Abstract

SHEIK NAINAR, MOHAMED ASHRAF ALI. The Effects of Gain Adaptation for QoS Deterioration in Internet-based Teleoperation Involving Use of a Virtual Reality Interface. (Under the direction of Dr. David B.Kaber)

The goals of this study included evaluating the affects of different types of communication network delays on remote-control rover (telerover) performance, operator telepresence experiences and workload. The study also evaluated the utility of gain adaptation for communication delays on telepresence, performance and workload. Finally, the work examined the relationship between performance and subjective presence in an Internet-based teleoperation scenario utilizing a virtual reality (VR) interface. Telepresence has been identified as a design ideal for teleoperation systems; and task environment factors, such as disturbances in human-machine interaction, have been identified as potential underpinnings of presence experiences.

A VR-based simulation of a telerover navigation task was developed for this study. The task involved navigating the rover in a virtual environment (VE) between obstacles, like a slalom ski race. Task performance measures included time-to-task completion (TTC) and the number of collisions of the rover with task obstacles (errors). Two levels of telerover automation (LOA) were implemented including teleoperation, or manual control, and telerobotic or automation assisted control. Combinations of LOAs and delay types, including constant and random, were tested with and without gain adaptation. A mixed between-within experimental design was used in which LOA served as a grouping variable. Each subject experienced 10 test trials (2 no-delay + 2 × (2 delay types × 2 adaptation settings)) under either the teleoperation or

telerobotic control mode. Subject exposure to various network conditions was randomized. Presence questionnaire and the NASA Task Load Index were used to capture subjective telepresence and workload ratings, respectively, at the end of each test trial.

Results revealed that LOA, delay, adaptation and the interaction of LOA and a variable describing the overall network condition (a combination of delay and adaptation) significantly affected TTC. The telerobotic control mode produced the best TTC irrespective of the delay type and adaptation. Both delay types combined with adaptation produced the worst TTC within each LOA, as compared to all other network conditions. Performance errors/collisions were significantly affected by LOA, delay and adaptation. The telerobotic control mode produced the greatest number of errors and the adaptation conditions were superior to no-adaptation conditions. The constant delay produced more errors than the random delay type.

Both telepresence and workload were significantly affected by LOA and individual differences with telerobotic control producing higher telepresence ratings along with lower workload scores.

Telepresence was found to be significantly correlated with TTC, specifically there was a reduction in TTC with an increase in telepresence ratings. Workload was significantly positively correlated with telepresence. Although the telerobotic control mode reduced operator workload, it off-loaded some of the rover control responsibilities from the user to the machine system allowing the operator to pay more attention to the VR displays promoting their knowledge of the current state of the VE and possibly presence sensations. These correlation analysis results are similar to those established by previous research. It was expected that the gain adaptation would better support users in achieving and sustaining telepresence. Although changes in telepresence across the adaptation and no-adaptation conditions under telerobotic control were inline with this hypothesis, similar results were not found with teleoperation control.

The results of this study are directly applicable to the selection of guaranteed communication network parameters through Quality of Service (QoS) in Internet-based telemanipulation systems. The results also can be used as guidelines for telerover control mode selection for time and error critical teleoperation. Finally, the results support the notion that telepresence may be important to performance in teleoperation tasks (and that gain adaptation for network delays under certain control modes may be beneficial to telepresence).

THE EFFECTS OF GAIN ADAPTATION FOR QoS DETERIORATION IN INTERNET-BASED TELEOPERATION INVOLVING USE OF A VIRTUAL REALITY INTERFACE

by

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Dedication

Dedicated to my dearest Dad and Mom and to my Sister who is my friend, philosopher and guide.

Biography

Mohamed Ashraf Sheik Nainar was born in a small town called Nagore, in the state of Tamil Nadu in the southern part of India. He was raised in Madras (now called Chennai), where he completed his high school education in 1994. He later joined the University of Madras for a Bachelor of Engineering in Mechanical Engineering and graduated in 1998. Following graduation, he joined Caborundum Universal Ltd., an abrasive manufacturing company as a Graduate Engineer Trainee.

In fall 2000, the author began his graduate study at North Carolina State University. Since that time, he has been working with Dr. David Kaber, primarily in creating virtual reality simulations for a number of research experiments and designing the websites for funded research projects.

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TABLE OF CONTENTS

List of Tables

List of Figures

Glossary

ADAC	Advanced Diagnosis and Control Laboratory
ANOVA	Analysis of Variance
ATM	Asynchronous Transfer Mode
CA	Constant delay with adaptation
CNA	Constant delay with no-adaptation
DOF	Degree of Freedom
FPS	Frames Per Second
GUI	Graphical User Interface
HMD	Head Mounted Display
HSD	Honestly Significant Difference
IEC	International Engineering Consortium
IPV6	Internet Protocol Version 6
ISO	International Standards Organization
ITU-T	International Telecommunication Union – Telecom Standardization
LOA	Level of Automation
MPLS	Multi-Protocol Label Switching
ND	No-delay
PQ	Presence Questionnaire
PC	Personal Computer

QoS	Quality of Service
RA	Random delay with adaptation
RNA	Random delay with no-adaptation
RSVP	Resource Reservation Setup Protocol
SE	Synthetic Environments
SBM	Subnet Bandwidth Manager
SSQ	Simulator Sickness Questionnaire
TCP	Transmission Control Protocol
TLX	Task Load Index
TTC	Time-to-Task Completion
UDP	User Datagram Protocol
VE	Virtual Environment
VR	Virtual Reality
WWW	World Wide Web

Chapter 1

INTRODUCTION

Synthetic Environments (SE) have been defined as computer-generated worlds used to facilitate human interaction with an environment that is physically separate from the user and to allow human perceptual, cognitive and psychomotor capabilities to be projected into normally inaccessible, hostile or simulated situations (Draper, Kaber & Usher, 1999). Virtual Environments (VE) and teleoperation interfaces have been classified as forms of SE. In 1965, Ivan Sutherland presented a program of research in computer graphics, which has challenged and guided the field of VE research and development (Sutherland, 1965). According to Sutherland, the display screen is a window through which one can behold a virtual world. Real-time interactive graphics with three-dimensional models, combined with a display technology that gives the user immersion in the model world and direct manipulation of virtual objects, is called Virtual Reality (VR) (Bishop & Fuchs, 1992). Teleoperation means to operate a system from a remote location. The remote location may be in the next room (e.g., a "hot cell" in a nuclear laboratory) or may be on another planet (e.g., space exploration). The first teleoperator, a mechanical pantograph, was developed in Argonne National Laboratory in 1940 by a group headed by R. Goertz. Since then, teleoperation research has advanced rapidly with innovations in computation and communication. Typical applications include space exploration, military surveillance and reconnaissance, medical surgery, industrial mining, etc.

Teleoperators represent a true symbiosis of human and machine relying on the human to act as controllers of remote systems through SE. Teleoperators serve to extend human perceptuo-cognitive abilities to hostile and hazardous environments like the exploration of the sunken Titanic, surveying of the collapsed reactor in Chernobyl, etc.

Traditionally, the remote work-package, or robotic system, as part of a teleoperator integrates video cameras, which provide visual feedback to the operator through a visual display. The operator plans the motion of the system based on telemetry data and sends motion control commands to the remote system. Typically, these types of systems have minimal on-board intelligence and hence, performance is largely dictated by the remote operator.

The drawbacks associated with video-based feedback in teleoperation include performance problems due to temporal disturbances in communications (long delays). For example, communication delays in earth-based control of the NASA Mars rover, Sojourner, were estimated to be as great as tens of minutes (Hine, Hontalas, Fong, Piguet, Nygren & Kline, 1995).

To alleviate the above-mentioned problem, sophisticated interfaces for teleoperation have become increasingly important. In applications like exploration or remote reconnaissance, human-robot interaction is the main feature driving the application (Fong, Thorpe, & Baur, 2001). Thus, it is critical to design effective interfaces to create truly integrated and efficient human-robot systems (Fong et al., 2001). Virtual environment or VR technology have been used in recent researches to create multi-modal, intuitive and effective interfaces to teleoperation systems by taking advantage of the bandwidth of human sensory channels to a greater extent than it is possible with conventional display technologies (Hine et al., 1995).

Contemporary VR-based interfaces have been designed with the objective of providing users the sense of being part of a realistic environment and direct performance of tasks. This sensation has been labeled as telepresence. Telepresence, the perception of presence within a physically remote or simulated site, has been identified as a design ideal for VEs and SEs in general, including interfaces for teleoperation systems (Draper, Kaber & Usher, 1998). It has been hypothesized by many researchers that telepresence shares a positive relationship with virtual task performance or teleoperation and, consequently, SEs and teleoperator design for telepresence has been advocated. Researchers have performed numerous studies to investigate the sense of presence (telepresence) within virtual environments in order to identify underlying factors in the phenomenon (Nash, Edwards, Thompson & Barfield, 2000). Work had focused on display factors that influence or enhance the feeling of actually being part of a VE (Nash et al., 2000).

Sheridan (1992) identified five variables that potentially contribute to inducing a sense of telepresence. Three of them are technological, including the extent of sensory information, control of sensors relative to the environment and the capability to modify the physical environment. The other two are context based, including the task difficulty and the level of system automation. Nash et al. (2000) also developed a classification scheme for the factors affecting presence, including five major categories – computers and virtual environments, communication medium, individual characteristics, disturbances in the real-world (surrounding) environment and the task. Each of the following subsections provides a description of these major categories and specific factors in telepresence experiences:

1.1 Computers and Virtual Environments:

It is through a computer and VE interface, that the remote work package as part of a teleoperation system transacts information with the human. The human uses input devices and display devices presenting information in any of the modalities in order to control the work package. The VE interface, in addition to being a tool for remote space visualization, serves as a model of the robot's world and, thus, can be used to display the current status of the system and real-world objects in the remote environment (Simsarian, 2001). Some of the VR system factors potentially influencing telepresence include the breadth and depth of information presentation through system interfaces, as well as the responsiveness of the VE interface and the extent to which it represents the real remote environment. Each of these factors is discussed here.

1.1.1 Breadth. Breadth is the number of sensory channels used simultaneously to present information to a user (Steuer, 1992). The more sensory modalities used, the greater telepresence experiences are expected to be. This is because more information is provided to the user and because the individual is more isolated from the external world (Witmer & Singer, 1994).

1.1.2 Depth. Depth refers to the resolution of each sensory stimuli provided to a user (Steuer, 1992). It is hypothesized that more depth could lead to greater presence in a SE, if the depth provided through a sensory modality is essential to the task (Barfield & Weghorst, 1993).

1.1.3 Resolution. Resolution refers to the realism of the information presented through the SE (Simsarian, 2001). This quality of the VE or teleoperator interface may be manipulated through each sensory modality. As an example of the visual modality, Riley and Kaber (1999) recommended that high-resolution displays be used to maximize user perceptions of VE vividness and telepresence. Hendrix and Barfield (1996) reported that high-resolution stereoscopic cues along with head tracking increased presence significantly in an exploration type task.

1.1.4 Consistency. Consistency refers to the inherent capability of the environment to allow the person to predict what will happen next (Witmer &

Singer, 1994). This means that the context of the VE interface is predictable in its behavior such that the user can adapt to it.

1.1.5 Speed. The update rate of the controls and the displays can affect presence. A frame time of 50ms or 20 fps (frames per second) is acceptable for many applications.

1.1.6 Range. The range of interactivity refers to the number of attributes of the SE that can be manipulated and the amount of variation possible within each attribute (Steuer, 1992). The greater the capability of the user to affect and change the VE, the greater is the expected telepresence (Witmer & Singer, 1994).

1.1.7 Mapping. Mapping refers to the capability of a system to map its controls to changes in the mediated environment (SE) in a natural and predictable manner (Steuer, 1992). It is assumed that better mapping will lead to better telepresence because the user will not have to think about how to create the control actions he or she wishes to perform to achieve a specific teleoperation goal.

1.2 Communication Medium

The communication medium represents the way in which information from the VE is transmitted to the user and the way in which the commands from the user are sent to the VE. The components of interaction should allow a wide range of sensory information to be conveyed to and from the VE (Barfield & Weghorst, 1993). For example, Hendrix and Barfield (1996) have shown that head tracking can lead to increased sense of virtual presence in advanced VR systems integrating head-mounted displays with high-performance, graphics visualization workstations.

1.2.1 Individual (User). No matter how good the hardware or simulation, the sense of presence is still ultimately dependent on the person who must perceive and interpret the information as part of a SE. Limited data is available on how different individuals feel present even in the real world, so it is difficult to come to a consensus on the concepts purported to affect virtual presence in an individual (Nash et al., 2000).

1.2.2. Adaptability. Adaptability refers to the speed at which persons adjust to new circumstances, such as moving to a new country, experiencing a new form of travel for the first time, etc. (Slater & Usoh, 1993). Researchers have found a strong negative correlation between the sense of presence and human adaptability to change. Quick adapters take greater notice of their surroundings and, thus, may notice more faults in the VE than slow adapters do, ultimately leading to lower reported levels of presence (Slater & Usoh, 1993).

1.2.3 Experience and practice. It has been suggested that the sense of virtual presence might increase with more experience and practice in a virtual task or in use of a VE. It has been shown that presence has a positive correlation with VR system and VE familiarity (Barfield & Weghorst, 1993).

1.2.4 Motivation. The willingness of the individual to interact with the environment and accept the environment are both important determinants of presence. It has been hypothesized that more motivation will lead to a greater sense of presence and a greater allocation of attentional resources (Witmer & Singer, 1994).

1.2.5. Attentional resources. It has been hypothesized that the amount of attentional resources allocated to a VE will determine, to an extent, the amount of presence that the user experiences (Draper et al., 1998; Barfield & Weghorst, 1993). It has also been hypothesized that selective attention is required to ignore real-world stimuli while focusing on the VE (Witmer & Singer, 1994).

1.3 Disturbance from the real-world (surrounding) environment

A user's sense of immersion and presence in a VE may be degraded when real-world stimuli are present. These stimuli may serve as an attentional distraction; thus, less attention is focused on the VE (Draper et al., 1998). Alternatively, the computer and VE itself could be affected if the computer is connected to a corporate network and the network becomes busy or slows down (Nash et al., 2000). The current research will focus on this particular type of disturbance. More details on the potential role of network parameters in telepresence experiences in using SEs for teleoperation are provided later.

1.4 Task

Sheridan (1992) stated that the difficulty and degree of automation of the task will affect virtual presence. Other task factors potentially affecting presence include the required user attentional resources and the length of the task (Draper, 1998). If a task requires a lot of attentional resources, it may create higher levels of virtual presence for the user (Draper et al., 1998). An increase in time spent in a VE could either increase presence due to user adaptation and familiarity, or it could decrease presence if adverse effects intensify over time (Stanney, Mourant & Kennedy, 1998).

Chapter 2

INTERNET BASED TELEOPERATION

The Internet connects millions of computers all over the world, giving access to communication, data storage, banking, commerce, video conferencing and numerous such services and applications. It can eliminate traditional communication barriers, such as long-distance and time constraints, and, therefore, provide us with a new working environment where people living in different parts of world can work together collaboratively (Song & Kaber, 2000). The Internet, on account of its affordability, widespread usage, extensive applications and well-developed infrastructure, has been investigated as an alternative for remotely controlling real-time systems including robotic systems for teleoperations such as tele-manufacturing, tele-training, tele-services, etc.

2.1 History of Internet based-Telerobots

Since the appearance of the first networked device on the Internet "*The Cambridge Coffee Pot,*" the rapid growth of the World Wide Web (WWW) over the past several years has resulted in a growing number of telerobot sites and web accessible devices. The first Internet-based telerobotic system, developed at the University of Western Australia, came online in September 1994 (Taylor & Trevelyan, 1995). This system incorporated a 6 Degree-of-Freedom (DOF) tele-manipulator, allowing users to pick-up and manipulate various objects within its reach. This device was soon followed by a telerobotic garden at the University of Southern California, which integrated an Adept 6-DOF manipulator to tend a garden situated around it (Goldberg, Mascha, Gentner, Rothenberg, Sutter & Wiegley, 1995). Various other devices have become available over time, such as the Bradford Robotic Telescope (Cox & Baruch, 1994), the NetroLab at Reading (McKee & Barson, 1996), the *"forty two"* telerobot at Manchester (Nehmzow, Buhlmeier, Durer & Nolte, 1996), an interactive 3D art viewing system (Goldberg, Becky, Akatsuka & Bressanelli, 1998), the VISIT telerobot system (Kosuge, Kikuchi & Takeo, 1998) and *"MAX"* wireless teleoperation system (Ferwon, Roque & Vecchia, 1999).

Hu, Yu, Tsui and Zhou (2001) classified all of the above mentioned teleoperation system as first generation Internet-based telerobots, since they were directly controlled by human operators and they have minimal "on-board automation." Future Internet-based telemanipulation systems are expected to integrate human control with some system autonomy to promote overall web-based teleoperation performance and user control satisfaction. Teleoperators with some degree of "on-board" automation are often referred to as telerobots. Simsarian (2001) claims that these "semi-autonomous" telerobots are far more superior in complex task performance in unstructured environments than, for example, fully autonomous robots.

2.2 Communication Protocols

Internet-based control systems must rely on available communication protocols to exchange real-time data between local and remote sites. Today, most network protocols provide transparent and reliable support for data exchange among computers using the Transmission Control Protocol (TCP). This protocol provides a full-duplex stream service, with automatic error handling, retransmission, packet re-ordering and guarantee of safe delivery. However, from the point of view of a real-time application, like Internet-based teleoperation and telerobot control, this protocol has the drawback of unpredictable data arrival times.

This limitation can be overcome by using the User Datagram Protocol (UDP), which does not require any acknowledgement message between sending and receiving processes, and therefore it is not a blocking protocol. However, UDP does not guarantee data delivery, since it provides no feedback from the receiver about lost data packets.

Unfortunately, the TCP mechanisms ensuring data delivery cannot be de-activated or ignored and therefore real-time applications cannot be implemented using the TCP protocol. The UDP is a potential protocol for real-time applications, since it is designed for single-datagram exchange and offers faster access to networks (Comer, 2000). However, the UDP also relies on packet-switched techniques to send data over the network, and is therefore affected by delay jitter on data arrival. That is, data sent at a constant rate over a packet-switched network may arrive to destinations with a variable inter-arrival time. This jitter is due to the combined effects of buffering in routers and of different routing policies.

2.3 General limitations of the Internet

Beyond these specific problems with Internet protocols, other general drawbacks of the Internet that may negatively affect teleoperation performance and the potential for human operator telepresence experiences include:

Throughput: Bandwidth may be limited and vary depending upon network congestion.

Delay: Random time varying delay (jitter) may occur depending upon network traffic.

Reliability: Data packets may be dropped or re-routed due to network congestion resulting in loss or out-of-order packets.

This research will focus on the delay limitation in teleoperation applications. More details on the types of protocols and delays to be studied are provided later.

2.4 Internet-based teleoperation versus conventional teleoperation:

Many of the problems in Internet-based teleoperation applications are not prevalent in conventional teleoperation scenarios involving the use of dedicated network links between a local control station and a remote work package.

Hu et al. (2001) differentiated Internet-based teleoperation from conventional teleoperation as follows:

1. The delay and the throughput of the Internet are highly unpredictable, unlike traditional teleoperation, where the interfaces have fixed and guaranteed delays.
2. Web-based teleoperation requires a high degree of tolerance to possible data packet loss due to packet discard when there is no existing remedy.
3. Internet robots need innovative mechanisms for coping with shared control among multiple web users with different applications in mind.
4. Internet robots are remotely operated by people with little expertise and skills, while traditional telerobots are typically handled by trained operators.
5. Since web users are a central part of the control loop, their behaviors become an important consideration in the system design.

The current research will also examine specific differences in Internet-based teleoperation and conventional teleoperation on remote task performance and user telepresence experiences.

2.5 Quality of Service

Because of the aforementioned shortcomings of the Internet and because of the real-time requirements of teleoperation, providing or guaranteeing Quality of Service (QoS) on a network is crucial in order to obtain good performance. As defined by the ISO/IEC and the ITU-T, QoS means *the collective effect of service performance, which determines the degree of satisfaction of a user of the service* (ITU-T, 1994). In lower network layers, a QoS profile can be viewed as bounds and limits on requirements such as end-to-end delays, throughput, packet loss rates, peak rates and variances. This QoS is usually labeled as network QoS (Cheong & Lai, 1999). The concept of QoS has led to the development of several protocols such as Asynchronous Transfer Mode (ATM), Resource Reservation Setup Protocol (RSVP), Internet Protocol Version 6 (IPV6), Multi-Protocol Label Switching (MPLS), and Subnet Bandwidth Manager (SBM). This research examined an approach to achieving QoS in Internet-based and conventional teleoperation scenarios involving adaptive system control.

Chapter 3

MOTIVATION AND PROBLEM STATEMENT

Current research in Internet-based telerobotics focuses mainly on control issues, such as reducing the impact of time-delay induced by a network in order to maintain the stability of the system. Numerous models have been proposed to compensate for network-induced delays. Anderson and Spong (1989) used passivity and scattering theory to show that a teleoperator with known time delay is unstable, and they implemented a delay compensator that transforms the communication channel into a passive system. Niemeyer and Slotine (1991) offered an approach to overcome the limitation of known time delay by transforming the communication channel into a loss-less passive connection, which uses wave variables to represent velocities and forces exchanged between the master and the slave. Kim, Hannaford and Bejczy (1992) described a control, which exhibits good rejection of time-delay effects. The above three approaches were thoroughly analyzed by Eusebi and Melchiorri (1995) and they evaluated the ability of each control law to preserve stability for different values of communication delay. Luck and Ray (1990) proposed a state predictor using memory buffers to convert random network delays into time-invariant delays. Nilsson, Bernhardsson and Wittenmark (1990) utilized an optimal stochastic control concept by treating network delay effects as a Linear Quadratic Gaussian (LQG) problem. Walsh, Ye and Bushnell (1999) used non-linear control theory to formulate network delays as a vanishing perturbation. Göktas (2000) applied robust control theory to handle network delays as uncertainties in a networked mobile robot. Tipsuwan and Chow (2001) proposed a real-time application gain adaptation to compensate for QoS variation and deterioration.

Unfortunately, few, if any current studies on Internet-based telerobotics have considered a human factors perspective in designing or evaluating approaches to system compensation or adaptation to network delays. For example, research has not been conducted on the human performance or telepresence implications of a gain adaptation scheme in an Internet-based teleoperation. Beyond this, the integration of intuitive VE interfaces in teleoperation systems for facilitating presence experiences and performance with complex gain adaptation schemes has not been considered. The general objective of the current research was to evaluate one such implementation from a human factors perspective.

The Advanced Diagnosis and Control Laboratory (ADAC) at North Carolina State University has developed a networked mobile robot using the gain adaptation technique proposed by Tipsuwan and Chow (2001). According to this technique, when there is a change in the network delay or throughput, the adaptation scheme automatically adapts the gain of the system controller in order to reduce the impact of lag on system performance. The current research evaluated this adaptation scheme as to its effectiveness in terms of human performance and presence. A three-dimensional high fidelity VR interface was developed, which was run as a stand-alone application for conducting experiments. The specific objective of the experiment was to establish the effectiveness of the adaptation scheme under a variety of time-delay conditions, which have been identified through previous research to cause problems in human performance.

The experiment was also expected to reveal the effectiveness of the scheme in reducing detrimental effects on telepresence due to communication delays. It was believed that the use of an adaptation scheme would produce less degradation in performance compared to no-adaptation and would also greatly influence the sense of presence perceived by the user.

This research tested three types of delay including, no-delay (a control condition), constant delay and random delay. The no-delay condition is the idealistic condition and was studied to provide optimal points of comparison in terms of performance and presence. The constant delay condition simulated a dedicated network with predictable, deterministic delay. Finally, the random delay condition was used to study the effect of a simple model of Internet-based telerobot control. The constant and random delay conditions were tested with and without the use of the adaptation scheme. Each subject experienced all the delay conditions in random order under either of two modes of remote robot control – teleoperation and telerobotic. More details on these control modes are presented later in the Methodology section.

Thus, it was expected that this research would provide insight into the usefulness of gain adaptation schemes for reducing human performance and telepresence degradations in teleoperation scenarios. It was also expected to produce results on the relationship between performance and presence experiences as mediated by the level of system automation and type of communication delay. The effects of these factors in combination on telepresence have not been previously studied.

Chapter 4

VIRTUAL REALITY INTERFACE

The VR interface used in this research was developed using Sense8's WorldUp™ VE development software. The package integrates an easy-to-use graphical user interface for object creation, property specification and simulation design along with a BasicScript editor to add behaviors to objects. The VR simulation was based on the telerover developed by the ADAC laboratory. The mathematical model of the rover kinematics and the gain adaptation scheme were based on the model developed by Tipsuwan and Chow (2001) and are presented in Appendix A. This model was applied in the development of the VE interface.

4.1 Schematic of the VR Interface

The VR interface developed was a self-sufficient simulation, including the main controller, network, local controller and the telerover. Figure 4.1 shows a schematic of the functions implemented in the VR simulation. The following sub-sections present detailed descriptions of each of the components of the VR interface and the overall teleoperation system

4.1.1 Main Controller

The main controller, as part of the simulation, computes the control signal for the local controller in the telerover in order to track a desired path. In the teleoperation mode of control, the controller computes the angular velocity of the individual rover wheels based on the control input commanded directly by the user. Thus, the teleoperation involved real-time user control/direction of rover navigation.

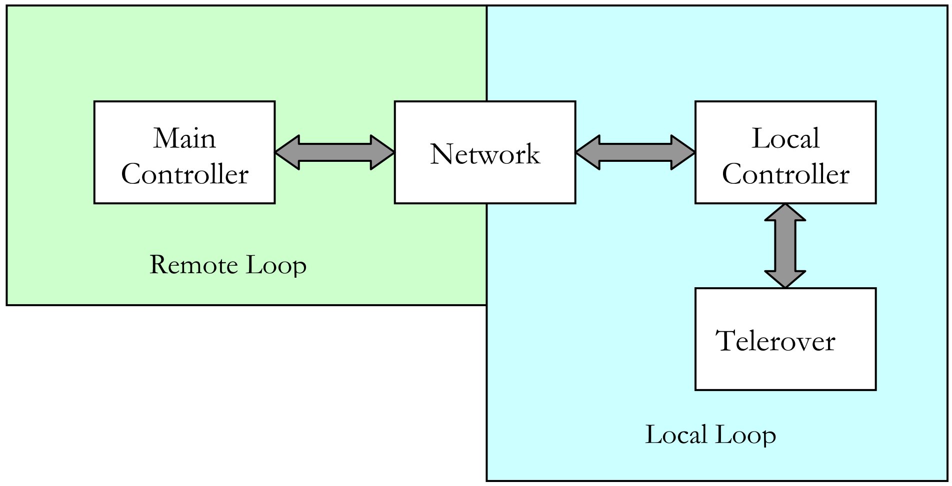

Figure. 4.1. Schematic of the VR Interface.

In the case of the telerobotic control mode, the user specified a target location and the controller computed the motion path using a quadratic path-tracking algorithm (Yoshizawa, Hashimoto, Wada & Mori, 1996). This algorithm lends itself to real-time applications because of its simplicity in computation with a minimal amount of information (Tipsuwan & Chow, 2001). The algorithm works as follows:

(1) identify initial distance between current robot position and reference point.
(2) compute error between them and transform error into telerover coordinates.
(3) find a quadratic curve between robot's coordinate and reference point.
(4) compute reference linear and angular velocities of telerover along quadratic curve.
(5) update distance for next sampling time.
(6) compute velocity of reference point along desired path based on actual velocity of telerover; and

(7) compute new reference point on desired path based on current reference point velocity;

The mathematical representation for the above algorithm can also be found in Appendix A. In this control mode, the telerover did not have the capability to automatically detect and avoid collision with task objects in the VE.

4.1.2 Local Controller:

The local controller was composed of two Proportional-Integral (PI) controllers. Each PI controller controlled the speed of one driving wheel of the rover. The control gains used to control both motors were set to be the same since the motors at both wheels were assumed to have the same characteristics. The signals from the main controller were the reference angular velocities of the wheels.

4.1.3 Telerover:

The telerover was a differential drive mobile robot with two driving wheels and one caster wheel. The kinematics of the telerover and its parameters are given in Appendix A.

4.1.4 Network:

The end-to-end network QoS can be defined in terms of two of the most popular QoS measures, the point-to-point maximal delay bound of the largest packet, indicating the worst-case time-delay scenario to deliver a packet, and the network throughput bound that limits how often packets can be sent across the network. Any change in the QoS affects the inter-arrival time between packets, assuming there is no packet loss. Thus, the QoS deterioration was simulated in this study by randomly generating the jitter or variable inter-arrival time.

4.2 Main Controller Adaptation

In order for the telerover to track the path properly under a nominal network QoS condition and constraints on performance, three adaptation parameters α, β, and d_{max} were set appropriately. These parameters represented the main controller adaptation, the reference position projection, and maximal distance between the robot and reference point, accordingly, and are explained in detail in Appendix A. When QoS deterioration occurred, the settings of the gains might not remain suitable for the network condition and robot state. The telerover might deviate from the reference path to an unacceptable track because of improper speed and projected reference points. Thus, the telerover has to gracefully degrade its performance by adapting itself to maintain its stability as much as possible under the current network QoS. This adaptation was applied to the main controller of the teleoperation system. Extensive experiments were conducted to determine a range of values for α, β, and d_{max} within the delay bounds of 700ms – 1300ms. Linear approximation was then used to arrive at a particular value based on the average delay observed between time periods. The general objective of the adaptation was to limit system performance errors and maintain system safety. This research was expected to demonstrate the effectiveness of gain adaptation under the different rover control modes and delay conditions for maintaining accurate performance and promoting operator telepresence.

4.3 Interface Design:

The VR interface for the telerover navigation consisted of four windows including: (1) a main window, which displayed an exocentric view of the telerover; (2) an aerial view of the telerover and its operating environment; (3) a virtual joystick, navigation control panel and (4) a speedometer display. The main window facilitated 3D viewing of the virtual environment.

The aerial view was integrated to provide a better overall sense of the environment and to facilitate operator judgments of the position of the rover relative to task objects. It also provided features like panning and zooming of the displayed view. When the right mouse button was clicked and held down over the aerial window, the display panned based on the position of the cursor such as forward, backward, left and right, as well as combinations of these directions. The aerial view could be zoomed by clicking and holding the middle mouse button in the upper-half of the window for zoom-in or lower-half of the window for zoom-out. Additionally, this window was utilized in the telerobotic control mode to select a destination for the rover to navigate. This was done by moving virtual crosshairs on the display. Clicking and holding the left mouse button in the appropriate position on the display produced the desired motion. The direction of motion of the crosshairs was dependent on the position of the cursor on the aerial window as depicted in Figure 4.2. The crosshairs are visible in Figure 4.3 as an "x" in the aerial window and main window (see the virtual object to the front-right of the rover).

The joystick navigation control was used in teleoperation mode for imparting motion to the telerover. The control included eight directional arrows corresponding to forward, backward, left, right, forward-left, backward-left, forward-right and backward-right motion. The speedometer was a passive display with the purpose of giving operators a sense of how fast the rover was traveling in the environment.

Forward Left	Forward	Forward Right
Left	No Motion	Right
Backward Left	Backward	Backward Right

Figure 4.2 Zones in aerial window for view panning and destination selection using crosshairs.

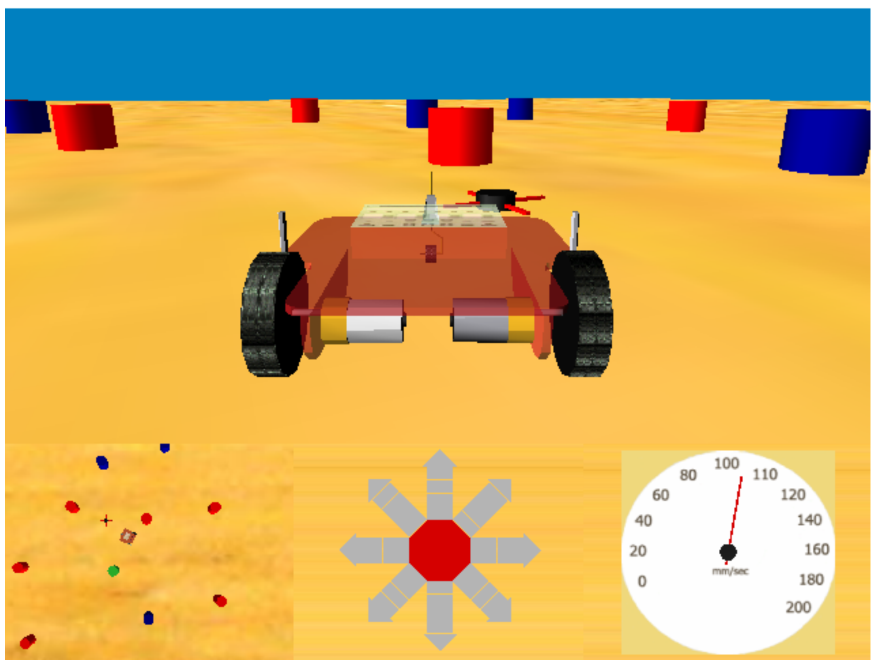

Figure 4.3. VR interface for telerover navigation.

Chapter 5

METHODOLOGY

In an attempt to further knowledge on how factors external to VE simulations affect the sense of presence and performance of tasks through SEs, an experiment was designed to study the various network-induced delays and the use of the different levels of automation in a teleoperation scenario. In this study, the participants were asked to perform a simulated teleoperation task using the telerover connected to a simulated Internet or private network. Performance data was collected during the experiment, which included time-to-task (TTC) completion and the number of control errors (collisions). The VR interface was presented using Virtual Research (VR8) head-mounted display to provide binocular depth cues on the VE to subjects.

5.1 Task

The task as part of the telerover control simulation was to navigate the rover in a desert-like VE between obstacles (virtual oil drums), much like a downhill slalom ski race. At the start of the simulation the obstacles were blue or red in color. All the obstacles were randomly positioned each time the simulation was started. Navigating the telerover between a blue obstacle (barrel) and its nearest red neighbor caused the blue obstacle to turn green in color. This can be seen in Figure 4.3 in Chapter 4. A sound cue was associated with this event as a redundant indication that an obstacle had been cleared. Colliding with any obstacle caused it to turn black in color (whether it was originally blue, red or green) and a redundant sound cue was provided. This was considered as a performance error and was recorded during the simulation. If a blue obstacle was involved in a collision causing it to turn to black, then the obstacle could not be made green in color. However, in the case of a red obstacle, if it was the nearest red neighbor to a blue obstacle, a user was still required to navigate between the blue and black obstacle to clear the blue obstacle (i.e., turn it green). The goal of the task was to convert all blue obstacles in the environment to green. The total time required to complete a set of obstacles and the number of collisions were recorded during simulation trials.

In the teleoperation control mode, the joystick navigation control was used to control the speed and direction of the rover. The speed could be increased or decreased by a left click or right click of mouse button, respectively and by pointing the cursor at the top of the arrow representing the desired direction of navigation. Five clicks of the left mouse button throttled the rover to its maximum speed, while five clicks of the right mouse button brought the rover to a stop. Additionally, the left or right mouse button could be clicked at the center of virtual joystick control to stop the rover.

In the telerobotic control mode, the aerial view was used to define the destination for the rover to navigate. As described in Chapter 4, this was accomplished by moving the virtual crosshairs using the mouse to the desired location of the rover in the aerial view. As long as the user held the left mouse button, the crosshairs could be moved anywhere in the aerial view. Once the button was released, the position of the crosshairs in the environment was taken as the destination and the rover began to drive towards it. Figure 5.1 and 5.2 are screen shots showing the telerover in the exocentric and aerial views as part of the simulation.

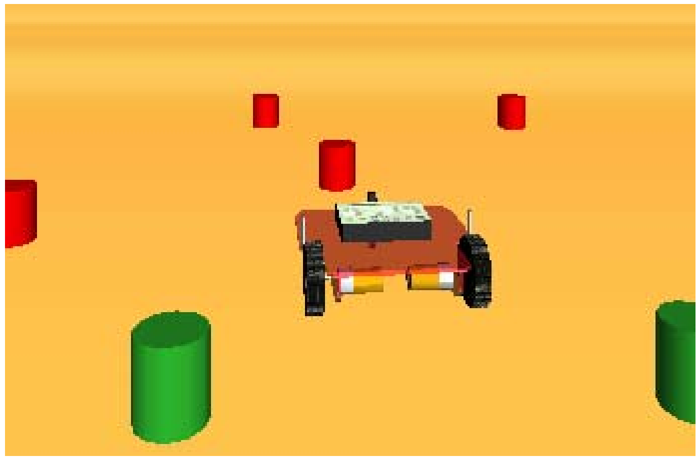

Figure 5.1. Exocentric view of telerover navigation.

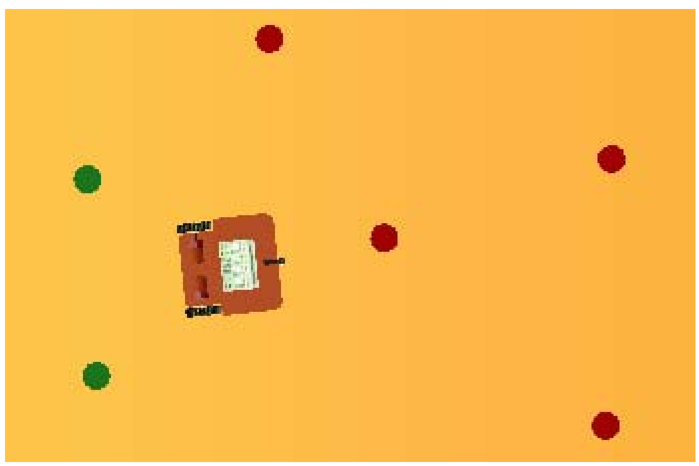

Figure 5.2. Aerial view of telerover navigation.

5.2 Independent Variables

The independent variables manipulated in this study included the network delay type, the level of automation (LOA) and the system gain adaptation to network delays. Three general delay conditions were examined including a no-delay (control) condition, a constant delay representing a teleoperation system using a dedicated network and a random delay condition to model Internet-based teleoperation. Two settings of LOA were used, including teleoperation, or manual control, and telerobotic, or shared control. Finally two settings of control gain adaptation were used including adaptation (ON) and no-adaptation (OFF).

Typical delays in teleoperation system communication networks cause lag between the time the user initiates an action and the time the action is reflected at the remote work package. It has been demonstrated in a number of studies that increased lag results in decreased performance and presence. MacKenzie and Ware (1993) argued that lag has been shown to degrade human performance in motor-sensory tasks with interactive systems. They found that at 75ms lag, an effect can be easily measured, and at 225ms, performance is substantially degraded. Watson, Walker, Ribarsky and Spaulding (1998) claim that a mean delay of 259ms, with a standard deviation of 83ms, has a major negative effect on performance. Eberst, Stoffler, Barth & Farber (1999) said that a delay of 250ms is easily recognized by human operators, while a delay of about 1000ms tremendously impairs performance. The lag, which was explored in this study, was on the order of 1000ms ± 300ms. A lag of 1000ms was used for constant delay, while a lag of 700ms – 1300ms was used for random delay.

A random number generator was used in the experiment to generate random delays. It was observed that the mean random delay for the experiment was at 960ms with a standard deviation of 140ms. Figure 5.3 shows a histogram of the distribution of the generated random lags within the delay range. The histogram is based on 13901 observations made during the entire period of trials involving the random delay condition. During the experiment, each subject was exposed to 4 trials involving the random delay condition, including, two adaptation and two non-adaptation trials. Thus, a total of 128 trials were conducted with the random lag across 32 subjects. The mean TTC for these trials was 412.5 seconds and the lag setting was updated every 0.5 – 5 seconds.

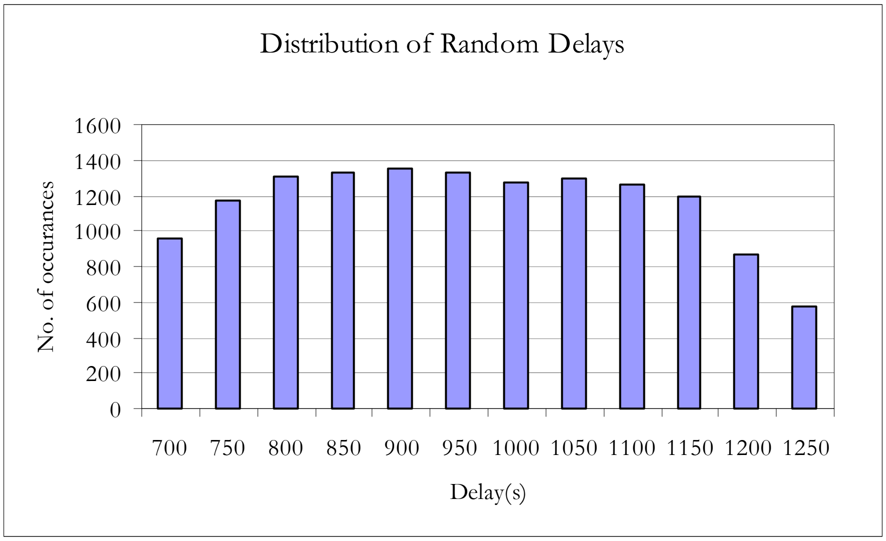

Figure 5.3. Histogram of random delays generated for the experiment.

5.3 Dependent Variables

The dependent measures of interest in this study included performance, telepresence and workload. As previously mentioned, both the efficiency and effectiveness of teleoperation task performance were recorded during the experiment. The time-to-navigate through the entire set of obstacles and the number of navigation errors/collisions with obstacles were captured by the workstation running the simulation.

Telepresence was measured using a 2-question Presence Questionnaire (PQ) developed by Draper and Blair (1996) (Appendix B). The items in the questionnaire included: "I felt as though I were actually in the remote environment as I performed the task" and "The experience involved unity or fusion of self with the remote environment". A 7-point rating scale was associated with each question and was used to capture the degree to which a user agreed with each statement (i.e., subjective rating of telepresence was made).

In order to assess the task workload experienced by subjects during the test trials, the NASA-Task Load Index (TLX) subjective workload survey (Appendix C) was administered. Subjects completed a subjective comparison of demand factors (mental, physical, temporal, performance, frustration and effort) once before the beginning of the test trials and rated the subjective perceived workload at the end of each test trial. The rankings and ratings of the demand components were used to compute a composite index of workload for the telerover navigation task (a weighted sum of the ratings across all demands).

5.4 Subjects

Thirty-two subjects were recruited from the graduate and undergraduate student population at NC State University for participation in this study on a voluntary basis. Appendix D presents an anthropometric data survey that was used in the study to record subject characteristics, such as personal computer (PC) and PC-based video game experiences. This information was used to characterize the subject sample. There were 29 male subjects and 3 female subjects. The average age was 23.72 years. All the subjects had 20/20 vision without correction. As part of the anthropometric data survey, the subjects were asked to rate their prior experience with PCs, in general, and PC-based video gaming using a five-point scale with "1" equal to no experience and "5" equal to frequent experience. The average rating for PC usage and PC games were 3.125 and 5.0, respectively.

5.5 Experimental Design

Each subject was exposed to all combinations of the three different delay conditions, including the no-delay (control condition), constant and random delays, and the two adaptation settings. That is, the type of delay and adaptation were manipulated as within-subjects variables. However, the LOA was used as a subject-grouping variable. Each subject was exposed to only one control mode. Half of the subject sample experienced teleoperation control mode and the remaining half used telerobotic control mode. LOA was handled as between-subjects variable in order to limit the potential of training carry over effects from one mode of control to another. The entire experimental design was replicated once. Thus, two trials were conducted under each delay–adaptation combination, which produced 10 trials per subject. Table 5.1 shows the complete data collection table for the experiment and specifically the distribution of subjects across the experimental conditions.

				LEVEL OF AUTOMATION	
				TELEOPERATION	TELEROBOTIC
				SUBJECT	
				1…………..16	17…………..32
TYPE OF DELAY	RANDOM	ADAPTATION	ON	Y1………..Y1	Y1………..Y1
				Y2………..Y2	Y2………..Y2
			OFF	Y1………..Y1	Y1………..Y1
				Y2………..Y2	Y2………..Y2
	CONSTANT		ON	Y1………..Y1	Y1………..Y1
				Y2………..Y2	Y2………..Y2
			OFF	Y1………..Y1	Y1………..Y1
				Y2………..Y2	Y2………..Y2
	NONE	CONTROL		Y1………..Y1	Y1………..Y1
		CONDITION		Y2………..Y2	Y2………..Y2

Table 5.1. Data collection table based on experimental design.

5.6 Procedures

The subject training and testing procedures for the experiment are summarized in Tables 5.2 and 5.3 respectively. The entire training procedure took 45-60 minutes, while the entire testing procedure took 90-120 minutes. Consequently, subjects were recruited to participate for a maximum of 3 hours in order to

Steps in procedure	Approximate Time in minutes
1. Introduction to experiment and equipment.	5
2. Completion of informed consent (Appendix F) and anthropometric data survey (Appendix D).	10-15
3. Familiarization of subject with different types of displays as part of VE interface.	10-15
4. Subject familiarization with simulation with no obstacles.	5
5. Completion of simulator sickness questionnaire (SSQ) (Kennedy, Lane, Berbaum, Lilienthal, 1993) to obtain baseline reading (Appendix G).	5
6. Completion of training with reduced number of obstacles with no-delay/lag.	10-15
7. Completion of SSQ (Appendix G).	5
8. Familiarization of subject with telepresence questionnaire (Appendix B).	5
9. Familiarization of subject with NASA-TLX subjective workload survey (Appendix C) and completion of demand factors comparison based on training experience.	10

Table 5.2. Training Protocol.

Step in procedure	Approximate Time in minutes
1. Each subject experienced 10 trials of approximately 5-7 minutes. Trials were separated by a 2-minute break.	50-70
2. At the end of each trial, the telepresence questionnaire and NASA-TLX rating form were administered.	20-30
3. After the 5th trial, the SSQ was administered followed by a 5-minute break.	5-10
4. After the 10th trial, the SSQ was administered.	5-10

Table 5.3. Testing Protocol.

complete the entire experiment. The specific instructions to subjects as part of the experiment are presented in Appendix E. Each of the steps presented in Tables 5.2 and 5.3 is covered in the Appendix E.

5.7 Hypotheses

This research primarily assessed the impact of network/communication delays in teleoperation on human operator performance, presence experiences and perceived workload. It was expected that when there was an increase in delay/lag, performance would degrade, or TTC and the number of errors would increase, with a corresponding decrease in presence and increase in workload.

To offset the impact of lag on user performance and perceived presence, the concept of gain adaptation was explored. When network delays increased, the telerover controller would automatically adapt its gain (or speed) to maintain safe and accurate performance and system stability. This adaptation of gain was expected to increase TTC, but limit the number of performance errors (collisions) in comparison to the conditions involving no-adaptation. It was also hypothesized that when there was deterioration in the network QoS, adapting the gain would result in a less significant decrease in presence ratings than when no-adaptation was used to account for the lag. Thus, the adaptation conditions were expected to result in higher presence ratings compared to the no-adaptation conditions.

It was also expected that changes in telepresence might vary between the teleoperation and telerobotic control modes. In the telerobotic mode, since the user specified a target location and supervised the telerover actions, the impact of network delay on the user was expected to be minimal. The user did not directly control the motion of the telerover and thus, only saw a slight decrease in navigation speed. In the teleoperation mode, the user directly controlled the telerover and hence when there was an adaptation to network QoS deterioration, the user perceived a drop in navigation speed. This would increase task completion time and was expected to cause user frustration with system performance resulting in reduced presence and increased workload. In general, it was hypothesized that subjects using telerobotic control would experience less deterioration of presence and lower workload compared to those using teleoperation control.

Finally, the research was expected to provide insight into the effectiveness of the adaptation scheme for maintaining performance and facilitating presence. The study was also expected to provide insight into the relationships between telepresence, performance and workload under the various teleoperation test conditions.

Chapter 6

DATA ANALYSIS

According to the experimental design, LOA was treated as between-subjects variable, and network delay and adaptation were handled as within-subjects variables. All statistical analyses were performed using SAS. They included multi-way analyses of variance (ANOVA) applied to the dependent variables to investigate the influence of the delay type, LOA and adaptation on the sense of telepresence and task performance. The entire experiment was replicated once. The full statistical model is as follows:

$$
\begin{aligned}
Y_{i,j,k,l,m} = {} & \mu + LOA_i + D_j + A_k + SUB(LOA)_{l(i)} + LOA \cdot D_{i,j} + LOA \cdot A_{i,k} + D \cdot A_{j,k} \\
& + D \cdot SUB(LOA)_{j,l(i)} + A \cdot SUB(LOA)_{k,l(i)} + LOA \cdot D \cdot A_{i,j,k} \\
& + D \cdot A \cdot SUB(LOA)_{j,k,l(i)} + \varepsilon_{m(i,j,k,l)}
\end{aligned}
$$

where,

μ	= Mean
$Y_{i,j,k,l,m}$	= Response variable.
LOA_i	= Level of Automation.
D_j	= Delay type.
A_k	= Adaptation.
$SUB(LOA)_{l(i)}$	= Subject nested within LOA.
$LOA \cdot D_{i,j}$	= Interaction between LOA and Delay.
$LOA \cdot A_{i,k}$	= Interaction between LOA and Adaptation.
$D \cdot A_{j,k}$	= Interaction between Delay and Adaptation.
$D \cdot SUB(LOA)_{j,l(i)}$	= Interaction between Delay and Subject nested within LOA.

$A \cdot SUB(LOA)_{k,l(i)}$ = Interaction between Adaptation and Subject nested within LOA.

$LOA \cdot D \cdot A_{i,j,k}$ = Interaction between LOA, Delay and Adaptation.

$D \cdot A \cdot SUB(LOA)_{j,k,l(i)}$ =Interaction between Delay, Adaptation and Subject nested within LOA.

$\varepsilon_{m(i,j,k,l)}$ = Error

i = 1, 2

j = 1, 2

k = 1, 2

l = 1,….,32

m = 1, 2

This model was used to make comparisons between teleoperated and telerobotic control under the various lag conditions. Since adaptation was not relevant to the no-delay control condition, data collected on this setting of the delay type was not analyzed using the full statistical model (i.e., there wasn't a complete crossing of the delay type and adaptation settings). The full statistical model allowed for separate analyses of the delay and adaptation main effects.

A reduced model was used for the control condition comparisons. Unlike the full model, this model included a single independent variable to represent the network conditions including the delay and adaptation settings. In this way it was possible to compare the no-delay control condition with the random and constant lag conditions with or without adaptation.

$$Y = \mu + LOA_i + NC_j + SUB(LOA)_{k(i)} + LOA \cdot NC_{i,j} + NC \cdot SUB(LOA)_{j,k(i)}$$

where,

LOA_i = Level of Automation.

NC_j = Network condition – combination of type of delay and adaptation, which include no-delay (ND), constant with adaptation (CA), constant with no-adaptation (CNA), random with adaptation (RA) and random with no-adaptation (RNA).

$SUB(LOA)_{k(i)}$ = Subject nested within LOA.

$LOA \cdot NC_{i,j}$ = Interaction of LOA and Network condition.

$NC \cdot SUB(LOA)_{j,k(i)}$ = Interaction of Network condition and Subject nested within LOA.

Further investigation of significant predictors was conducted using post-hoc tests, specifically Tukey's Honestly Significant Difference (HSD) tests with an alpha criterion of 0.05. Correlation analyses were also conducted on the various response measures recorded during the experiment, including TTC, number of collisions, telepresence and workload ratings. Pearson Product-moment coefficients were calculated to identify any positive or negative linear associations of the responses. The SAS PROC CORR procedure was used to establish the statistical significance of the correlations of interest to the study.

Chapter 7

RESULTS

7.1 Performance

The two measures used to assess the performance of subjects in the virtual telerover navigation task – TTC and number of collisions were analyzed using both the full statistical model and reduced statistical model (for comparison of the various network settings with the control condition).

7.1.1 Time-to-task completion

The results of ANOVA on the full statistical model revealed significant main effects of LOA ($F(1,255) = 44.61$, $p<0.0001$), delay ($F(1,255) = 8.54$, $p<0.01$) and adaptation ($F(1,255) = 8.88$, $p<0.01$) on TTC. Figure 7.1 shows the TTC across different network conditions under the two LOAs. The network condition in the plot is the combination of delay type and adaptation. There were four different network conditions compared in the analysis including: CNA, CA, RNA, and RA.

The ANOVA indicated that average TTC was higher for the teleoperation mode compared to the telerobotic control mode. The TTC for constant delay mode was greater than the random delay mode and similar results were observed for adaptation versus no-adaptation mode. The lower TTC under the random delay condition, compared to the constant delay mode, may be attributed to the random delay generator, which produced delays between 700ms and 1300ms. It was observed that many of the delays generated by the random generator were lower than 1000ms (lower than the constant delay setting) and hence, lower TTC occurred under the random condition (see Chapter 5, section 5.2 for more details on random number generator).

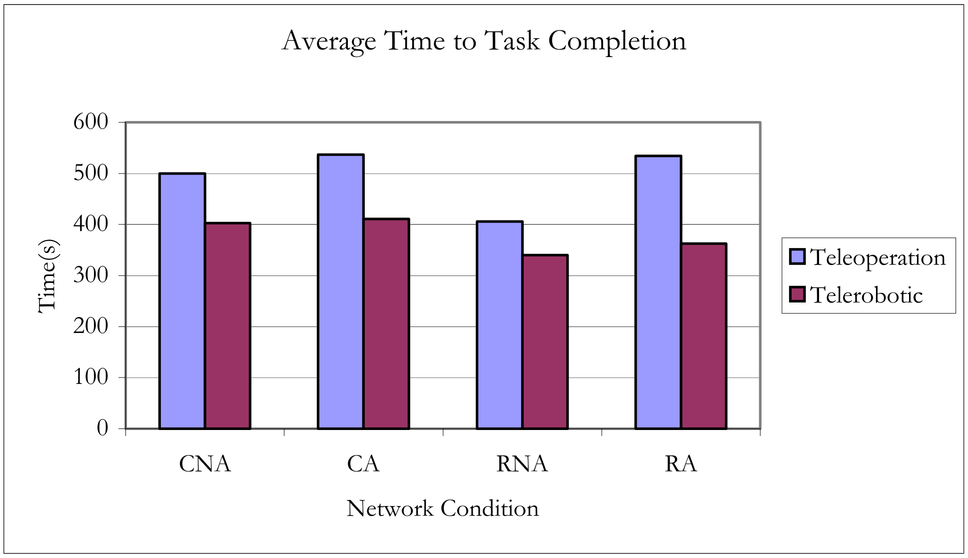

Figure 7.1. Mean TTC for LOA groups by each network condition.

Similar ANOVA results were obtained with the reduced statistical model, which included the ND (control condition). This model did not permit separate main effects analyses on delay type and adaptation settings, but did allow for comparison of the CNA, CA, RNA and RA conditions with ND. The LOA ($F(1,319)=45.13$, $p<0.0001$) and Network Condition (NC) ($F(4,319)=20.68$, $p<0.0001$) were found to significantly influence TTC. There were also significant individual differences among subjects within the automation groups. Finally, a significant two-way interaction of LOA and NC ($F(4,319)=2.86$, $p<0.05$) was present. Figure 7.2 shows the TTC across the two control mode conditions under the various network settings including the ND.

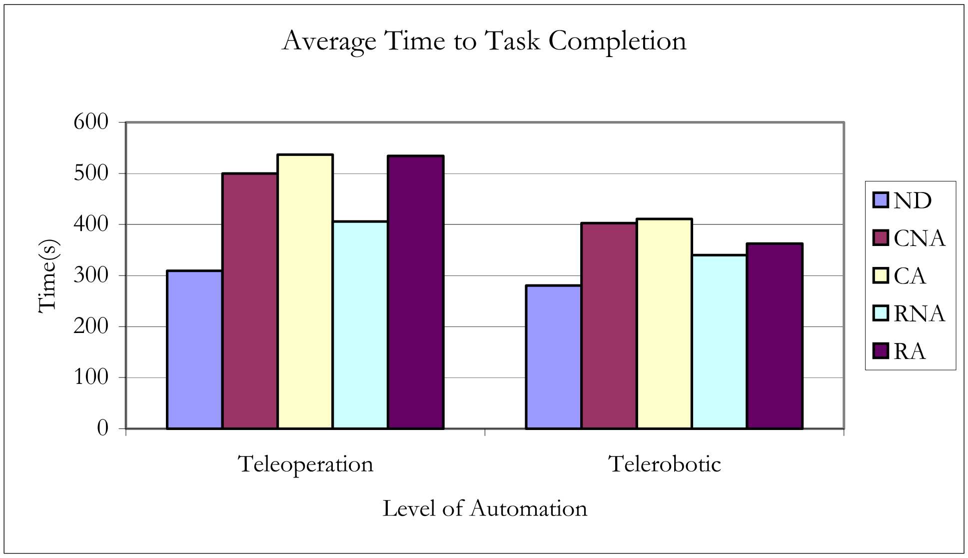

Figure 7.2. Mean TTC under various network conditions grouped by LOA.

The two-way interaction between LOA and NC suggested that the NC has a different implication on performance under the teleoperation control mode, compared to the telerobotic control mode. Tukey's HSD test was used to further analyze the significant interaction and revealed that RA and CA produced the worst TTC among all conditions except the CNA condition under the teleoperation mode. On average, the ND condition under the telerobotic mode produced the best TTC but it was not significantly different from the ND in teleoperation mode and the RNA and RA conditions in telerobotic mode. It was observed that regardless of the delay type or adaptation condition, the telerobotic mode resulted in higher performance in terms of TTC compared to the teleoperation mode.

7.1.2 Number of Collisions/Errors

The ANOVA results on the full statistical model revealed LOA, delay and adaptation to significantly influence the number of task related errors. Table

7.1 shows the F-values and the corresponding probabilities of significance for each main effect.

LOA	$F(1,255) = 47.08$	$p<0.0001$
Delay	$F(1,255) = 4.91$	$p<0.05$
Adaptation	$F(1,255) = 29.19$	$p<0.0001$

Table 7.1. F-values and p-values from ANOVA on error as response variable – Full model.

Figure 7.3 shows the average collisions/errors for each NC under different LOAs. The figure indicates that there was a dramatic difference in the number of errors between the LOAs. Similar to the differences observed in TTC across the teleoperation and telerobotic modes, significantly fewer collisions/errors occurred under teleoperation mode. This might have been due to the fact that under the teleoperation mode the subjects had complete control over the speed of the rover, while in the telerobotic mode they shared control with the rover. In addition, the teleoperation mode provided the subjects with the facility to stop the rover completely, but this was not available in the telerobotic mode since the rover only stopped if it reached the destination, as defined by the virtual crosshairs in the aerial view or it hit an obstacle. It can also be observed from figure 7.3 that the number of errors under the adaptation conditions was reduced by almost 50%, as compared to the no-adaptation conditions under both the teleoperation and telerobotic control modes.

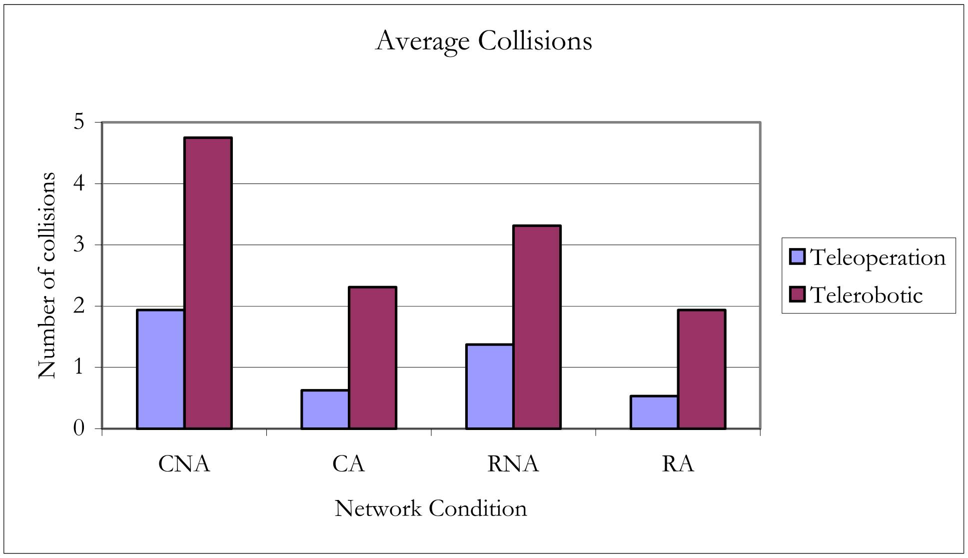

Figure 7.3. Average collisions for different LOA groups by network condition.

Similar ANOVA results were obtained with the reduced model, considering the ND control condition. Table 7.2 presents the F-values and their associated significance probabilities for the LOA and NC main effects. Figure 7.4 indicates that there were considerably fewer errors under the teleoperation mode compared with the telerobotic mode for the majority of network conditions. However, there was no significant interaction of the LOA and NC manipulations.

LOA	$F(1,319) = 51.34$	$p<0.0001$
Network Condition	$F(4,319) = 4.91$	$p<0.0001$

Table 7.2. F-values and p-values from ANOVA on error as response variable – Reduced model.

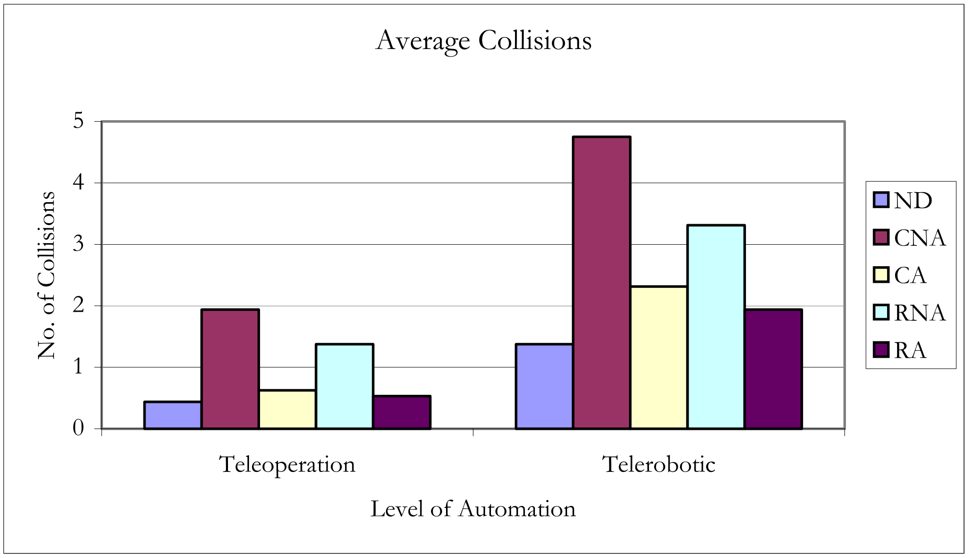

Figure 7.4. Average collisions for different network conditions grouped by LOA.

7.1.3 Potential Advantages of Gain Adaptation

Figure 7.5 shows the percent increase in TTC on account of using adaptation over the no-adaptation condition and the corresponding reduction in the number of errors. The plot clearly shows an average increase in TTC under both of the LOAs and corresponding substantial decreases in the number of errors for both constant and random delay conditions when using adaptation. Upon initial inspection of the plot, it can be observed that the effect of gain adaptation is more pronounced under constant delay mode compared to the random delay mode. This means the ratio of the percent decrease in errors to the percent increase in TTC is higher for the constant delay as compared to the random delay under both LOAs (the higher the ratio, the greater the performance improvement). This can be attributed to the nature of the random delay, where the delay varied between 700ms and 1300ms as compared to the constant delay, which was constant at 1000ms. It can also be noticed that the increase in TTC for the telerobotic mode was very negligible, as compared to the teleoperation control mode. The resulting reduction in the number of errors across LOA was comparable.

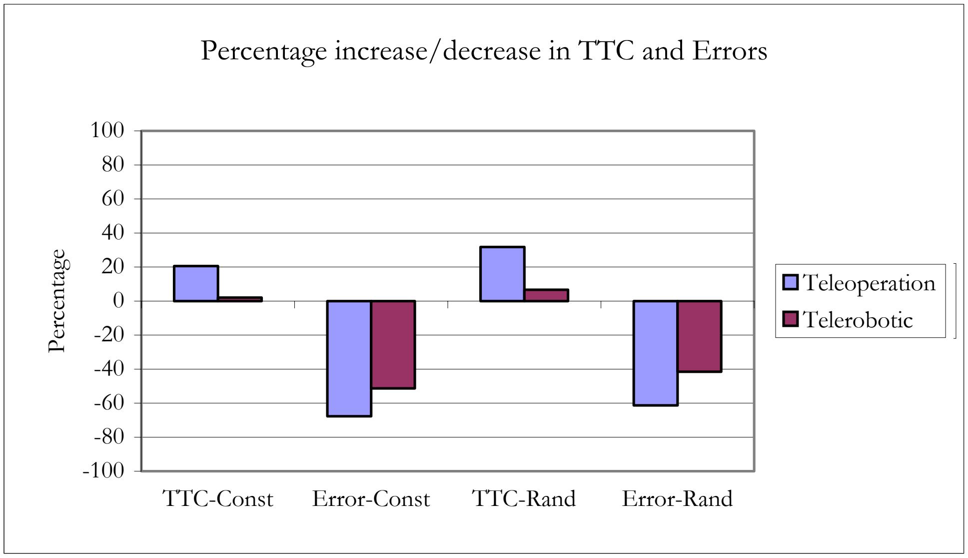

Figure. 7.5. Effects of gain adaptation on TTC and errors under the two LOAs.

7.2 Telepresence

Telepresence was measured by administering the 2-question PQ, developed by Draper and Blair (1996), after each test trial. An ANOVA on the sum of the ratings for questions (Appendix B) revealed that there were significant individual differences among subjects within the automation group. Comparable F-test values and p-values were obtained for the subject variable in both the full statistical model ($F(2,255)=26.71$, $p<0.0001$) and the reduced statistical (control condition) model ($F(2,319)=32.64$, $p<0.0001$).

Further analysis was conducted on the separate PQ1 and PQ2 ratings. It was observed with the reduced model that the PQ1 response was significantly influenced by LOA ($F(1,319)=5.88$, $p<0.05$). Significant individual differences ($F(2,319)=31.66$, $p<0.0001$) were also observed. From figure 7.6 it can be seen that the average PQ1 (Telepresence) rating was significantly greater for the telerobotic control mode, as compared to the teleoperation mode, under each network condition. It can also be observed that the mean telepresence ratings

(PQ1) were slightly greater for the adaptation conditions than the no-adaptation conditions under the telerobotic mode, however, there was no significant interaction of the LOA and NC manipulations.

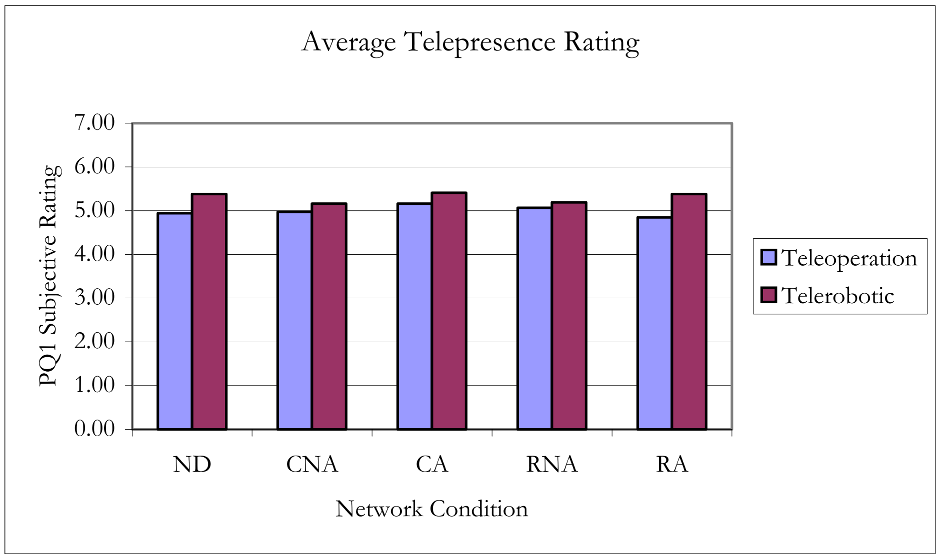

Figure 7.6. Average telepresence ratings for different LOAs grouped by Network conditions.

7.3 Workload

The NASA-TLX survey was administered after each test trial. Results on the subjective workload responses were similar to those obtained on the telepresence measures. An ANOVA on the full statistical model only revealed significant individual differences ($F(2,255)=16.99$, $p<0.0001$) within automation groups in terms of the composite workload scores. However, ANOVA results on the reduced model, allowing for evaluation of the control condition data, indicated that LOA was significant ($F(1,319)=4.34$, $p<0.05$) in effect on the overall workload score. In addition, there were significant individual differences ($F(3,319)=24.88$, $p<0.0001$) in the workload response. From figure 7.7 it can be observed that the average workload index was slightly greater for the teleoperation control mode compared to the telerobotic control mode across the NCs. There was no observable trend on the adaptation and no-adaptation conditions, which was expected based on the lack of a significant NC main effect.

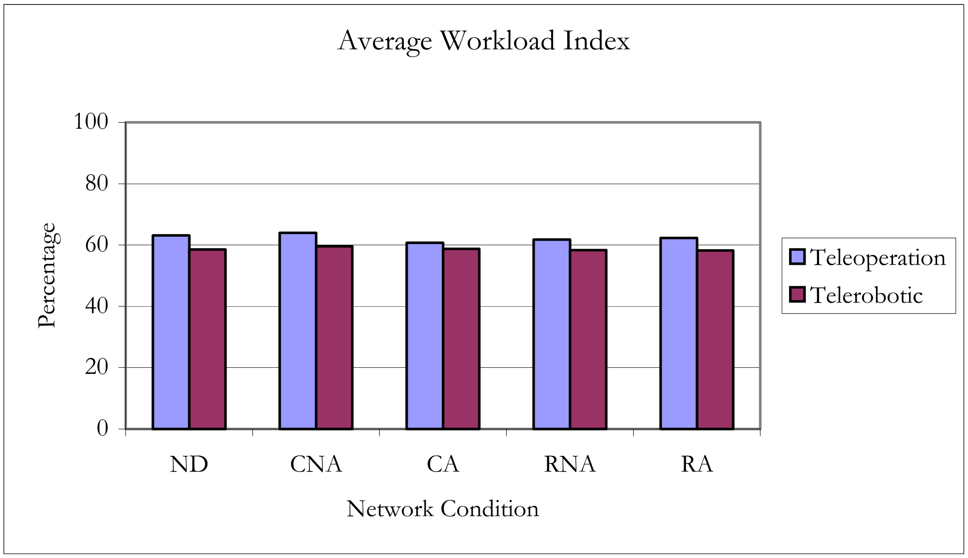

Figure 7.7. Average workload index under different LOA grouped by Network condition.

Further analysis was conducted on the subjective ratings for each demand component of the NASA-TLX. Although it was expected that the temporal demand and frustration component might be the most sensitive to the specific experimental manipulations, time pressure and stress were not highly ranked performance demands based on subject training experience. Based on ANOVAs on the full statistical model, all demand components revealed significant individual differences among subjects within the teleoperation and telerobotic control groups. Other interesting significant main effects included an influence of LOA on perceived physical demand ($F_{(1,319)}=38.87$, $p<0.0001$) and an influence of LOA ($F_{(1,319)}=12.37$, $p<0.001$) on operator ratings of performance in the telerover navigation task.

7.4 Correlation Analysis

Correlation analyses were conducted to explore the relationships between the various dependent variables. It was observed that TTC and the total telepresence rating (PQ1+PQ2) were significantly negatively correlated ($r=-0.13663$, $p<0.05$). This means as ratings of telepresence increased the TTC decreased. It was also observed that the overall workload index was positively correlated with telepresence ratings ($r=0.20236$, $p<0.001$). This linear association indicates that the subjective perception of workload increased with increases in the sensation of telepresence. Also the TTC was significantly positively correlated with frustration ($r=0.19499$; $p<0.001$) and physical demand ($r=0.11883$; $p<0.05$) and negatively correlated with performance ($r=-0.10974$; $p<0.05$) ratings. This indicates that as subject frustration increased and subjective perceptions of performance decreased, TTC increased.

The linear association of the telepresence ratings with other response measures was further analyzed by decomposing the ratings into PQ1 and PQ2 scores. This analysis revealed that PQ1 ($r=-0.13541$, $p<0.05$) was significantly correlated with TTC. Similarly, the overall workload index was broken-down into its demand components and the linear association of individual demand ratings with telepresence scores was analyzed. Table 7.3 presents a complete listing of all the correlations between the telepresence measures and the components of the workload index.

	Mental	Physical	Temporal	Performance	Frustration	Effort	TLX
PQ1	0.31433	0.36439	0.05320	0.11350	0.03634	0.12374	0.21335
	<0.0001	<0.0001	>0.05	<0.05	>0.05	<0.05	<0.001
PQ2	0.24305	0.31845	0.06156	0.14348	-0.06100	0.06743	0.16388
	<0.0001	<0.0001	>0.05	<0.05	>0.05	>0.05	<0.05
PQ1+PQ2	0.31438	0.36583	0.06110	0.13659	-0.01094	0.10341	0.20263
	<0.0001	<0.0001	>0.05	<0.05	>0.05	>0.05	<0.001

Table 7.3. Pearson product moment coefficients for telepresence and workload ratings. (Grayed blocks indicate insignificant correlations)

From the table it is clear that the telepresence ratings have strong positive association with subject perceptions of mental workload, physical workload, and performance. From this analysis, it can be inferred that with increases in telepresence, the subjective perception of performance increases. There was also a negative correlation between telepresence and frustration, but it was not significant. Overall, it can be said, that subjective telepresence has an important role in the subjective perception of workload.

In general, it can be observed from the correlation analyses that the r-values were relatively small. Even though the values were statistically significant, they generally indicate weak linear associations of the various response measures.

Chapter 8

DISCUSSION

8.1 Performance

8.1.1. Time-to-task completion:

The results of the experiment showed that TTC was longer for the teleoperation control mode as compared to the telerobotic control mode. This is because the user controls the speed in the teleoperation mode as compared to the telerobotic mode.

It was hypothesized that the TTC for the random delay would be greater than the constant delay because the random delay varied between 700ms and 1300ms while constant delay was fixed at 1000ms. Based on the results, the TTC for the constant delay was actually greater than that of the random delay. This may be attributed to the nature of the random number generator used for setting the delay between the defined upper and lower limits. It was observed that many of the random delays generated were less than 1000 ms and hence a lower TTC was observed for the random delay mode (see Chapter 5, section 5.2 for more details about the random number generator).

The TTCs observed for no-adaptation mode and adaptation modes were in line with the research hypothesis (i.e., the TTC would be greater for the adaptation mode). This can be attributed to the gain adaptation algorithm, which adapts (or reduces) the speed of the rover based on the delay experienced in the communication in order to maintain system stability.

The ability of the subjects to control the speed of the rover under the teleoperation mode most likely produced the significant individual differences within the automation groups. Interestingly, there was a two-way interaction between LOA and NC, meaning that performance under teleoperated control is affected by network conditions in a different manner than telerobotic control performance. This might be due to the differences in the extent of control of the speed available to the subjects under each LOA.

8.1.2. Errors

The performance errors under the teleoperation control were much lower than under telerobotic control. It is possible that this result was due to users having complete control over the speed of the rover in the teleoperation mode and the liberty to stop the rover at any time. This was not the case under the telerobotic control mode. Once the user selected the destination position for the rover, the vehicle only stopped if it had reached the destination, as marked by the crosshairs, or if it collided with some obstacle. This was a major difference between the teleoperation and telerobotic control mode that may explain the differences in the number of errors between the LOAs.

The difference in the number of errors between the no-adaptation and adaptation modes was inline with the research hypothesis. There were more errors in no-adaptation mode compared to the adaptation mode.

Finally, the delay type also had a significant influence on the errors with the constant delay producing the greatest number of collisions compared to the random delay. One would expect that the random delay type would produce more errors than the constant delay. However, it is important to note that in this study the random delay condition did not vary for each packet but there was a random change in the average delay between the source and destination.

It was observed that the no-delay condition produced on average the fewest errors, compared to all other types and the reasons are obvious. The random delay combined with the gain adaptation was significantly different from the constant delay without adaptation, which reinforces the significance of delay types. There was no difference in the number of errors between the adaptation and no-adaptation mode within a delay type. There was a difference between constant delay and random delay network conditions but it was not significant as demonstrated by an ANOVA.

8.1.3. Correlation Analysis

The correlation analysis demonstrated that TTC was negatively correlated with the subjective telepresence ratings. It is possible that user telepresence experiences may have actually improved the performance in the telerover navigation task. Neither the TTC nor the number of errors had any significant relationship with the composite NASA-TLX. However, analysis of the individual demand components of the index revealed that several subjective ratings were significantly correlated with TTC including physical demand, performance and frustration perception. As TTC increased subjects perceived increased physical demand and frustration with a corresponding decrease in performance.

Similarly, the number of errors had significant relationships with perception of physical demand, performance, frustration and effort. As the number of errors increased, subjects perceived lower physical demand, reduced performance, increased frustration and effort. The negative correlation between error and physical demand suggests that as the subject made less of an effort in controlling the rover, the task errors increased.

8.2 Telepresence

Only the LOA manipulation had a significant impact on subjective telepresence ratings (PQ1). It was hypothesized that the no-delay condition would produce a greater sense of telepresence as compared to other delay modes and that any degradation in telepresence under the random mode would be greater than for the constant mode. It was also expected that adaptation would result in higher ratings than the no-adaptation mode. The ratings across the network conditions did not support these hypotheses.

In the telerobotic control mode, users may have had greater attentional resources to concentrate on the details of the VE due to the off-loading of some task responsibility to the remote rover, which might have led to increased telepresence experiences. It might also be possible that increases in telepresence could have been due to lower impact of lag conditions on telerobot control since users were not required to control the speed of the rover.

It was observed from the telerobotic control condition, that on average, ratings were higher for no-delay condition, constant delay with adaptation and random delay with adaptation, as compared to constant delay with no-adaptation and random delay with no-adaptation. Although, not significant, this observation on the telepresence means supports the research hypothesis that ratings would improve on account of gain adaptation. A similar observation could not be made on the teleoperation mode. This may have been due to the user control of the rover speed under the teleoperation mode in that they could have developed their own adaptation strategy based on the nature of the task and personal attitudes (i.e., more conservative or more risky). It was observed during the experiment that subjects who were more conservative were more prone to drive the rover at a lower speed resulting in reduced errors in their control actions, as compared to those individuals who were risky in their actions and committed errors in order to finish the task faster. Related to this argument, there were considerable individual differences among subjects within the various control mode groups, as demonstrated by ANOVA results.

Telepresence had a significant positive correlation with the overall workload index. It is possible that greater task load may have led to increases in telepresence. Ma (2002) showed a positive correlation between telepresence and mental workload. It was also found that the telepresence ratings were significantly correlated with individual components of the NASA-TLX including mental demand, physical demand, and performance. Telepresence increased with increases in mental demand, physical demand, and user perception of performance.

8.3 Workload

The results demonstrated significant effects of LOA and individual differences on subjective perceptions of workload. The teleoperation mode resulted in higher workload that the telerobotic mode. This was consistent with the widely accepted notion that workload is greater for manual control of a system compared to automation assisted control modes. In this study, teleoperation referred to the manual/direct control mode and telerobotic referred to the automated assisted control mode. There was no apparent trend in workload across the adaptation and no-adaptation conditions.

As mentioned in the preceding sections, Pearson product-moment coefficients revealed a significant positive relationship between workload and telepresence ratings. With increases in workload, there were corresponding increases in telepresence. This result on the relationship between workload and telepresence is similar to the results obtained by Draper and Blair (1996), in which telepresence rating was significantly correlated with composite workload scores during completion of a pipe-cutting task using a teleoperator. Although the two responses were positively correlated, telepresence was higher and workload was lower under the telerobotic control mode, as the user essentially acted as a supervisor of the system whereas under the teleoperation mode, the user was responsible for complete control of the rover.

Chapter 9

CONCLUSION

The goals of this study were to: (1) evaluate the effects of different types of communication network delays (constant and random delays) on telerover control performance and operator telepresence experiences and workload; (2) evaluate the effects of gain adaptation on telepresence, performance and workload; and (3) examine the relationship between performance and presence in an Internet-based teleoperation scenario.

9.1 Limitations of current research:

Every research study has limitations that may form the basis for future work in an area. The limitations of the present study are related to the subject population, the VR simulation and the specific characteristics of the VE interface design. The subjects used in the experiment were students who were familiar with PC-based video games. These subjects cannot be compared to human operators of telerobotic devices who have received dedicated training on a system and have applied experiences in real teleoperation scenarios. Such operators may take the task of driving a remote rover very seriously and may be more motivated to high performance.

The simulation used in this experiment was not linked to a real telerover nor was the task implemented in the experiment a real teleoperation task. It is possible that this affected subject perceptions of realism in driving the telerover and, consequently, telepresence. It is expected that operator stress levels and perceptions of workload would be different if the VE interface were used to control a real rover on which subjects received live-video feedback. Furthermore, modeling and presentation of a more representative telerover task, such as mine excavation and neutralization (see Riley and Kaber, 2001) might also serve to promote higher perceived realism and affect subject behavior. It is important to note, however, that the relevance of VE interfaces to teleoperators is currently limited to structured and known task environments because of limitations in near real-time modeling methods, as observed by Ballantyne, Greenspan and Lipsett (1997).

Finally, in regard to the specifics of VE interface features, it was observed during the experiment that under the teleoperation control mode subjects tended to use the exocentric view more extensively than the aerial view, save a few subjects who solely used the aerial view for task completion. One disadvantage of focusing on the aerial view was that the orientation of the telerover continuously changed with respect to the joystick navigation control and, as a result, subjects lost their sense of direction relative to the joystick control. For example, when subjects wanted to make the telerover turn right, they steered it to the left. With the current joystick display design, there was a lot of eye movement required back and forth between the main window and joystick display; that is, the user observed the direction of the desired motion and clicked on the corresponding arrow in the joystick control display. It is possible that using a real joystick would result in reduced distraction from the task possibly promoting more telepresence and performance.

Under the telerobotic mode, users selected a destination for the rover using the aerial window and the main simulation window was considered to be of less importance to task performance. The aerial view was located in the lower-left part of the VR interface, which was in peripheral vision but outside foveal vision of subjects. This may have resulted in eyestrain for some users potentially impacting overall performance. Providing users with the capability to swap the aerial view window and exocentric view window under the telerobotic control mode might serve to reduce the visual requirements of the simulation and possibly improve performance.

9.2 Design Implications

Given the results of the current research, a number of design recommendations can be offered for implementing gain adaptation in teleoperation systems, including:

1. When the number of performance errors is more important than the time to complete the task, teleoperated control is more suitable than telerobotic control. Teleoperated control is applicable to this type of task goal irrespective of the nature of the network condition (i.e., constant, random or no-delay).

2. When the task completion time is more important than the number of errors, then a telerobotic control mode is more appropriate. This is true for constant, random and no-delay network conditions.

3. When the task involves higher workload, utilizing the telerobotic control mode can distribute the overall load between the user and rover.

4. When the task requires high level of attention from user promoting higher telepresence, a telerobotic mode can be used to best exploit the user's state in terms of overall system performance.

9.3 Future research directions

This study established the importance of gain adaptation in Internet-based teleoperation and its impact on performance and system safety. The study also established the relationship between performance, presence and workload under LOAs and NCs. The study identified gain adaptation as an important concept for human factors research in promoting performance and maintaining system safety in mission critical and dangerous situations.

Based on the results of the experiment and the caveats, it would be interesting to integrate the VR interface with a real teleoperator using the Internet and study the effects of gain adaptation on system stability and human performance and presence experiences. In addition, the use of a more complex task, representative of an actual teleoperation task, might improve the utility to generalize the research results.

Based on the VE interface design issues discussed above, it would also be interesting to explore user preferences in exocentric and aerial viewpoint use in controlling a telerover by allowing subjects to customize the interface before testing. In addition, the use of a natural control, like a joystick, instead of a keyboard and mouse might eliminate additional interface-affects on user performance.

Finally it would be interesting to implement user selectable LOAs, where the user could switch between teleoperated and telerobotic control modes whenever he/she deems necessary. This mode of operation would take advantage of reduced time-to-task completion due to telerobotic control and reduce task performance errors due to teleoperation control. It would also be interesting to investigate how much task processing capability (e.g., collision avoidance) could be integrated into the remote rover in order to reduce the operator workload and the negative impact of lag on performance. This might be dependent upon the complexity of the task and the minimal amount of information required by the user in the control loop in order to take over the system control at times of emergency.

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Appendices

Appendix A

MATHEMATICAL MODEL OF THE SYSTEM

The following mathematical model is adapted from Tipsuwan and Chow (2001).

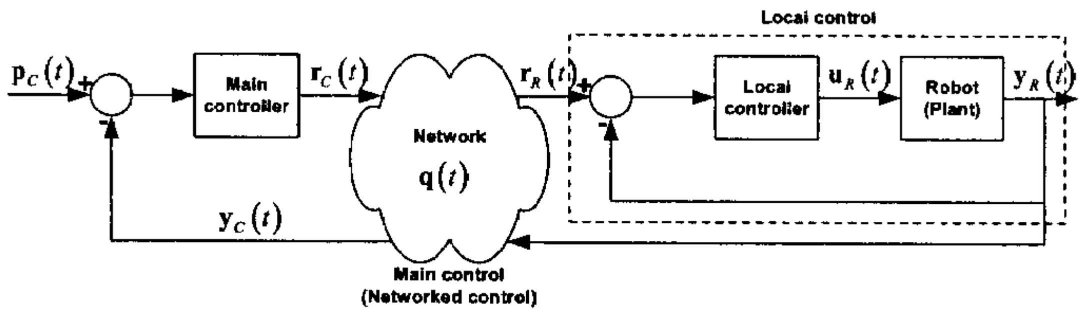

Figure A.1. Block diagram of Main controller and Local controller

QoS Adaptation Scheme

The networked telerover system is shown in figure A-1. The mobile robot state-space is described as follows

$$\dot{x}_R = f_R(x_R, u_R, t)$$

$$y_R = h_R(x_R, u_R, t)$$

where the state vector $x_R = [x_{R1},...,x_{Rn}]^T \in X^n$, the state space; the output vector $y_R = [y_{R1},...,y_{Rn}]^T \in Y^n$, the output space; the input vector $u_R = [u_{R1},...,u_{Rn}]^T \in U^n$, the input space and $t \in R^+$ is the time parameter.

QoS of the network from the main controller to the telerover and vice versa, at time t is defined as $q(t) = [q_1(t),...,q_s(t)]^T \in Q^s$, the network QoS space. We can define $q_1(t)$ as the available bandwidth on the network, $q_2(t)$ as end-to-end delay bound etc. These depend on the characteristics of the network protocols, network topologies, etc.

At every sampling time period t, the telerover packetizes and sends y_R across the network to the main controller. The output measurement after depacketized at the controller is in the form

$$y_C(t) = y_R(t - \tau_{RC}(q)),$$

where $\tau_{RC}(q)$ is the network-induced delay from the telerover to the main controller. The main controller computes the control signal

$$r_C(t) = g_C(y_C, \alpha_C, p_C),$$

where $p_C(t)$ is the reference path and α_C is the adaptation scheme to be selected by the main controller to compensate for deteriorative changes in QoS. When this control signal is sent to the telerover, it receives as

$$r_R(t) = r_C(t - \tau_{CR}(q)),$$

where $\tau_{CR}(q)$ is the network-induced delay from the main controller to the telerover.

The local controller uses the received signal to compute the local control signal during every sampling time as

$$u_R(t) = g_R(y_R, \alpha_R, r_R),$$

where $\alpha_R = [\alpha_{R1}, \ldots \alpha_{Rb}]^T$ is the adjustable local controller parameter vector which can also be used to compensate for changes in QoS. We assume α_R as a pre-calculated vector and use α_C for adaptation.

Quadratic path tracking algorithm

Telerover Dynamics

The dynamics of the telerover is described as

$$\begin{bmatrix} v \\ \omega \end{bmatrix} = \begin{bmatrix} \frac{\rho}{2} & \frac{\rho}{2} \\ \frac{\rho}{W} & \frac{\rho}{W} \end{bmatrix} \begin{bmatrix} \omega_R \\ \omega_L \end{bmatrix}$$

$$\dot{x}_I = v\cos\theta$$

$$\dot{y}_I = v\sin\theta$$

$$\dot{\theta} = \omega$$

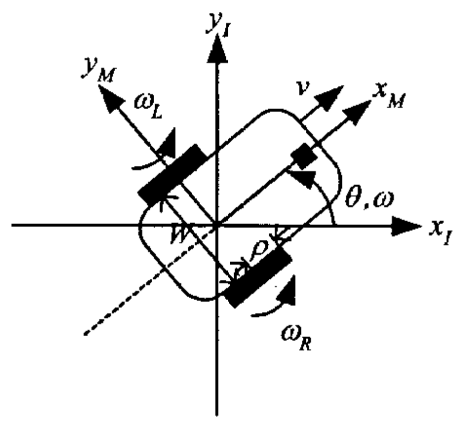

Figure A.2. Differential-drive telerover

where (x_I, y_I) is the position in the inertial coordinates, (x_M, y_M) is the position in the telerover coordinate, θ is the azimuth angle of the telerover, v is the linear velocity of the telerover, W is the distance between two wheels, ρ is the radius of the wheels, ω is the angular velocity of the telerover where ω_L and ω_R corresponds to the left and right wheels respectively.

The state-space description of the telerover is given as

$$\dot{x}_R = \begin{bmatrix} \dot{x}_{R1} \\ \dot{x}_{R2} \\ \dot{x}_{R3} \\ \dot{x}_{R4} \end{bmatrix} = \begin{bmatrix} \frac{\rho}{2}(x_{R4} + x_{R6})\cos x_{R3} \\ \frac{\rho}{W}(x_{R6} - x_{R4})\sin x_{R3} \\ \omega_L \\ \omega_R \end{bmatrix}$$

$$\dot{y}_R = \begin{bmatrix} y_{R1} \\ y_{R2} \\ y_{R3} \\ y_{R4} \end{bmatrix} = \begin{bmatrix} \frac{\rho}{2}(x_{R4} + x_{R6}) \\ \frac{\rho}{W}(x_{R6} - x_{R4}) \\ x_{R4} \\ x_{R6} \end{bmatrix}$$

where $x_{R1} = x_1, x_{R2} = y_1, x_{R3} = \theta, x_{R4} = \omega_L, x_{R5} = \omega_R, u_{R1} = e_a, u_{R2} = e_a$

Telerover Parameters:

The following table gives the parameters of rover such as wheel diameter and wheelbase.

W	Distance between two wheels	0.3 *m*
ρ	Radius of wheels	0.03 *m*

Table A.1 Parameters of telerover

Local Controller

The local controller is two simple Proportional-Integral (PI) controllers, one for each wheel and is defined as

$$u(t) = K_P e(t) + K_I \int_0^t e(\xi)d\xi$$

where K_p is the proportional gain and K_i is the integral gain, $r(t)$ is the reference speed for the motor to track, $y(t)$ is the system output and $e(t)=r(t)-y(t)$. The output $y(t)$ for the left and right wheels are y_{r3} and y_{r4} respectively. Similarly, the input $u(t)$ for the left and right wheels are u_{r1} and u_{r2} respectively. The control gains used to control both motors are set to be same since they are assumed to have identical characteristics.

Main Controller

The main controller computes the control signal for the local controller in the telerover to track a desired path. In teleoperation mode, the controller computes the speed of the motors based on the input given by the user, which are then sent to the local controller.

In the case of telerobotic mode, the user specifies a target location and the controller computes the path-tracking algorithm based on the quadratic curve approach [40] as implemented by Tipsuwan and Chow [39]. This algorithm lends itself suitable for real-time application because of its simplicity in computation with minimal amount of information [39]. The algorithm works as follows:

(1) Setup an initial distance $d_0(k) > 0, k = 0$ between current robot position $x_I = [x_I, y_I, \theta]^T$ and the reference point $p(t) = x_{ref}[x_{ref}, y_{ref}, \theta]^T$. Both positions are in inertial coordinates.

(2) Compute the error $x_{ref} - x_I$ and transform the error into telerover coordinates.

$$e = \begin{bmatrix} e_x & e_y & e_\theta \end{bmatrix}^T = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \left(x_{ref} - x_I \right)$$

(3) Find a quadratic curve between the robot coordinate and the reference point.

$$y = Ax^2, where \qquad A = \mathrm{sgn}(e_x)\frac{e_y}{e_x^2}$$

(4) Compute the reference linear and angular velocities of the telerover along the quadratic curve.

$$v_{ref,k} = K_k$$

$$\omega_{ref,k} = 2A_k K_k$$

$$\omega_{R,ref} = \frac{v_{ref,k}}{\rho} + \frac{\omega_{ref,k}W}{2\rho}$$

$$\omega_{L,ref} = \frac{v_{ref,k}}{\rho} - \frac{\omega_{ref,k}W}{2\rho}$$

where $K_K = sign(e_x)\frac{\alpha}{1+|A_k|}$ and $A = sign(e_x)\frac{e_y}{e_x^2}$.

The result is the control signal $r_c(t) = [\omega_{L,ref}, \omega_{R,ref}]^T$.

(5) Update the distance for the next sampling time.

$$d_0(k+1) = \frac{d_{\max}}{1+\beta|A_k|}$$

where β is the positive constant indicating how far the next reference point is projected ahead, $d_{\max}$ is the maximum distance between reference point and the telerover.

(6) Compute the velocity of the reference point v_{path} along the desired path based on the actual velocity of the telerover, which keeps the distance between the robot, and the reference point.

(7) Compute the new reference point on the desired path based on the current reference point velocity v_{path} and update x_{ref} and repeat the above seven steps.

Network QoS profiles

$q_1(t)$ denotes the point-to-point maximal delay bound of the largest packet and $q_2(t)$ denotes the network throughput bound.

Path tracking performance measures

$$J_1 = \frac{1}{T}\int_0^T \min\left\{\sqrt{(x_I(t) - x_{path})^2 + (y_I(t) - y_{path})^2}\right\} dt$$

$$J_2 = T = \int_0^T dt$$

where (x_{path}, y_{path}) is any point on the pre-computed path and T is the elapsed time. The first relation measures how close the telerover is tracking the desired path and second relation measure how quick the telerover tracks the path.

Appendix B

PRESENCE QUESTIONNAIRE

Indicate your preferred answer by marking an "x" in the appropriate box of each seven-point scale in accordance with the question content and descriptive label. Please consider the entire scale when marking you responses, as intermediate levels may apply.

WITH REGARDS TO THE EXPERIENCED ENVIRONMENT

1. "I felt as though I were actually in the remote environment as I performed the task"

VERY RARELY SOMEWHAT VERY FREQUENTLY

2. "The experience involved unity or fusion of self with the remote environment"

VERY RARELY SOMEWHAT VERY FREQUENTLY

DO NOT WRITE BELOW THIS LINE.

Subject #: ______ Trial #: ______

A p p e n d i x C

SUBJECTIVE COMPARISION OF DEMAND FACTORS: NASA-TLX

Indicate the demand of greater importance by circling its label on each line below.

Mental Demand / Physical Demand

Mental Demand / Temporal Demand

Mental Demand / Performance

Mental Demand / Frustration

Mental Demand / Effort

Physical Demand / Temporal Demand

Physical Demand / Performance

Physical Demand / Frustration

Physical Demand / Effort

Temporal Demand / Performance

Temporal Demand / Frustration

Temporal Demand / Effort

Performance / Frustration

Performance / Effort

Frustration / Effort

DO NOT WRITE BELOW THIS LINE.

Subject #: ______

SUBJECTIVE RATING OF PERCEIVED WORKLOAD: NASA-TLX

Indicate the level of demand experienced during the navigation task for each of these factors by drawing a straight vertical line on the scale directly below.

Mental Demand

Low High

Physical Demand

Low High

Temporal Demand

Low High

Performance

Low High

Frustration

Low High

Effort

Low High

DO NOT WRITE BELOW THIS LINE.

Subject #: ______ Trial #: ______

Appendix D

ANTHROPOMETRICS DATA SURVEY

SUBJECT SURVEY

The intended purpose of this form is to establish a subject profile based on volunteered anthropometrics data. Please complete the sheet to the best of your knowledge following the example formats indicated in the parentheses adjacent to each data field label.

Age (XX yr.): _____ Gender (M/F): ______ Handedness (Left/Right): _____

Corrected Visual Acuity: Left Eye (XX/XX): ____ Right Eye (XX/XX): ____

Video Game Experience	1	2	3	4	5
	None		Occasional		Frequent
PC Experience	1	2	3	4	5
	None		Occasional		Frequent

DO NOT WRITE BELOW THIS LINE.

Subject #: ______

Appendix E

SUBJECT INSTRUCTIONS

I. Introduction

Thank you for volunteering to participate in this experiment. The goal of this study is to examine performance and presence in a virtual environment (VE) as a control interface to a teleoperation system. The experimental task will require you to use a head-mounted display, or HMD. You will control the inputs to the system via a standard mouse and graphical controls as part of visual displays. The virtual task is a high-fidelity 3-dimensional simulation of telerover navigation.

You will be asked to navigate the telerover between obstacles in the VE until you pass/negotiate all of them at least once without collision. The obstacles are cylindrical objects that may be either blue or red in color. During the experiment, you will complete an extensive training session and ten test trials.

Overview of Procedures

The procedures we will follow during the experiment will be executed in one session. You will first experience 3 training trials. A 5-minute break will follow training. You will then complete 10 test trials with the first 5 trials separated from the later 5 trials by a 5-minute break.

An overview of the procedures for the session includes:

1. Introduction to the experiment.
2. Collection of anthropometric survey data.

3. Familiarization with the equipment.
4. Administration of a sim-sickness questionnaire.
5. Familiarization with different types of control displays as part of system interface.
6. Completion of 3 training trials
7. Administration of a sim-sickness questionnaire.
8. A 5-minute break.
9. Familiarization with presence questionnaire.
10. Familiarization with NASA-TLX subjective workload survey.
11. Completion of 5 test trials, each of which will be followed by the presence questionnaire and NASA-TLX subjective workload survey.
12. Administration of sim-sickness questionnaire.
13. A 5-minute break.
14. Completion of the last 5 trials (total 10 trials), each of which will be followed by the presence questionnaire and NASA-TLX subjective workload survey.
15. Administration of sim-sickness questionnaire.

Informed Consent

[Give the subject the informed consent form. Summarize the informed consent for the subject and encourage them to read the form.]

This form summarizes the information that has been presented to you thus far and identifies the persons responsible for the study. The form also addresses University liability to the experiment. I encourage you to read the form. You must sign the form, however, it will not be associated with any of the other survey forms used in this experiment. In order to participate in this study you must have 20/20 or corrected vision, and you must not have a seizure disorder or use a pacemaker. You may experience sim-sickness (or "motion-sickness" like symptoms) from using the HMD, but precautionary measures will be taken to insure your well-being. Please sign and date this form.

[The reason for not allowing persons with seizure disorder or one using a pacemaker to participate in these kind of experiments because of the Electromagnetic field which is found to cause problems to them]

Anthropometric Data Sheet

[Present the subject with the Anthropometric sheet.]

This form asks about your personal characteristics and will serve to verify your qualifications for the study. Please take a few moments to complete the survey. If you have any questions, I will be happy to address them. This form, like the informed consent form, will not be associated with any of the other survey forms used in this experiment.

Payment Sheet

[Have subjects complete the payment forms for participation. Be sure to record the start time.]

This is the payment form that will be used to calculate your compensation for participating in this experiment. Please fill-out the information. Your Social Security number must be included on this form for tax purposes; however, this form will not be associated with any of the other survey forms used in the study. The income you earn from this experiment is taxable and you should report it to the IRS. You will also have an opportunity to win $30 gift certificate to Udupi Indian Restaurant, if you are the best performer among all other subjects in terms of lowest average number of errors and lowest average time to task completion. However, this gift is not taxable.

[Be certain to sign the form at the close the experiment]

II. Familiarization

I will present all instructions to you orally. If you do not understand certain instructions, you will be able to ask questions before completion of each step in the procedure. You may also ask questions about the experiment during the familiarization, training, and rest periods. You will need to follow all instructions carefully.

Equipment Familiarization

The equipment to be used in this experiment includes, a high-performance graphics visualization workstation presenting the virtual environment and task. The system is integrated with a standard keyboard and standard mouse. A HMD will be used to isolate your vision to the VE and to simulate 3-D viewing of the VE.

[Check to see if the subject has any questions about the equipment or setup.]

Simulator Sickness Information

It is possible that you may experience simulator sickness when using the immersive VE displays. Therefore, procedures will be employed to assure your safety and well-being. Please inform us at any point if you begin to experience motion sickness-like symptoms.

In order to determine the possible presence of simulator sickness symptoms, the Simulator Sickness Questionnaire (SSQ) will be administered to you at the beginning of experimental testing, after the training session, and after trials 5 and 10. If your pre-exposure scores on the SSQ indicate that you are not currently in good health, you will not be permitted to continue your participation. If the post-exposure scores indicate that you may be suffering from sim-sickness, the questionnaire will be administered at 20-minute intervals after a trial for up to 1 hour. If scores do not return to pre-test levels within 1 hour after an experiment, you will be advised not to drive a motor vehicle for 24 hours, and a ride will be provided to you. It will also be recommended that you seek medical counsel for "motion sickness-like" symptoms. This first sim-sickness form will be used as a baseline to compare your post-trial scores. Please fill out this form carefully.

[Present the subject with sim-sickness form and let them fill out. Calculate sim-sickness score SimSick.xls on the desktop of computer. If scores exceed criteria, dismiss subject.]

[Read if subject scores exceed criteria.]

Thank you for coming today. This concludes your participation in the experiment. You will be compensated for the time you have spent here.)

[After the training session, and after trials 5 and 10, make subjects fill-out the SSQ form again. Calculate sim-sickness score using SimSick.xls on the desktop of the computer.]

III. Training

[Before completion of the training, explain the various control displays.]

The VE interface to the telerover consists of – a main simulation window displaying the telerover, an aerial display of the telerover and operating environment, *a joystick navigation control display* and a speedometer display, which will show the speed of the rover.

The joystick control is used to navigate the telerover in the environment. Place the cursor on top of the arrow pointing in the direction of the desired navigation. Click the left mouse button to increase the speed and right mouse button to decrease the speed. Five clicks of the left mouse button will throttle the telerover to its maximum speed and five clicks of the right mouse *button will bring the rover to its minimum speed. Place the cursor on top of the red hexagon at the center of the display and press the left/right mouse button to stop the telerover.*

[Show the subjects how the joystick navigation control works]

The aerial map will show the current position and direction of the telerover in the environment.

You will use this display to select the destination position for the telerover to reach/navigate. The destination selection is achieved by moving the cross-wire by clicking and holding down the left mouse button in the required direction. When the left mouse button is released, the corresponding position of the cross-wire in the environment is taken as the target position and rover starts to navigate towards the destination.

The aerial view can be panned by clicking and holding down the right mouse button over the aerial display in the required direction. Also the aerial view can be zoomed in or out by clicking and holding the middle mouse button in the upper half or lower half of the display for zoom in and zoom out respectively.

[Show the subjects how to select the destination, pan and zoom using aerial display]

The speedometer display gives you an idea of how fast the telerover travels in the environment in mm/sec.

As mentioned, you will now complete 3 training trials. This training is provided to allow you to learn the control of telerover. Please utilize the time period to get accustomed with the visual displays. The goal of the task is to successfully navigate the telerover between all the obstacles in the environment much like a slalom ski race. At the start of the simulation, the obstacles will be red or blue in color. Navigating the telerover between a red and blue obstacle will make the blue obstacle turn green in color. A sound cue will also be provided to notify that an obstacle has been cleared. This indicates that you have successfully navigated this obstacle. A blue obstacle may or may not change its color to green even though you navigated between a blue and a red obstacle because each blue obstacle is paired with only one nearest red obstacle. If you collide with any obstacle either blue or red, it will change to black in color. A sound cue will be provided to notify you. You are expected to navigate the telerover through all the obstacles until no blue colored obstacles remain in the environment.

[Setup the computer to run the training trial]

[After completion of the training, make the subject fill out sim-sickness form. Calculate sim-sickness score using SimSick.xls on the desktop of the computer.]

You will now be provided with a 5-minute break.

Telepresence Questionnaire

Now, I will provide you with a brief explanation of the Telepresence Questionnaire, which is intended to assess your association with the virtual task and environment during performance. The telepresence questionnaire will be completed after each trial. It is intended to capture the degree to which you felt as part of the telerover navigation task and environment. I will show you the survey and please read the instructions on the survey so that you will know how to respond to the questions with a rating following the test trials.

[Show the subject the Telepresence Questionnaire and read the statement at the top of a copy of the Telepresence Questionnaire.]

NASA-TLX Subjective Workload Survey:

In order to assess the task workload that you experience during experimental testing, you will complete a subjective comparison of various mental and physical demand factors [*show NASA-TLX demand comparison form*] that you will also rate during task performance. Both your comparisons and ratings of these factors will be used to compute a composite score of workload for the telerover navigation task.

At the end of each test trial, you will be required to complete subjective ratings of perceived workload. You will rate task workload using this form. [*Show hard copy of NASA-TLX*]

You will complete the NASA-TLX form by drawing a straight vertical line on the scale directly below each of the factors indicating the level of demand experienced during the telerover navigation task.

A sheet of descriptions of each of the factors to be rated will be provided. [*Give subject NASA-TLX factor description sheet*.] Please make reference to this sheet when rating the various demands.

Please fill out the demand comparison form by referring to the description sheet.

[Ask the subject to complete the comparison of demand factors referring to the factor description sheet based on the task experienced during the training session]

Do you have any questions?

IV. Experimental Testing

Now we will begin the test trials. The goal of the task remains the same as in training trials, but your task completion time and number of collisions will be recorded. All the obstacles will be placed at random during the start of each test trial.

Now, you will complete 10 test trials in the navigation task that you have trained on.

[Check to see if the subject has any questions.]

Due to the nature of the experiment, keeping your attention focused on completing the task is important. I ask that you refrain from talking during the testing periods. If you have any difficulties, however, please do not hesitate to bring them to my attention and I will assist you.

You will now begin your first test trial.

[Help the subject to put on the HMD.]
[Open and start the simulation for the 10 testing trials. Run the subject through test conditions in random order, according to the condition form for the trial.]

[Have subject complete presence questionnaire after each test trial.]

[Also have subject complete SSQ (after trials 5 & 10). Calculate sim-sickness score using SimSick.xls on the desktop of the computer.]

[Allow subject a 5-minute break between the trials 5 and 6.]

1. *Calculate sim-sickness score after subject has completed the SSQ form (after trial 5 and trial 10).*
2. *If sim-sickness score <= pretest score, skip step 3.*
3. *If sim-sickness score is higher than pre-test score, have subject wait for 20 minutes.*
    a. *After 20 minutes, give sim-sickness test again.*
    b. *(This sequence may be repeated for an hour. If scores are not back to normal after an hour, dismiss subject.)*

[Read if subject sim-sickness scores do not return to pretest levels.]

Thank you for coming today! This concludes your participation in the experiment. You will be compensated for the time you have spent here.

[Give subject instructions for obtaining payment. Calculate their total payment and instruct them to go to Riddick to collect their money.]
[Set up next trial.]

[After the completion of 10 trials, ask the subject to fill out Simulator sickness questionnaire and presence questionnaire. Check to see if the subject's SSQ score is within permissible limits. If so, then direct the subject on obtaining payment. Else follow the sim-sickness recovery procedure]

Appendix F

INFORMED CONSENT FORM

I hereby give my consent for voluntary participation in the research project titled, "The effects of gain adaptation on QoS deterioration on Internet-based teleoperation using virtual reality interface". I understand that the person responsible for this project is Dr. David B. Kaber, who can be telephoned at (919) 515-3086. He or one of his authorized assistants, Mohamed Sheik Nainar, has explained to me the objective of the study is to investigate the effects of QoS adaptation on user performance and presence in a Internet-based teleoperation scenario using a VR interface. Dr. Kaber, or one of his authorized assistant, Mohamed Sheik Nainar, have agreed to answer any inquiries I may have concerning the procedures of the research and have informed me of my right to refuse to answer any specific questions asked of me. He or his authorized assistant has also informed me that I may contact the North Carolina State University (NCSU), Institutional Review Board for the Protection of Human Subjects by writing them in care of Dr. Matt Zingraff, Chair of IRB, Research Administration, NCSU, 1 Leazar Hall, Box 7514, Raleigh, NC 27695, or by calling (919) 515-2444.

Information concerning compensation for my participation in this study has been explained to me as follows: (1) I will receive $7.50 per hour for each hour of my participation in the experiment. (2) I also have the opportunity to win a $30 gift certificate, if I achieve the overall best performance of all subjects in the experiment. (3) In the event that I choose to terminate my participation in the experiment, I will be paid for only the time I have provided. (4) The researchers for the study have the right to terminate my participation if I am not cooperative or I experience discomfort or fatigue.

Dr. Kaber or one of his authorized assistants has explained to me the procedures to be followed in this study and the potential risks and discomforts. In summary the procedures include: (1) an equipment familiarization period; (2) a sim-sickness questionnaire; (3) an extensive training session to learn and practice the control displays and features of the VR navigation task; (4) 10 test trials with the VR interface using a head-mounted display (HMD); (6) and a debriefing on the study. All training and testing will be conducted during a single experimental session that will require approximately 3 hour of my time.

The risks have also been explained to me, as a potential exists for visual strain and/or fatigue in viewing the virtual environment displays through immersive displays including the HMD and desktop VR display. These risks are not substantially different from those associated with my everyday PC use. In the event that I experience fatigue or discomfort, I will inform the experimenters immediately. In addition, I will be tested for motion sickness symptoms before and after the experiment. I understand that if the symptoms have not dissipated after 1 hour, I will be advised not to drive a car for 24 hours and a ride will be provided.

I understand that if this research project results in any physical or mental harm to me, treatment is not necessarily available at the NCSU, Student Health Services, nor is there necessarily any insurance carried by the University or its personnel applicable to cover any such injury. Financial compensation for any such injury must be provided through my own insurance program. Further information about these matters may be obtained from the Institutional Review Board at (919) 515-2444, 1 Leazar Hall, NCSU Campus.

I understand that I will not derive any therapeutic treatment from my participation in this study. I understand that I may discontinue my participation in this study at any time without prejudice. I understand that all data will be kept confidential and that my name will not be used in any reports, written or unwritten. I have received a copy of this consent form for my personal records.

Signature of Subject: ______________________ Date: ______________________

Signature of Authorized Representative:

____

Appendix G

SIMULATOR SICKNESS QUESTIONNAIRE

Instruction: Circle the items that apply to you RIGHT NOW.

SYMPTOM	RATING			
General Discomfort	None	Slight	Moderate	Severe
Fatigue	None	Slight	Moderate	Severe
Headache	None	Slight	Moderate	Severe
Eye Strain	None	Slight	Moderate	Severe
Difficulty Focusing	None	Slight	Moderate	Severe
Increased Salivation	None	Slight	Moderate	Severe
Sweating	None	Slight	Moderate	Severe
Nausea	None	Slight	Moderate	Severe
Difficulty Concentrating	None	Slight	Moderate	Severe
"Fullness of the Head"	None	Slight	Moderate	Severe
Blurred Vision	None	Slight	Moderate	Severe
Dizzy (eyes open)	None	Slight	Moderate	Severe
Dizzy (eyes closed)	None	Slight	Moderate	Severe
Vertigo	None	Slight	Moderate	Severe
Stomach Awareness*	None	Slight	Moderate	Severe
Burping	None	Slight	Moderate	Severe
Other. Please describe.				

* "Stomach Awareness" is usually used to indicate a feeling of discomfort, which is just short of nausea

DO NOT WRITE BELOW THIS LINE.

Subject #: ______ Base/Training/Trial 5/Trial 10