining scenarios. I argued that gaming environments with MR interface and HSC is a great innovation and can be applied for other real telerobotic applications, especially in a telemanipulation scenario. In order to apply these gaming interfaces to other telerobotics scenarios, further research and tests are required. A number of suggestions for future works are described below:

Firstly, since it is not possible in a high productivity mining environment to carry out extensive experimentation, I propose conducting further testing by using higher fidelity models with better recreations of the actual operation (e.g., using a machine which has similar control with the actual mining robot). Further testing with higher fidelity model, including having a real operator, should determine the possibility of combining gaming features with HSC and MR concepts for mining, or other related telerobotic applications. Testing can be expanded to compare the performance of this proposed interface with current and commercial interfaces, such as contrasting performance between the *Rockbreaker* system interface [5] and my proposed gaming environment.

Secondly, from a technological perspective, this research can be improved in relation to multiuser functions. Multiuser functionality is one of a number of advantages of gaming environments. Real mining scenarios have many processes running concurrently or in parallel. The *Rockbreaker* [5] scenario involves multiple tasks, including operating the robot and moving big rocks from the mining site to the rock bin, which is run by another operator (e.g., truck driver). Hence, there is potential to mimic a complete mining scenario in a gaming environment, including multiuser interfaces, with real-time synchronisation of information and control between environments. Further testing can address latency issues, especially latency communications (command and response delays) among operators or between operators and telerobots, to avoid problems in real-world applications.[5]

Next, HSC provides an incremental upgrade path from direct/manual control to full automation. In this research, gaming environments had been used to evaluate user performance for direct/manual control and HSC in a low level telemanipulation scenario. Future research is still required to evaluate this gaming technology and to test it with more advanced telerobotics scenarios to be a proper automation system

Future work should address the use of improved sensors and input devices. For example: (1) Microsoft *Kinect* or 3D laser scanner devices could be applied as remote sensors to improve the accuracy of position, size and 3D virtual shapes of the different types of rocks (or other objects serving as targets in the telerobotic scenario). A number of researchers [112, 113] have worked with these sensors to build advanced 3D modelling, which could be used to improve the virtual modelling within a gaming environment for telerobotic scenarios. (2) Haptic devices can enhance the operator's immersive feeling. *Haptics* are widely used to improve the sense of immersion by providing force feedback to the operator. This input device works well for manipulating 3D models. Many researches have successfully improved control commands to the interface with haptic devices. However, in a HSC scenario, where the human operator is not required to continuously operate the telerobot, the environmental response must be modelled to provide haptic feedback. In many situations this is not possible and the advantages of haptic feedback are ameliorated.

Appendix A

A.1 Coordinate Transformation

During the system development, it is essential to convert the complete workspace into a virtual model. The remote sensor, in this case the remote camera, has an important role in capturing the missing information needed. It is important for the camera sensors to record the position and characteristics of the camera. These are used to determine the camera's intrinsic and extrinsic parameters that are used to calculate the image's projection between coordinates in three dimensions (world coordinate) and two dimensions (camera/screen coordinate). The Coordinate Transform concept (see Figure A.1) is commonly applied to transform three-dimensional coordinates (3D) to two-dimensional coordinates (2D) and vice versa. It is useful to obtain initial variables based on which one is used to process further interaction, x_{pix} and y_{pix}. I used this concept to synchronise between the object in world coordinates from the camera perspective and 3D objects in the virtual environment.

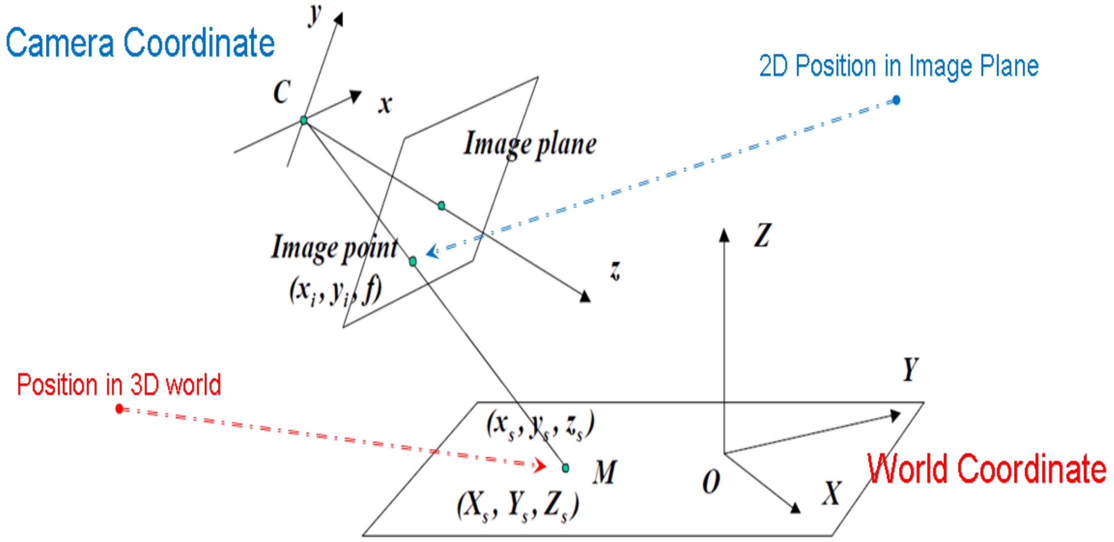


Figure A.1: Coordinate transforms

From Figure A.1 using the concept of coordinate transformation, gives:

$$x_{pix} = k_x.x_i + x_0 = fk_x\left(\frac{x_s+z_s.x_0}{z_s}\right) \qquad \textit{\textbf{Equation (A.1)}}$$

$$y_{pix} = k_y.y_i + y_0 = fk_y\left(\frac{y_s+z_s.y_0}{z_s}\right) \qquad \textbf{\textit{Equation (A.2)}}$$

A.2 Inverse Kinematics

I used the inverse kinematic to generate the position and rotation of each link arm of the 3D virtual model, which is useful to predict the position of the 3D model for simulation. The inverse kinematics is also used on the telerobotic controller to provide feedback information from the robot. It works by calculating the required motions (position and rotation of joint angles) to achieve the desired position. Based on the example in Figure A.2, the inverse kinematic is used to calculate the required joint angles (γ, θ_4, α, β and θ_5) to model the position and rotation of each 3D arm model when a target position is defined.

Based on Figure A.2 the required joint angles (γ, θ_4, α, β and θ_5) are given by the Equations below:

$$\gamma = arcsin\left(\frac{a_3}{a_4^{\prime}} sin\theta_3\right) \qquad \textbf{\textit{Equation (A.3)}}$$

$$\theta_4 = -arccos\left(\frac{a_5^{\prime\,2} - a_5^2 - a_4^{\prime\,2}}{2a_4^{\prime}\,a_5}\right) \qquad \textbf{\textit{Equation (A.4)}}$$

$$\beta = arccos\left(\frac{a_4^{\prime\,2} - a_5^2 - a_5^{\prime\,2}}{2a_5^{\prime}\,a_5}\right) \qquad \textbf{\textit{Equation (A.5)}}$$

$$\alpha = \arctan\left(z/r^{\prime}\right) \qquad \textbf{\textit{Equation (A.6)}}$$

$$\theta_5 = \alpha + \beta \qquad \textbf{\textit{Equation (A.7)}}$$

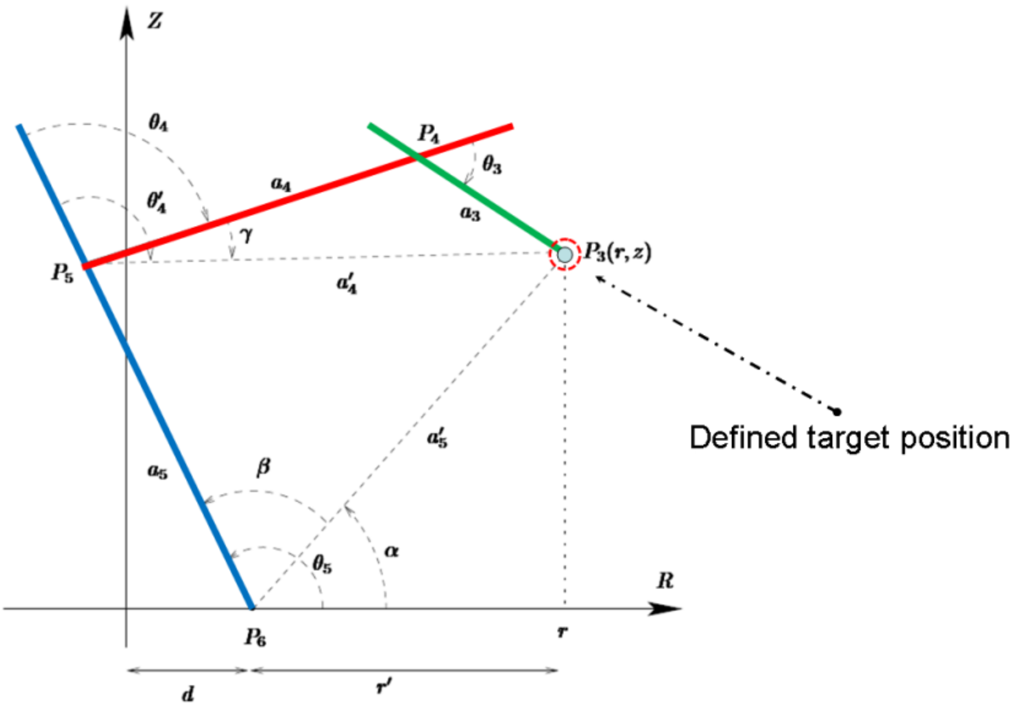


Figure A.2: Example of different angles and length used for the inverse kinematical problem

Appendix B

B.1 User Study Questionnaire for Experiment 1

User Study Questionnaire

Thank you for taking the time to fill in this questionnaire. Please respond as truthfully as possible, as criticism is appreciated as much as positive feedback.

Personal Details

1. Name:____________________________________

2. Age: ________________

3. Sex: male female

4. Occupation (if you are a student, please specify your major):

5. How often do you use a computer?

Never Occasionally Often (at least one hour a day)

6. How often do you play virtual world video games?

Never Occasionally Often (at least one hour a day)

7. Do you know or ever heard about Games Second Life?

Yes No

8. Do you know or ever heard about Sims Urban application?

Yes No

9. Do you any have problems with colorblindness?

Yes No

Presence Questions

Used **<u>“Second Life”</u>** as User Interface

1. How long did it take you to get familiar to this user interface?

Very Short Short Moderate Long Very Long

2. How much difficult did you feel to use this user interface when you were doing the task 1 (Move arm to some spot)?

Very Easy Easy Moderate Difficult Very Difficult

3. How much consciousness/attention did you have to pay on those user interfaces when you were doing the task 1 (Move arm to some spot)?

Very Less Less Moderate Much Very Much

4. How much difficult did you feel to use this user interface when you were doing the task 2 (push the object to move from one spot to another)?

Very Easy Easy Moderate Difficult Very Difficult

5. How much consciousness/attention did you have to pay on those user interfaces when you were doing the task 2 (push the object move from one spot to another)?

Very Less Less Moderate Much Very Much

6. Which part of the display you paid lots of attention when you were doing the tasks?

	No Attention	Less	Moderate	More	Most Attention
3D Model:					
(task 1)	**1**	**2**	**3**	**4**	**5**
(task 2)	**1**	**2**	**3**	**4**	**5**
Video Streaming:					
(task 1)	**1**	**2**	**3**	**4**	**5**
(task 2)	**1**	**2**	**3**	**4**	**5**

7. Please give rank (1 – 5, where 1 is the lowest mark and 5 the highest mark) for this user interface in:

	Lowest				**Highest**
a. Easy to use	**1**	**2**	**3**	**4**	**5**
b. Interface performance	**1**	**2**	**3**	**4**	**5**

Presence Questions

Used **“Simmersion”** as User Interface

1. How long did it take you to get familiar to this user interface?

Very Short Short Moderate Long Very Long

2. How much difficult did you feel to use this user interface when you were doing the task 1 (Move arm to some spot)?

Very Easy Easy Moderate Difficult Very Difficult

3. How much consciousness/attention did you have to pay on those user interfaces when you were doing the task 1 (Move arm to some spot)?

Very Less Less Moderate Much Very Much

4. How much difficult did you feel to use this user interface when you were doing the task 2 (push the object to move from one spot to another)?

Very Less Less Moderate Much Very Much

5. How much consciousness/attention did you have to pay on those user interfaces when you were doing the task 2 (push the object move from one spot to another)?

Very Less Less Moderate Much Very Much

6. Which part of the display you paid lots of attention when you were doing the tasks?

	No Attention	Less	Moderate	More	Most Attention
3D Model:					
(task 1)	**1**	**2**	**3**	**4**	**5**
(task 2)	**1**	**2**	**3**	**4**	**5**

Video Streaming: (task 1)	**1**	**2**	**3**	**4**	**5**
(task 2)	**1**	**2**	**3**	**4**	**5**

7. Please give rank (1 – 5, where 1 is the lowest mark and 5 the highest mark) for this user interface in:

	Lowest				**Highest**
a. Easy to use	**1**	**2**	**3**	**4**	**5**
b. Interface performance	**1**	**2**	**3**	**4**	**5**

Open Ended Questions

1. Please rank from the user interface between “Second Life” and “Simmersion” based on your own opinion (the best one goes first).

2. Based on your experience in this experiment, what do you ***like*** from

a. Second Life?

b. Simmersion?

3. Based on your experience in this experiment, what do you ***dislike*** from

a. Second Life?

b. Simmersion?

4. Did you feel any differences using those user interfaces, if so, in what way?

5. Do you have any other comments about the user interfaces or anything related to them?

B.2 User Study Questionnaire for Experiment 2

User Study Questionnaire

Thank you for taking the time to fill in this questionnaire. Please respond as truthfully as possible, as criticism is appreciated as much as positive feedback.

Personal Details

1. Name:

2. Age:

3. Sex: male female

4. Occupation (if you are a student, please specify your major):

5. How often do you use a computer?

Never Occasionally Often (at least 1 hours a day)

6. How often do you play video games?

Never Occasionally Often (at least 1 hours a day)

7. How much have you used a joystick or gamepad?

Never Occasionally Often (at least 1 hours a day)

8. How much have you participated in teleoperation (remote control) tasks?

Never Occasionally Often

9. How much have you used an head-tracking based interface?

Never Occasionally Often

Presence Questions

1. It was natural to use this camera control method.

	Strongly Disagree						**Strongly Agree**
Joystick	1	2	3	4	5	6	7
Head Tracking	1	2	3	4	5	6	7

2. I felt intuitive to use this camera control method.

	Strongly Disagree						**Strongly Agree**
Joystick	1	2	3	4	5	6	7
Head Tracking	1	2	3	4	5	6	7

3. It was easy to learn to use this camera control method.

	Strongly Disagree						**Strongly Agree**
Joystick	1	2	3	4	5	6	7
Head Tracking	1	2	3	4	5	6	7

4. It didn’t take long to get used to this camera control method.

	Strongly Disagree						**Strongly Agree**
Joystick	1	2	3	4	5	6	7
Head Tracking	1	2	3	4	5	6	7

5. It was simple to find the stuff I wanted to see in the remote place using this camera control method.

	Strongly Disagree						**Strongly Agree**
Joystick	1	2	3	4	5	6	7
Head Tracking	1	2	3	4	5	6	7

6. I was able to gain enough visual information from the 3D stream using this camera control method.

	Strongly Disagree						**Strongly Agree**
Joystick	1	2	3	4	5	6	7
Head Tracking	1	2	3	4	5	6	7

7. I was able to obtain enough situational awareness for the teleoperation task using this camera control method.

	Strongly Disagree						**Strongly Agree**
Joystick	1	2	3	4	5	6	7
Head Tracking	1	2	3	4	5	6	7

8. I didn’t have to pay much attention or consciousness on the camera control using this method when conducting the other control task by hands.

	Strongly Disagree						**Strongly Agree**
Joystick	1	2	3	4	5	6	7
Head Tracking	1	2	3	4	5	6	7

9. It was not distracting to use this camera control when conducting the other control task by hands.

	Strongly Disagree						**Strongly Agree**
Joystick	1	2	3	4	5	6	7
Head Tracking	1	2	3	4	5	6	7

10. I felt the zooming function of this camera control was useful.

	Strongly Disagree						**Strongly Agree**
Joystick	1	2	3	4	5	6	7
Head Tracking	1	2	3	4	5	6	7

11. I could effectively complete the rock pushing task using this camera control method.

	Strongly Disagree						**Strongly Agree**
Joystick	1	2	3	4	5	6	7
Head Tracking	1	2	3	4	5	6	7

12. I was able to quickly complete the rock pushing task using this camera control method.

	Strongly Disagree						**Strongly Agree**
Joystick	1	2	3	4	5	6	7
Head Tracking	1	2	3	4	5	6	7

13. I was able to efficiently complete the rock pushing task using this camera control method.

	Strongly Disagree						**Strongly Agree**
Joystick	1	2	3	4	5	6	7
Head Tracking	1	2	3	4	5	6	7

14. I believe I could become productive using this camera control method.

	Strongly Disagree						**Strongly Agree**
Joystick	1	2	3	4	5	6	7
Head Tracking	1	2	3	4	5	6	7

15. Overall, I am satisfied with this camera control method.

	Strongly Disagree						**Strongly Agree**
Joystick	1	2	3	4	5	6	7
Head Tracking	1	2	3	4	5	6	7

16. I felt the 360 camera rotation was useful.

Strongly Disagree						**Strongly Agree**
1	2	3	4	5	6	7

17. I felt the camera vertical rotation was useful.

Strongly Disagree						**Strongly Agree**
1	2	3	4	5	6	7

18. I felt the camera horizontal rotation was useful.

Strongly Disagree						**Strongly Agree**
1	2	3	4	5	6	7

19. It was easy to place the robot arm tip next to the rocks.

Strongly Disagree						**Strongly Agree**
1	2	3	4	5	6	7

20. I felt the tip tracking was useful.

Strongly Disagree						**Strongly Agree**
1	2	3	4	5	6	7

21. It was easy to decide when to nudge.

Strongly Disagree						**Strongly Agree**
1	2	3	4	5	6	7

22. The rocks blinking / shaking was annoying.

Strongly Disagree						**Strongly Agree**
1	2	3	4	5	6	7

Open Ended Questions

1. Please rank the camera control methods you used in the experiment based on your experience (the best one goes first).

2. Please rank the tip tracking methods you used in the experiment based on your experience (the best one goes first). Please comment.

3. In what way do you feel those control methods either enhanced, or detracted the performance of the tasks?

4. Do you think those control methods could be improved, if so, how?

5. Do you have any other comments about the control methods or anything related to them?

6. What do you think about the 3D rocks behavior ?

7. Please rank the tip control methods you used in the experiment based on your experience (the best one goes first).

B.3 User Study Questionnaire for Experiment 3

User Study Questionnaire

Thank you for taking the time to fill in this questionnaire. Please respond as truthfully as possible, as criticism is appreciated as much as positive feedback.

Personal Details

1. Exp_ID: (Please make sure this number with the reseacher)

2. Name:

3. Age: years in 2011

4. Sex:

☐Male ☐Female

5. Occupation (if you are a student, please specify your major):

6. In average, how many hours do you use computer in a week?

< 7 hours	>7 hours but < 21 hours	>21 hours
☐1	☐2	☐3

7. In average, how many hours do you play the virtual game in a week?

< 7 hours	>7 hours but < 21 hours	>21 hours
☐1	☐2	☐3

8. Teleoperation/Telerobotic is a common term that normal heard in daily life?

Strongly Disagree					Strongly Agree	
☐1	☐2	☐3	☐4	☐5	☐6	☐7

9. Using a gaming environment for a teleoperation/telerobotic application is a new thing?

Strongly Disagree					Strongly Agree	
☐1	☐2	☐3	☐4	☐5	☐6	☐7

Questions

Interface

10. The interface provide enough information to perform the task

Strongly Disagree Strongly Agree

☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7

11. Information from video camera helps the user to perform better

Strongly Disagree Strongly Agree

☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7

12. Information from 3D virtual model helps the user to perform better

Strongly Disagree Strongly Agree

☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7

13. Information from 3D virtual model more useful rather than Information from video camera

Strongly Disagree Strongly Agree

☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7

14. Changeable viewpoint on 3D model is useful

Strongly Disagree Strongly Agree

☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7

15. **Different** viewpoint between video camera and 3D virtual model gives better information rather than **same** viewpoint

Strongly Disagree Strongly Agree

☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7

16. I was using more than 50% of my attention to get information from the 3D virtual model on each task performance

Strongly Disagree Strongly Agree

☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7

17. I was using more than 50% of my attention to get information from the video camera on each task performance

Strongly Disagree Strongly Agree

☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7

Human Supervisory Control Function

Model's movement

18. Queue model is easier to be operated than Adaptable model

Strongly Disagree Strongly Agree

☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7

19. Queue model works better rather than Adaptable model

Strongly Disagree Strongly Agree

☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7

Virtual-information

20. Target information (green circles) helps me to perform the task

Strongly Disagree Strongly Agree

☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7

21. Video overlay information helps me to perform the task

Strongly Disagree Strongly Agree

☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7

22. Shadow information helps me to perform the task

Strongly Disagree Strongly Agree

☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7

23. Line information helps me to perform the task

Strongly Disagree Strongly Agree

☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7

24. Interface with virtual information works better than using none virtual information

Strongly Disagree Strongly Agree

☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7

Interrupt/Stop function

25. Stop function is a useful function to help me in performing the task

Strongly Disagree Strongly Agree

☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7

26. Full stop function is useful

Strongly Disagree Strongly Agree

☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7

27. Temporary stop function is useful
Strongly Disagree Strongly Agree
☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7

28. Click target to stop ‘s function is useful
Strongly Disagree Strongly Agree
☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7

29. Combination all function tested and information given on the experiment have enabled the interface to perform better
Strongly Disagree Strongly Agree
☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7

Human Supervisory Control (HSC) versus Manual Control (MC)

30. HSC performs better than MC
Strongly Disagree Strongly Agree
☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7

31. HSC provides easier control than MC
Strongly Disagree Strongly Agree
☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7

32. If you work more than 5 hour/day, HSC requires less effort than MC
Strongly Disagree Strongly Agree
☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7

General Performance

33. For each model below, this interface has good performance

a. Model 1
Strongly Disagree Strongly Agree
☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7

b. Model 2
Strongly Disagree Strongly Agree
☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7

c. Model 3
Strongly Disagree Strongly Agree
☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7

d. Model 4
Strongly Disagree Strongly Agree
☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7

e. Model 5
Strongly Disagree Strongly Agree
☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7

34. For each model below, this interface is easy to use
a. Model 1
Strongly Disagree Strongly Agree
☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7

b. Model 2
Strongly Disagree Strongly Agree
☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7

c. Model 3
Strongly Disagree Strongly Agree
☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7

d. Model 4
Strongly Disagree Strongly Agree
☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7

e. Model 5
Strongly Disagree Strongly Agree
☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7

35. For each model below, this interface gives enough immersive environment
a. Model 1
Strongly Disagree Strongly Agree
☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7

b. Model 2
Strongly Disagree Strongly Agree
☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7

c. Model 3
Strongly Disagree Strongly Agree
☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7

d. Model 4
Strongly Disagree Strongly Agree
☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7

e. Model 5
Strongly Disagree Strongly Agree
☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7

36. For each model below, I felt time delay between command and response from the robot when I perform the task

a. Model 1

Strongly Disagree Strongly Agree

☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7

b. Model 2

Strongly Disagree Strongly Agree

☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7

c. Model 3

Strongly Disagree Strongly Agree

☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7

d. Model 4

Strongly Disagree Strongly Agree

☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7

e. Model 5

Strongly Disagree Strongly Agree

☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7

Open Questions

1. What do you think about the interface in general?

2. What do you like from the interface in general?

3. In general which part in the interface need to be improved?

4. Do you have any additional comment regarding to the experiment?

Thank you for your participation in this Experiment
Please do “Save As” and name this document with your Exp_ID

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