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An Augmented Interaction Strategy for Designing Human-Machine Interfaces for Hydraulic Excavators

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A dissertation submitted to the graduate faculty
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School of Graduate Studies
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This is to certify that the Doctoral Dissertation of

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Greensboro, North Carolina
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Biographical Sketch

Joseph Owusu-Banahene Akyeampong was born on June 6, 1985, in Accra, Ghana. In June 2007, he received a Bachelor of Science degree in Mechanical Engineering from Kwame Nkrumah University of Science & Technology (Kumasi, Ghana), graduating with First Class Honors. Upon graduating, he completed a one-year mandatory national service at his alma mater as a teaching assistant in the Mechanical Engineering Department. Immediately following, he won a scholarship to study in a Ph.D. program in Industrial & Systems Engineering at North Carolina Agricultural and Technical State University (Greensboro, NC, USA), starting in August 2008.

During his tenure as a graduate student, he has worked both as a teaching and research assistant in the Department of Industrial and Systems Engineering. He is the recipient of numerous awards including the: Creativeness in Ergonomics Student of the Year Award (2013), E. Wayne Kay Scholarship (2012), Thurgood Marshall Scholar Award (2011), Italian Machine Tool and Technology Award (2011), Outstanding Teaching Assistant Award (2010), and Alpha Pi Mu National Excellence Award (2009). He is also affiliated with several professional associations including the: Institute of Industrial Engineers, Human Factors & Ergonomics Society and Society of Manufacturing Engineers. Joseph has an avid passion for leadership and has served in several leadership positions. He was the President of the Society of Manufacturing Engineers North Carolina A&T Student Chapter for the 2010/2011 academic year.

Joseph's doctoral studies culminated into the production of this dissertation and 10 scholarly publications including peer-reviewed articles and white papers. Upon completing his PhD, he plans to pursue careers in areas including but not limited to academia, industry, and consulting.

Dedication

This dissertation is dedicated to the memory of my father, the late Peter Mieh Akyeampong, whose parenting has shaped me into the individual I am today. May his soul reset in perfect peace.

I also dedicate it all my family members and friends who have always supported me in my endeavors and encouraged me to pursue my dreams. May God richly bless you.

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Abbreviations

AR	Augmented Reality
D.IV.E	Design, Implementation/Visualization, Evaluation
HEARS	Hydraulic Excavator Augmented Reality Simulator
HMI	Human-Machine Interface
MR	Mixed Reality
NASA TLX	National Aeronautics and Space Administration Task Load Index
SPQ	Subjective Preference Questionnaire
VR	Virtual Reality
E_c	Number of collisions
E_m	Number of misses
O_{pc}	Total number of opportunities for collisions
O_{pm}	Total number of opportunities for misses
O_{ER}	Operating error
P_{ER1}	Error probability of collisions
P_{ER2}	Error probability of misses
R	Ratings
μ	Mean
TCT	Task completion time
W	Weights

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Abstract

Lack of adequate information feedback and work visibility, and fatigue due to repetition have been identified as the major usability gaps in the human-machine interface (HMI) design of modern hydraulic excavators that subject operators to undue mental and physical workload, resulting in poor performance. To address these gaps, this work proposed an innovative interaction strategy, termed "augmented interaction", for enhancing the usability of the hydraulic excavator. Augmented interaction involves the embodiment of heads-up display and coordinated control schemes into an efficient, effective and safe HMI.

Augmented interaction was demonstrated using a framework consisting of three phases: Design, Implementation/Visualization, and Evaluation (D.IV.E). Guided by this framework, two alternative HMI design concepts (Design A: featuring heads-up display and coordinated control; and Design B: featuring heads-up display and joystick controls) in addition to the existing HMI design (Design C: featuring monitor display and joystick controls) were prototyped. A mixed reality seating buck simulator, named the Hydraulic Excavator Augmented Reality Simulator (H.E.A.R.S), was used to implement the designs and simulate a work environment along with a rock excavation task scenario. A usability evaluation was conducted with twenty participants to characterize the impact of the new HMI types using quantitative (task completion time,TCT; and operating error,O_{ER}) and qualitative (subjective workload and user preference) metrics. The results indicated that participants had a shorter TCT with Design A. ForO_{ER}, there was a lower error probability due to collisions (P_{ER1}) with Design A, and lower error probability due to misses (P_{ER2}) with Design B. The subjective measures showed a lower overall workload and a high preference for Design B. It was concluded that augmented interaction provides a viable solution for enhancing the usability of the HMI of a hydraulic excavator.

CHAPTER 1

Introduction

Hydraulic excavators are a class of heavy mobile equipment with a unique human-machine interface (HMI). The contemporary hydraulic excavator HMI design is rife with a number of interaction problems related to ease of use and safety, which includes inadequate information feedback and work visibility, and fatigue due to repetitive use of the joystick controls. Historically, the design evolution of the hydraulic excavator HMI, albeit appreciable, has been slow compared to other vehicle applications like automobiles and airplanes. Unlike the hydraulic excavator, HMI design in these other vehicles is a work of art with a lot of innovation, and great consideration for the user. As a result, in automobiles, for example, innovation has led to the development of HMIs that feature a display with multiple menu selection items, touch screen interface, voice recognition, electronic storage for data logging, and global positioning system (GPS) among others. Also methods for incorporating haptic interfaces and reducing visual distraction have been introduced as a means of transmitting large amounts of disparate information concisely to the driver. Hydraulic excavators, on the other hand, have maintained a basic HMI architecture that is limited to a monitor display, a pair of joystick controls and motion control levers/pedals. This machine works in data-rich environments (with large amounts of information that need to be processed) and operators are constantly subjected to undue amounts of mental and physical workload. Therefore, the operator's ability to process and rapidly assimilate all the relevant information for effective job performance becomes essential, calling for the need to design a more usable HMI for enhancing the operator's job performance and improve safety.

Usability is the quality of a user’s experience. The important role usability plays in enhancing job performance cannot be over-emphasized. It is an important aspect of human-machine interaction which seeks to facilitate the design of interfaces that minimize the barrier between the human's cognitive model of what they want to accomplish and the system’s understanding of the user’s task goals (Boy, 2011). For a HMI to be usable, it must be useful, efficient, effective, satisfying, learnable, and accessible (Rubin & Chisnell, 2008).

To illustrate the importance of usability, let us consider the example of the mobile phone. In recent years, the mobile phone has become a ubiquitous device, and an integral part of almost every individual’s life. It could be described as an extension of one’s hand. So one may ask: why has the mobile phone become such an important aspect of life today? There may not be a single answer to this question but a more general one will be that it provides several resources that allow for voice and data communications wirelessly. By so doing, it acts as an agent that supports many real-time facets of an individual’s life. Today, the mobile phone market is flooded with phones of all kinds including standard mobile phones, feature phones and smartphones. The number of possible uses of these phones is endless. You can interact with the phone to exchange information with others via text messages, voice/video calls, and email; shop online; use it as a navigator; and setup appointments to mention a few. Such interaction is made possible via a powerful interface that features the high resolution touch screen for visual information input and output, a mouthpiece and earpiece for voice input and output respectively, a vibrate alert, web browsers, applications (or apps), integrated digital cameras, blue tooth, high speed data access via Wi-Fi, and GPS navigation. In spite of all the multimedia capabilities of the phone, the factors that influence a user’s choice of phone are: its ease of use and how it affects the user’s productivity (Kiljander, 2004) – which are simply delivered by the user interface or

HMI. A good example of a smartphone with a usable HMI can be found in the Apple iPhone^{TM}. The iPhone^{TM} is based on capacitive technology, and offers enhanced usability through an elegant user interface that delivers superior functionality and productivity.

Owing to the problems identified with existing hydraulic excavator HMIs, the question of how to properly design more usable HMIs with innovative information visualization and interaction schemes that makes operators of hydraulic excavators more productive has received attention from researchers in the past few years. This work proposes an innovative interaction strategy, termed augmented interaction, as a solution for addressing this question. This section, therefore, discusses the background into a hydraulic excavator's HMI and how it influences an operator's job performance and then based on the background information; the research problem, existing gaps, the newly proposed interaction strategy and its relevance are discussed. Also, the research objectives are stated, and how this dissertation is organized is presented.

1.1 Background

Fluid power systems are systems that employ pressurized hydraulic and pneumatic fluids to perform work, which is typically accomplished by means of a piston pushing against the fluid directly on an operating cylinder. A prime example of a fluid power application is the hydraulic excavator, which belongs to a family of vehicles - including bulldozers, scrapers, wheel loaders and dump trucks - popularly referred to as heavy mobile equipment. Due to its flexibility and utility, the hydraulic excavator is a machine that is typically found working on almost every residential and commercial construction, mining, water and sewer, and farm project. The external structure of a hydraulic excavator, shown in Figure 1.1 (Hitachi Construction Machinery America, 2004) consists of an upper carriage made up of the cab, swing, engine, hydraulic pump and motors; an under carriage that uses tracks or wheels for motion; and a front manipulator comprising of the boom, arm (sometimes referred to as the stick), and a bucket attachment for performing work. The boom, arm and bucket are actuated by hydraulic cylinders. The cab serves as the operator's workstation and houses the HMI which allows the human operator to interact with the machine.

Figure 1.1. The hydraulic excavator.

Over the years, the technologies applied to hydraulic excavators have continued to evolve to allow for more efficient, effective and safer operation. An important aspect that is part of this on-going transformation is the HMI. The HMI, described as the brains of the machine by Tatum, Vorster, and Klingler (2006), serves as a control and information system that enables the operator to direct and control all the other system functions. It also provides information about the performance and health of the machine. It influences the ability of the operator to input information to the machine, to receive and understand information outputs, and to monitor the state of the system. While maintaining the same basic architecture of a single seater cab with a set of joystick controls and a monitor display, the HMI has undergone an appreciable transformation in recent years with the integration of new technologies. Gone are the days when the operator sat in an open air pedestal seat and used mechanical (non-power assisted) controls, while occasionally checking a set of mechanical gauges which were limited to oil pressure, temperature and voltage/amperage. In contrast, today's hydraulic excavators come with air-conditioned, heated, radio-equipped cabs with power-assisted hydraulic and electronic pilot controls, and electronic clusters, with optional working modes that match power supply to demand (Boyanovsky, 2005). The current state-of-the-art design of a modern hydraulic excavator HMI (Figure 1.2) primarily features a set of pilot-operated joysticks, a monitor display, travel levers and pedals, and operator seat; as well as auxiliary buttons, levers and switches for controlling secondary functions such as the temperature, and safe-locking the machine. While this is the standard form, some advanced forms integrate work guidance and telematics technologies into the HMI. The joysticks which are the most utilized elements control the front manipulator. A common control sequence is the Society of Automotive Engineers' (SAE) pattern wherein the left joystick controls the raising/lowering of the boom (up/down movements of joystick) and the rotation of the swing (right/left movements of joystick); and the right joystick controls the raising/lowering (up/down movements of joystick) of the stick and the opening/closing of the bucket (right/left movements of joystick).

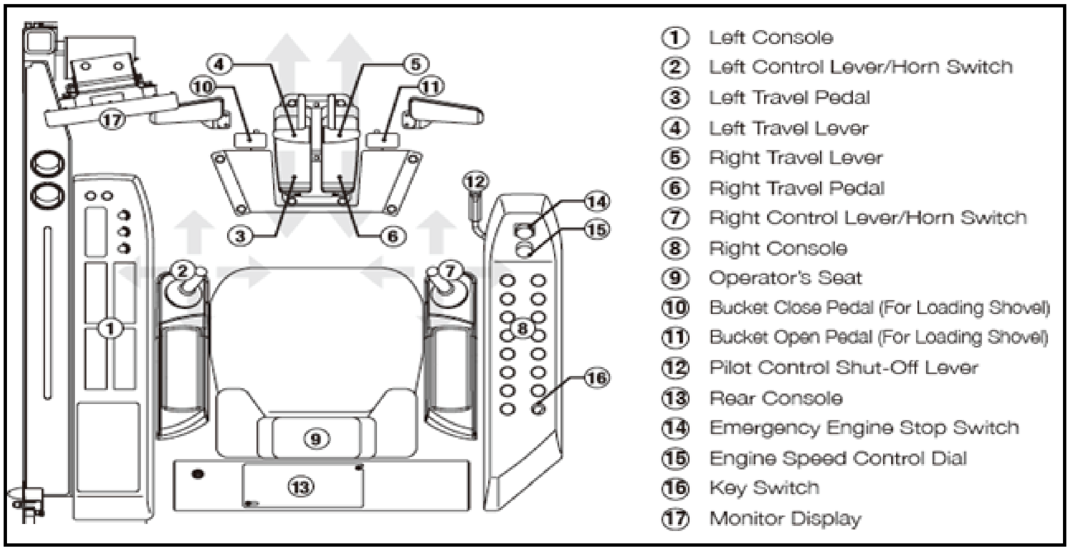


Figure 1.2. Modern standard hydraulic excavator HMI.

1.2 Problem Statement

While a hydraulic excavator's HMI may appear to be simple, it presents one of the most complex forms of human-machine interaction. Operators must interact with an HMI that is not well conceived – to the extent that it requires significant amounts of effort to use, intense task concentration and high skill level. The operator by having to combine displayed information with moving a pair of controls and transferring such actions into reality becomes subjected to increased amounts of mental and physical workload. Mental workload stems from factors such as lack of adequate information feedback and poor work visibility. Physical workload arises from awkward postures due to the layout of the interface elements (controls and seating) and repetitive movements with the joysticks.

The sources of these workloads come into sharp focus by analyzing the operation of the HMI via a control loop (Figure 1.3). The system components are the operator and the HMI which is equipped with the monitor display and joystick control elements. The most common task that hydraulic excavators perform is excavation. This typically involves a series of dig and dump cycles from one location of the worksite to another or the filling of another mobile heavy equipment like a dump truck with excavated material. To accomplish the excavation task, the operator manipulates the joystick controls and occasionally checks the monitor display for system status information. During this process, the operator sitting in an erected posture in the cab encounters many dynamic variables. The operator first receives information by sensing elements within an unstructured work environment characterized by a heterogeneous terrain (muddy/rock, clay etc.), exhaust gases, ambient noise and the presence of obstacles. For instance, obstacles may present apparent (e.g. visible structures) or hidden hazards (e.g. underground lines) while working. Such information must be perceived, assessed, and the right decisions made. The perceived information is then translated to the system for selection (input) and execution of a response (output). The input provided by the operator results in an output that must be verified by the operator and adjusted based on the system feedback received. For example in situations such as performing deep cuts and working around underground structures where there is much uncertainty and visibility is occluded, the existing HMI elements become limited in providing the information needed by the to successfully accomplish the task. Under such working conditions, the operator gets subjected to high mental and physical workloads that negatively impact performance.

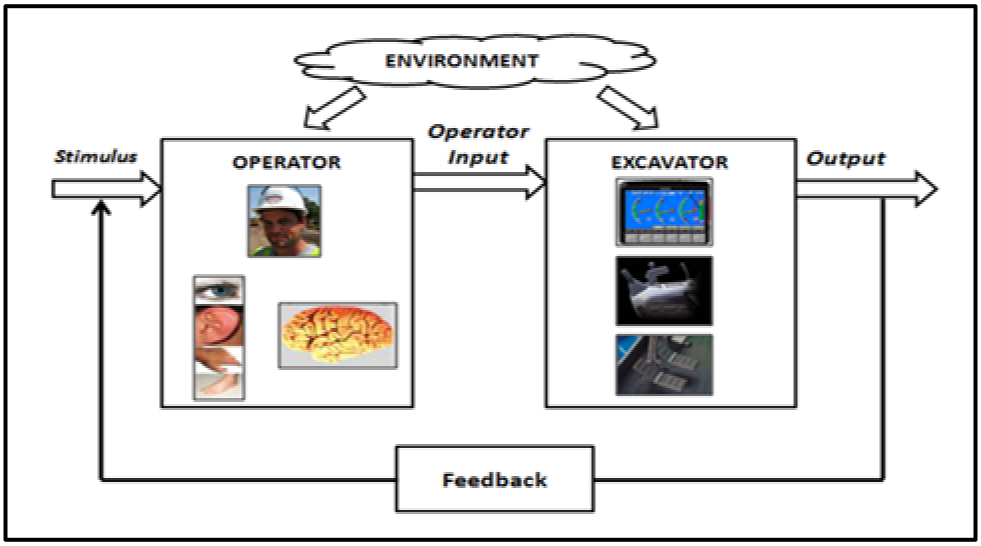


Figure 1.3. Hydraulic excavator HMI control loop.

The mental and physical workload factors (lack of adequate information feedback, poor visibility, and repetition) thus reveal the presence of gaps in the design of the HMI. The existence of such design gaps can be attributed designers' inclination to a particular design solution (i.e. monitor display/joystick HMI) and an incomprehensive analysis of user and system. Such inadequate design by designers decreases the usability of the HMI by making it less efficient (i.e. long operating hours), less effective (i.e. high operating errors) and less safe (i.e. more awkward postures), which results in poor operator performance.

Without adequate means to capture and present the critical information needed by the operator to accomplish the task, as well as provide an easy means of control, the operator’s workload will continue to increase thereby decreasing performance. Thus, in order to keep the increasing amount of information easily accessible and also to minimize the operator’s workload, advanced information presentation and interaction strategies become essential.

1.3 Research Gap

Excavation work processes can be complex for operators due to the unstructured nature of their environment and demands of attentional resources needed to translate huge amounts of perceived information into the right system input in order to obtain the desired system output. Unfortunately, despite significant improvements that have been made in the design of the HMI over the years, substantial usability gaps still persist in current HMI designs. These have been identified as lack of adequate information feedback, inadequate visibility that induces intense task concentration and high skill deployment, and over exertion and fatigue caused by repetitive movements of the controls. In this research, it is hypothesized that operator performance is significantly influenced by the type of interaction provided via the HMI. Thus, the question that remains to be answered is:

- How do we design a more usable HMI for a hydraulic excavator that provides job-critical information, adequate work visibility and an effective means of control in order to reduce mental and physical workload, and thereby enhance both operator and system performance?

1.4 Proposed Solution: Augmented Interaction

There have been a number of recent research efforts geared toward solving some of the aforementioned HMI design gaps (i.e. lack of adequate information feedback), in the form of testing new control strategies that provide haptic feedback (Elton, 2009; Hayn & Schwarzmann, 2010). This has contributed a third modality, which provides an additional force feedback informational cue to support task performance. While this is a significant step in the HMI design improvement effort, much was still left to be done as there were still some potential sources of improvement for addressing the design gaps. This research seeks to complement previous efforts in overcoming the HMI design gaps. Whereas previous work focused solely on control strategies, this research adopts a holistic approach to the problem. It extends the solution to the problem by proposing an innovative interaction strategy, termed "augmented interaction," which solves the design gaps in both the display and control aspects of the HMI. Augmented interaction seeks to use innovative display and control schemes to provide additional job-critical information to operators to enable them to easily execute their task goals successfully. To exemplify this interaction strategy, an alternative, futuristic HMI concept was envisioned. This HMI embodies an advanced display in the form of a heads-up display and a control scheme in the form of a coordinated control device (the phantom) to provide an efficient, effective, intuitive and safe operational concept for the next generation of hydraulic excavators.

1.5 Research Objective and Scope

1.5.1 Objective. This research proposes an innovative interaction strategy, augmented interaction, for designing an improved and more usable HMI for a hydraulic excavator. The objective the research is, therefore, to assess the viability of using heads-up display and coordinated control schemes as a futuristic HMI concept to enhance the usability of a hydraulic excavator towards achieving gains in operator and system performance.

1.5.2 Scope. The augmented interaction strategy was guided by a framework comprising of three phases – Design, Implementation/Visualization, and Evaluation (D.IV.E). Based on this framework, the scope for this research was defined using the three phases as follows:

1. Design Phase: Employ a user-centered design process supported by hierarchical task analysis to guide the design of alternative HMI designs for a hydraulic excavator.
2. Implementation Phase: Develop a mixed reality simulator to implement the designs.
3. Evaluation Phase: Conduct a usability study to quantitatively and qualitatively evaluate the relative usability of the alternative HMI designs against the current HMI design.

1.6 Organization of Dissertation

This dissertation is divided into ten chapters. It starts with a general introduction and then moves on to cover specifics in the remaining parts. The following sections briefly describe what you will find in each chapter:

Chapter 1 provides a general introduction of the research, a brief background about hydraulic excavators, the research problem, the research gap, the proposed solution, and the research objective and scope.

Chapter 2 presents a review of relevant literature. It starts with an overview of fluid power applications, followed by a detailed state-of-the-art review of hydraulic excavator HMIs, and then continues with a review of mixed reality, the technology that used to implement the proposed solution strategy. This was followed by a review of related work.

Chapter 3 outlines the research methodology. This chapter is divided into sections which describe the research approach (or framework), the unit of analysis, the apparatus, the experimental design procedures, and the ethical practices applied in conducting the research.

Chapters 4 through 6 detail the three-phase research framework with which the augmented interaction design strategy is demonstrated. These three phases are: Design, Implementation/Visualization, and Evaluation. Chapter 4 covers the Design Phase, which explicates a user-centered design process for specifying new requirements from which two alternative HMI design concepts based on augmented interaction were obtained in addition to the standard HMI design, yielding three candidate HMIs. Chapter 5 focuses on the Implementation Phase, which involves the development of a mixed reality seating buck simulator, named the Hydraulic Excavator Augmented Reality Simulator (H.E.A.R.S), for prototyping the candidate HMIs, and providing the platform for evaluating them. Chapter 6 covers the Evaluation Phase, and presents a usability evaluation aimed at investigating the relative usability of the three candidate HMIs. The sections detailed in this chapter include: the usability metrics, both quantitative (task completion time and operating error) and qualitative (subjective workload ratings and subjective preference rankings); the usability testing methodology; the experimental design; and the data collection and analyses procedures.

Chapter 7 presents the results derived from the usability study conducted in the Evaluation Phase. The results presented are based on the quantitative and qualitative outcomes of the usability study.

Chapter 8 provides a discussion on the significance of the augmented interaction design strategy, and a discussion of the results of the usability study and how well the research objectives were met.

Chapter 9 concludes the research. It presents a summary of the research, the research contributions made, the research limitations and recommendations for future work.

CHAPTER 2

Literature Review

In this chapter, account is given on the relevant literature related to this research. It starts with a broad definition of fluid power systems, and then focuses the discussion on the hydraulic excavator, providing a historical overview of its product development and new forms. Next, the design evolution of hydraulic excavator HMIs to provide an understanding of the previous, current and future changes in the HMI design. Following this, the relevant literature explaining the techniques of the HMI design strategy that this research will use to address the research question are presented. Thereafter, previous efforts made by other researchers in an attempt to answer the research question are summarized. In the last section, their shortcomings are highlighted and the focus of the current research is presented. Light is shed on how the research gap, as well as the shortcomings highlighted in previous work would be bridged.

2.1 Fluid Power Systems

Fluid power is a technology that deals with the generation, control, and transmission of power using pressurized fluids. Fluid power is generally used to describe pressurized hydraulic and pneumatic fluids. Hydraulic systems employ liquids such as petroleum oils, synthetic oils, water and molten metal, but petroleum oils are widely used. Pneumatic systems use gases, mainly air, as the medium for transmitting power. Fluid power systems are designed specifically to perform work, which is generally accomplished by means of a piston pushing against the fluid directly on an operating cylinder, thereby creating the pressure or power needed to do the work. In addition, there are control components that ensure that the work is done accurately, efficiently and safely. Fluid power is versatile and spans a wide range of work applications including automobile steering and braking systems, airplanes and spacecraft, machine tools, food processors, and earthmoving machines (Esposito, 1997). A prime example of fluid power technology in mobile applications is the hydraulic excavator, which is the focal point of this research. The hydraulic excavator uses fluid power to push, pull, regulate and drive systems components via pumps, valves and cylinders to accomplish tasks such as digging, leveling and material handling.

Fluid power and electrical power are the two main competing technologies for transmitting power in mobile applications. However, fluid power transmission has important competitive advantages over electric power. These include: accuracy and ease of control; higher power to weight ratio for actuation; multiplication of force; higher forces or torques; continuously varying transmission; and simplicity, safety and economy (Center for Compact and Efficient Fluid Power, 2011; Esposito, 1997). Some drawbacks of current fluid power systems are component and system inefficiencies, energy storage density, limitations in currently available compact power supplies, and unresolved environment issues such as leakage and noise. These weaknesses are the fundamental barriers that have created the need to transform fluid power systems so that they can become more compact, efficient and effective. Transforming fluid power systems promises to provide benefits including: a substantial reduction in energy consumption, creation of new scale fluid power devices, enhanced precision and safety, cost savings, and a reduction in carbon emissions. For the hydraulic excavator in particular, such transformation includes improvements in hydraulic system operation through the integration of advanced component and system designs, as well as developing effective control strategies via HMIs that make work processes more manageable for the operator (Center for Compact and Efficient Fluid Power, 2011).

2.2 The Hydraulic Excavator: A Fluid Power System

The heavy mobile equipment sector is one of the largest fluid power application areas. This sector makes heavy machines which include bulldozers, loaders, excavators, dump trucks, tractors, scrapers, and compactors that are commonly used in industries such as construction, agriculture, mining, and forestry for digging and leveling operations, material handling, heavy lifting, and demolition. Fluid power in the form of pressurized liquids (hydraulics) is the technology of choice in these machines due to its ability to exert large forces and torque relative to their size and weight (Center for Compact and Efficient Fluid Power, 2011; Nichols, 1976). The hydraulic excavator is one of the most common types of heavy mobile equipment and represents the largest vehicle sector of construction, agricultural and forestry equipment market. It also has one of the most expansive ranges of sizes of heavy mobile equipment, ranging from small (20,000 to 50,000 lbs.) through medium (50,000 - 80,000 lbs.) to large (80,000 lbs. and bigger) (Zubko, 2007).

The hydraulic excavator is capable of performing a wide variety of complex tasks such as trenching, scooping, leveling, material handling, heavy lifting, demolition and so on. This is accomplished by using hydraulic fluids to provide the power for actuating the working parts – mainly, the boom, arm/stick, bucket and swing (Haddock, 2002).

The hydraulic excavator is a multipurpose machine and can be used differently by changing the bucket attachment. It can be used with a ripper attachment to cut big trees, with a crusher attachment to cut steel or concrete, with a cutter attachment to mow grass and also with a drill attachment to make deep holes into the ground (Kikki's Workshop, 1997).

2.2.1 History of product development and new forms. Hydraulic excavators are the most flexible machine in the earthmoving machinery product family, which makes them one of the most useful machines in their industry (Zubko, 2007). Even though their basic function has remained unchanged for decades, the technologies applied to them have changed remarkably in recent years (Boyanovsky, 2005). A number of authors have documented the major technological advancements that have been made in various earthmoving machines including the hydraulic excavator. These documented works include historical reviews of each type of equipment from its early developmental years (Caterpillar, 2004; Cohrs, 1995; Haddock, 2002; Heycraft, 2000); analysis of the market conditions and innovations leading to the creation of new forms (Tatum et al., 2006); details of the work they perform, detailed descriptions of their technical design and operation, and their management (Nichols, 1976); system analysis of their technical advancement (Tatum et al., 2006); transition from sustaining (cable) to disruptive (hydraulic) technology (Christensen, 1997); and metrics for analyzing changes in technology on productivity and costs (Goodrum & Haas, 2004; Rossow, 1977).

Haddock (2002) describes the history of product development for sixteen types of earthmoving equipment. A wide variety of examples of each type of machine offered by some pioneering and new manufacturers in the industry are highlighted to illustrate their early development and the innovations that have led to the new forms we see today. He pointed out that the world's first hydraulic excavator was developed in the late1940s, simultaneously in France, Italy and the United States. This first prototype of a wheeled excavator was introduced in 1948 in Turin, Italy, followed by several prototypes in 1950. The 1950s were the pioneering years and saw the popularity of this new piece of equipment leap; many manufacturers ventured into the industry and further wheeled and crawler excavators were developed. The 1960s saw the development and rapid growth of the hydraulic excavator with the evolution of more reliable hydraulic systems. By the end of the 1960s, the hydraulic excavator had replaced its predecessor, the cable excavator, and graduated into the designs we see today. The advent of new technologies took hold from the 1970s and machines with relatively higher efficiencies, easier operation and expansive sizes were developed.

The innovations and technological advancements of five new forms of earthmoving equipment including the track-type tractor, the off-highway truck, the wheel tractor scraper, the hydraulic excavator, and the loader-backhoe were neatly analyzed by (Tatum et al., 2006). For each of the five new forms, the analysis of the new form considered the markets and the state of technology at introduction, the differences of the new form, and changes during subsequent development. They explained that the reconstruction of Europe and Japan after World War II prompted significant efforts into the development of the hydraulic excavator. In the USA, massive infrastructure and construction projects including water projects from the early 1900s to the 1950s; mining projects from the 1850s to the 1990s; and intense highway construction from 1955 to 1965 created the demand for hydraulic excavators. The cable excavator (also known as cable shovel) was originally the leader in the earthmoving since it provided the advantage of large excavation. Utility and residential contractors working with small excavation quantities and in constrained spaces created a new market for the hydraulic excavator. As hydraulic technology improved, it met the needs of the contractors who were the purchasers of cable excavators, and took over the market. The authors also noted that there have been remarkable changes in the basic machine form between the earlier and current hydraulic excavators since they disrupted the cable excavator market. Some of the significant changes were made to: the traction system (e.g. wheeled models); the structure and suspension components (e.g. articulated frames, high pressure piston hydraulic pumps, and attachment capability for multiple implements); the power train (e.g. turbocharged engine, and power shift transmission); and the control and information systems (e.g. electro/hydraulic and GPS blade control, and equipment monitoring).

2.3 Hydraulic Excavator HMI Design Evolution

In the early days, hydraulic excavators used levers and linkages to control hydraulic functions. They have now evolved to use primarily pilot controls and manufacturers have continued to make small, but significant, improvements (Zubko, 2007). Needless to say, HMI design for hydraulic excavators has been industrial art; it was only in the past decade that HMI design in the heavy mobile equipment industry began to attract some attention from members within the research community. This has been driven by the need for more advanced forms of interaction to enhance operator and system effectiveness. Thus, the evolution of the HMI has been a gradual one with only slight design changes which are mostly in the form of enhanced control strategies. To track the design evolution of the HMI, some past, current and future HMI designs efforts were explored. These have been grouped and reviewed under three categories of work, namely: earlier HMI designs, current state-of-the art, and emergent and future HMI designs.

2.3.1 Earlier HMI designs. The HMI in earlier hydraulic excavators were complicated and offered no consideration for the operator. They were characterized by less intuitive mechanical controls and displays which resulted in complex interactions between the operator and the system, and this presented several challenges relating to operator and system safety, efficiency, and comfort. The characteristics of control and display designs that were common in some of the earlier hydraulic excavator systems are presented subsequently.

2.3.1.1 Control. The earlier designs offered a bewildering set of controls which were mechanically connected by cable or rod-and clevis linkage to a valve that it operates. They came in different arrangements of levers, pedals and buttons, tied directly to the valves they operated. The hand levers were usually self-centering, the pedals were spring returned, the propel/travel levers had a detent to hold it in full-on position and so on. A typical arrangement of backhoe controls in earlier systems is shown in Figure 2.1.

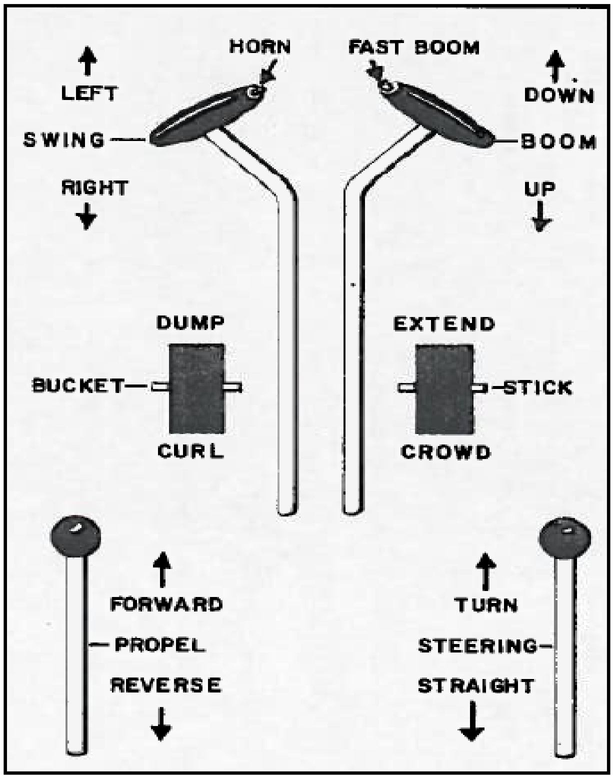


Figure 2.1. Control scheme of some earlier hydraulic excavator HMI designs.

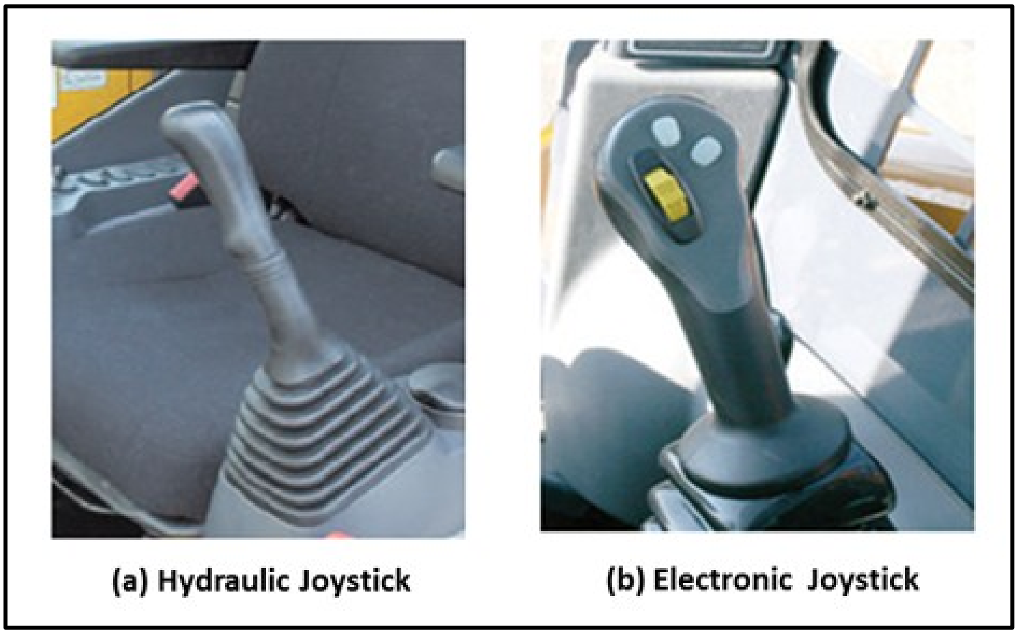
In this arrangement, the left and right hand levers controlled the boom and swing respectively; the left and right pedals, the bucket and stick respectively; and the propel (left) and right (travel) levers controlled the forward and reverse motion of the machine, and the turning of the machine respectively (Nichols, 1976).

2.3.1.2 Display. Some earlier systems like the cable excavator provided no display for monitoring the status of the machine. With the introduction of the hydraulic excavator, a set of mechanical gauges were added. These gauges were limited to monitoring oil pressure, coolant temperature and voltage/amperage. These were an appropriate form of display at the time of their introduction, they rapidly became obsolete as a new form, the analog-digital display, was introduced, which was made possible by the advancement in electronic display and sensor technologies (Boyanovsky, 2005).

2.3.2 Current state-of-the-art. Because the early machines offered HMIs that were less intuitive and not easy to use, operators were subjected to high levels of cognitive and physical stress, thus exposing them to mental and physical health risks. Modern machines therefore sought to address these issues by implementing HMI designs that were relatively intuitive in order to lessen stress on the operator. To this end, some significant changes have been made to the HMI controls and displays used in earlier hydraulic excavator machines. In today's machines, manufacturers assert that their machines are equipped with HMI functions and features which provide operators with a high degree of command and control, high efficiency, much improved comfort features and less fatigue. This assertion can be attributed to the digital revolution which is creating major changes in heavy mobile equipment HMIs, to enable bringing new features and functionality to operators. Furthermore, the era of electronics is changing many aspects of hydraulic system design through such features as the use of electronic controls and advanced displays that have touch sensitive screens. Advances in software have also made possible the integration of such controls with traditional components such as pumps and valves (Costlow, 2008).

To track the changes that have been introduced, a review of the current state-of-the-art of hydraulic excavator HMIs was done. The review covered HMI designs offered by leading manufacturers including Caterpillar, Komatsu, Hitachi, Deere, Bobcat, and Volvo, and some Original Equipment Manufacturers (OEMs). Fortunately, the HMI designs used by these manufacturers maintain a standard architecture of a pair of joysticks, monitor display, pedals, levers and push buttons that perform the same primary functions, thereby making the review generalizable. There are only slight differences in terms of design features that focus on delivering faster performance, intuitive interfaces, and better aesthetics – which have been incorporated to gain competitive advantage. The important interface elements that were identified which showed improvements made in modern hydraulic excavator HMIs included: controls, windshields and mirrors, monitor display, consoles, levers and pedals, operator seat, and machine guidance/telematics/GPS interfaces.

2.3.2.1 Controls. Hydraulic excavator joysticks control the arm, bucket, swing and other auxiliary hydraulic functions. Joystick controls are also referred to as pilot controls, pilot joysticks and even hydraulic assist. The major types of joystick controls used in excavators are hydraulic (manual), electronic, and hybrid joysticks. Figure 2.2- (a) and (b) respectively show a John Deere hydraulic joystick (John Deere, 2010) and a Caterpillar electronic joystick (Caterpillar, 2009).

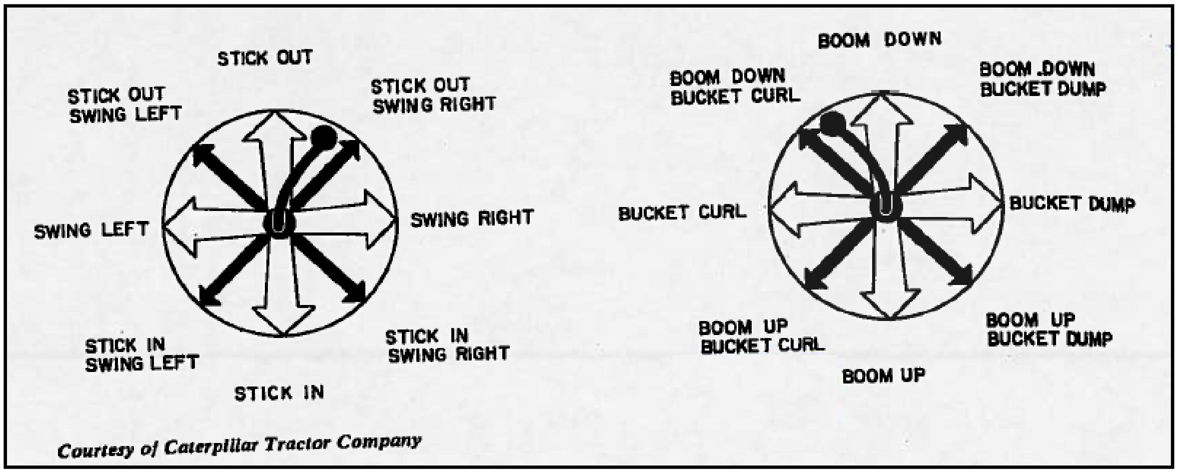

(a) Hydraulic Joystick

(b) Electronic Joystick

Figure 2.2. Types of hydraulic excavator joystick controls: (a) hydraulic; (b) electronic.

Hydraulic control joysticks are mechanical and offer a direct linkage to hydraulic lift arm and bucket control valves. Unlike these manual control joysticks, electronic control joysticks are equipped with electronic functional embedded buttons that allow smoother control system movement, such as rotation, travel, and tool movements (Bennink, 2010; Berndtson, 2010).

In the HMI, there are two joysticks, one mounted on the right and left consoles respectively. The right joystick controls the boom and lifting of the bucket. Moving it towards you (backward) raises the boom, and moving it away from you (forward) lowers the boom. Moving it to the right lifts/opens the bucket and moving it to the left lowers/closes the bucket. The left joystick controls the arm. Moving it away from you (forward) raises the arm, and moving it towards you (backward) lowers the arm. Moving it to the right swings the upper carriage to the right and vice versa (see Figure 2.3) (Kikki's Workshop, 1997; Nichols, 1976).



Courtesy of Caterpillar Tractor Company

Figure 2.3. Joystick control functions.

Joysticks are specified by number of axes, friction hold, spring return, and protocol support. They can support up to six degrees of freedom (DOF) corresponding to the axes of the direction of movement - x, y, z, yaw, pitch and roll. Devices with friction-hold features latch the switching lever in the selected position. Spring return or centering returns the device to the center position due to mechanical or programmable spring force. Joysticks use potentiometric, inductive or photoelectric sensing systems and/or switches to translate joystick motion into an output signal. They also vary in terms of handle options, and mounting styles and features. The control lever grips are straight, conical tubes, contoured or ball-like shaped to fit into the operator's hands. Electronic joystick grips provide multifunction capability (horn, low-idle, oil flow control, etc.) by means of a rocker switch, pushbutton, thumbwheel or trigger. Most hydraulic excavator joysticks are mounted on the consoles or part of an original equipment manufacturer (Kroemer, Kroemer, & Kroemer-Elbert) kit. Other joystick features include bellows, gaiters, or boots; shielding from electromagnetic interference (EMI) and radio frequency interference (RFI); protection against electrostatic discharge (ESD); and temperature compensation. Some joysticks also feature force-feedback which provides tactile sensations via resistance, recoil, vibration, axis force or vector force (Global Spec - The Engineering Search Engine, 2010).

2.3.2.2 Windshield and mirrors. Windshields with a wider expanse of glass supported in narrower front cab posts and large overhead hatch are now used to provide visibility of the work environment. In most hydraulic excavator models, numerous mirrors are mounted on both sides of the cab to provide virtually unobstructed all-around visibility.

2.3.2.3 Display. This is a compact, full color, multi-lingual Liquid Crystal Display (LCD) monitor, popularly known as the monitor display (Figure 2.4) (Caterpillar, 2009). It displays machine maintenance, diagnostic and prognostic information. It includes gauges for showing engine oil, coolant and fuel status; LED-lighted icons indicating when various machine functions are active and several warning icons with audible alarm. For example, the master caution lamp on the monitor display of some Caterpillar models blink ON/ OFF when one of these critical conditions occurs: engine oil pressure low, coolant temperature high or hydraulic oil temperature high. The monitor is equipped with a keypad (or a touch pad in some designs) that allows the operator to select machine operation conditions to view detailed information and to customize view preferences. A set of function switches on the keypad facilitate multi-function operations. It also allows adjustment of different attachments like the bucket, blade, ripper, crusher, cutter and driller. In some excavators, the LCD monitor features a rear view camera, which allows the operator to see what is behind the machine, adding more visibility. Some monitors display an eco-gauge for environment-friendly energy-saving operations. This allows the operator to maintain work in the green zone and reduce fuel consumption (Caterpillar, 2009; Hitachi Construction Machinery America, 2004; John Deere, 2010; Komatsu, 2009).

Figure 2.4. Monitor display.

2.3.2.4 Consoles. The consoles are mounted on the left and right side of the operator seat. They serve as a base for mounting joysticks, secondary display information, keypad (or other input devices). Both consoles have attached armrests with height adjustments. They also serve as holders for various items such as beverage cans.

2.3.2.5 Travel pedals and levers. *Travel* pedals are located on the floor board and are used for drive motion. There are usually two (left and right) main foot pedals, each controlling the left and right tracks respectively. Pushing against both of them at once will make the excavator travel in a straight line. Pressing the left foot pedal relative to the right steers the excavator towards the left and vice versa. Attached to the foot pedals are two vertical hand levers that can serve the same purpose as the foot pedals. These hand levers are used infrequently in order to free the hands for controlling the joysticks. On both sides of the main travel pedals, are two other small pedals. The one on the left is high speed control, used to boost the drive pump and speed the machine's travel when moving it from one location to another. Usually this pedal is used when on a smooth, level terrain. The small pedal on the right is a two-way foot switch for pivoting the front manipulator so that the machine does not have to swing to reach the location that the bucket is needed at.

2.3.2.6 Operator seat. Most seats feature an ergonomic design that allows a variety of adjustments to suit the operator’s size and weight, and provides a comfortable workspace. The seat is installed between the left and right consoles and is usually equipped with a retractable seatbelt. Some seat designs allow the seat to be reclined into the backrest position for resting.

2.3.2.7 Telematics, global positioning and work guidance systems. Modern construction equipment communicates information via monitor panels and telematics, and that information is accessible remotely via wireless technologies and web interfaces (Calvert, 2009; Hull, 2009; Roth, 2010). Telematics interfaces allow monitoring of the equipment through retrieval of data about equipment locations, utility and maintenance diagnostics. The goal is that machine problems will, through fault reporting, activity warnings and by facilitating remote diagnosis, be identified sooner and resolved faster. Machine operation and deployment can be optimized via functions that monitor fuel consumption, location, hours of operation, speed, and approaching service intervals. Fleet management also becomes easy. Some examples of telematics interfaces include Komtrax, Komatsu's wireless equipment monitoring system and CareTrack, Volvo Construction Equipment's state-of-the-art monitoring system (Komatsu, 2010; Volvo Construction Equipment, 2010).

Global Positioning System (GPS) technology has found its way into more earthmoving sites to assist hydraulic excavators and other heavy equipment to more efficiently cut and fill to grade. The GPS interface allows operators to know information about the machine's location on the site and position of work tool in relation to the final grade (Moore, 2004). The benefits of GPS machine-control is that it enhances grading quality and eliminates the need for survey stakes. A GPS application example is the Caterpillar AccuGrade Grade Control System. The AccuGrade 3D system uses GPS technology to compare the blade position to a three-dimensional computerized site plan (or digital terrain model-DTM) and signals the operator to raise or lower the blade to achieve the design requirements (Caterpillar, 2006).

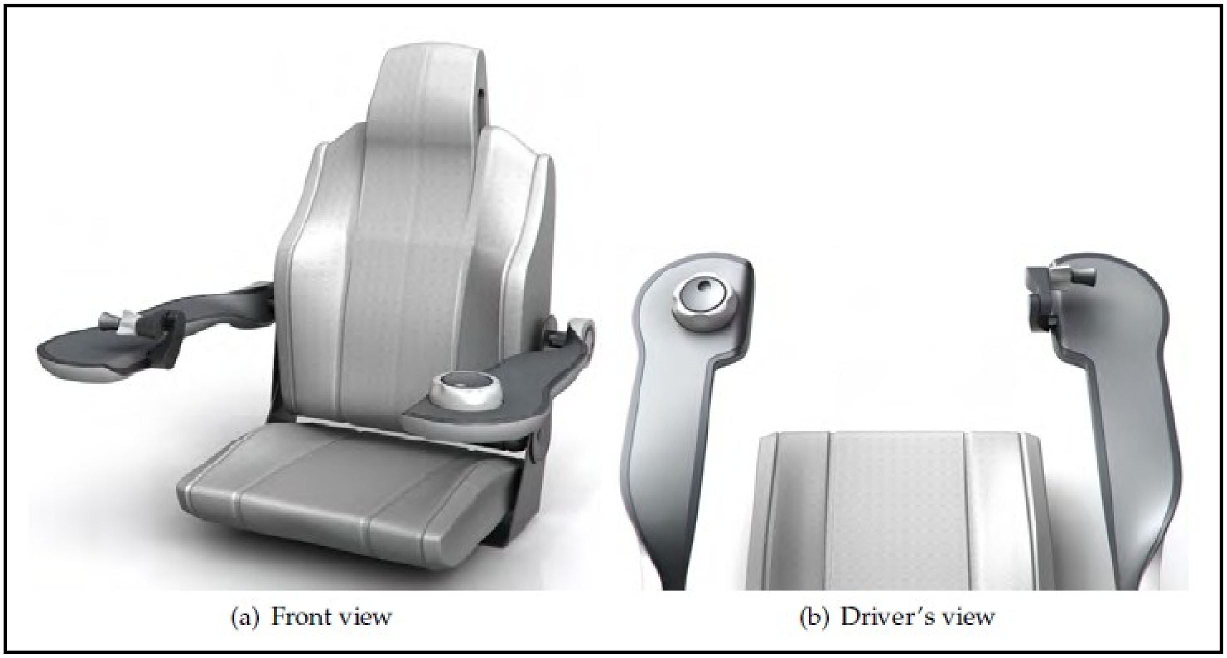
In traditional earthmoving, visualization of the surface contours of the construction site was made possible for the machine operator by means of profile templates, visors, stakes etc. These were used to guide the operator to accomplish work tasks such as digging or cutting a grade. The visible templates, for example, provided the operator with an image of the finished surface and the excavator bucket's edge approaching the grade height more accurately. Support by a site worker was required and work was restricted to daylight times. In some of today’s systems, this function has been integrated into a user-friendly machine guidance system that shows the operator a three-dimensional image of the work to be done. This has been accomplished by a combination of digital terrain models (DTMS) with technologies such GPS and Global Navigation Satellite Systems (GNSS) (Schreiber & Rauch, 2008).

2.3.3 Emergent and future HMI designs. Emerging and future operational concepts have been explored and proposed in a number research studies. These operational concepts have focused on the development of novel control strategies that seek to, among other things, provide a more intuitive interaction, facilitate task completion and provide adequate sensory feedback to support task goals.

One of such emergent HMI designs is the research published by Yoon and Manurung (2010) wherein they developed an intuitive interface based on a novel joystick configuration with hybrid cylindrical coordinate and independent bucket control for controlling a hydraulic backhoe. The proposed method sought to allow operators to control the hydraulic backhoe intuitively and operate complex motions smoothly with no constraints. It had several advantages compared to Cartesian coordinated control methods which included: independent horizontal and vertical motion control; more natural and intuitive control for excavator operations; less complicated and inexpensive operation; proximity to conventional joystick operation mode; and easy return to standard mode. A virtual simulator and an actual backhoe testbed were developed to demonstrate the effectiveness of the proposed interface scheme and preliminary user studies were performed for simulated flattening and digging tasks. The results showed that the proposed intuitive interface facilitated faster and more precise operation than the conventional actuator control scheme.

Another emerging and more transformative HMI design is one based on a haptically-enabled, coordinated input operational concept (Elton, 2009; Hayn & Schwarzmann, 2010;

Kontz, 2007). This operational concept introduces a third modality, the haptic modality, which seeks to complement the two existing modalities of the HMI (i.e. the visual and auditory). The embodiment of these three modalities into an interface has brought about the concept of multimodal HMI design for hydraulic excavators. Haptic feedback (also known as tactile or force feedback) involves sending tactile sensations to the operator via the control to provide an additional informational cue for augmenting the operator's performance. Coordinated control is based on using a controller whose segments resemble the front manipulator geometry of the hydraulic excavator, providing an intuitive cognitive mapping between system input and output. For instance, the coordinated control scheme proposed by Hayn and Schwarzmann (2010) is depicted by Figure 2.5 and Figure 2.6. For their intuitive concept, the rotation of the cab is controlled using a rotary operating element, the translation of the tool center point is controlled using an element which is free-moving within a vertical plane, and tilt of the bucket is controlled using a rotary element.


(a) Front view

(b) Driver's view

Figure 2.5. An example of the haptically-enhanced coordinated control operational concept.

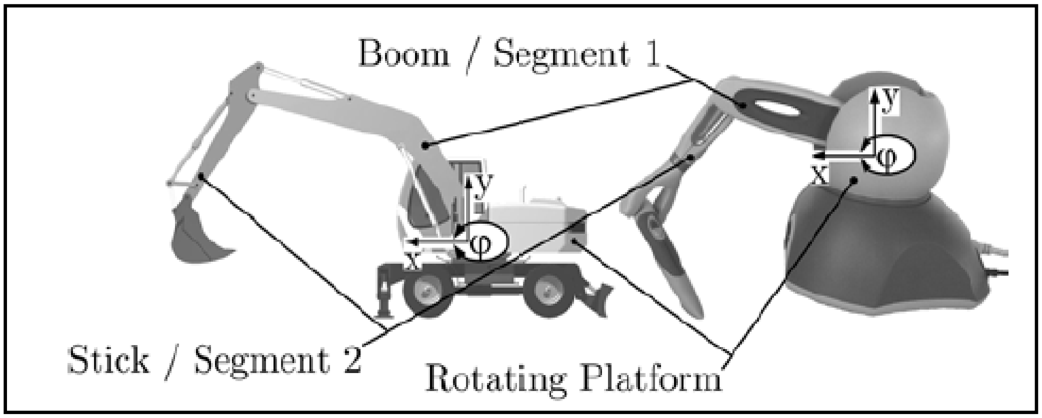


Figure 2.6. Analogy of the geometry of the coordinated control and the front manipulator.

The proposed concept promises to offer some significant benefits for human-machine interaction which include: to increase machine efficiency (handling capacity) by providing a vehicle assistance system via haptic feedback; to reduce the learning curve to operating machine proficiently; and reduce operating errors especially for novice operators. Furthermore, some of the ways by which the haptic feedback could be used to support the operator's working tasks include: warning the operator of damaging obstacles; providing feedback of digging or gripping forces; imitating open-center hydraulic systems; enabling the operator to sense the inertia of the machine's manipulator; simplifying leveling and slope cutting; limiting the excavator's workspace; guiding the bucket on a specific trajectory; and assisting in the collaborative manipulation of a heavy building element by multiple operators.

2.4 Virtual, Augmented and Mixed Reality

Milgram and Colquhoun (1999) used a taxonomy to describe Mixed Reality (MR) – a variant of Virtual Reality (VR) – as one in which real and virtual environments exist as opposite poles of a reality-virtuality continuum (Figure 2.7). They defined MR as an environment wherein real and virtual objects are presented together within a single display. The major distinction between VR and MR is the degree of immersiveness of the environment. While VR seeks to completely immerse users in a synthetic world by blocking out the surrounding real environment, MR strives to augment the real world scene requiring that the user maintains a sense of presence in that world. Thus in MR environments, virtual and real objects are merged to create an augmented scene.

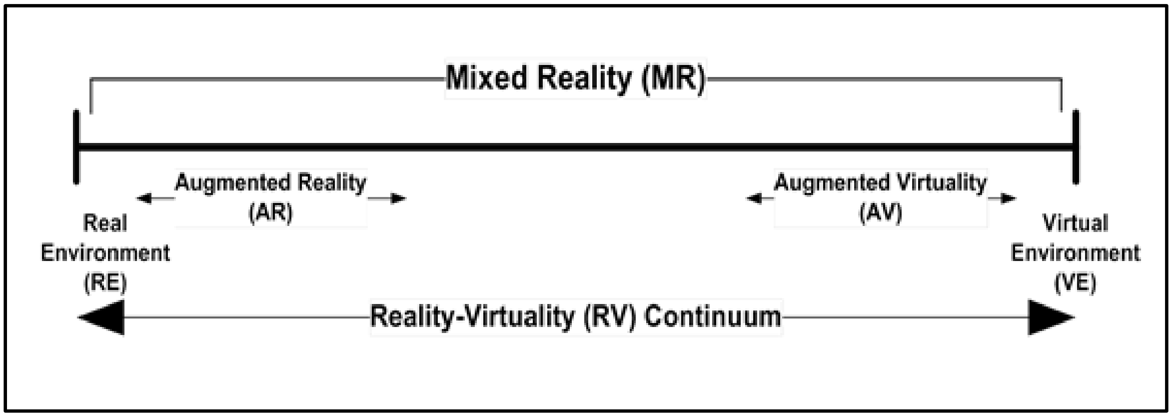


Figure 2.7. Milgram's reality-virtuality continuum.

In their construct, Milgram and Colquhoun (1999) pointed out that two classes of MR environments can be identified in the reality-virtuality continuum – Augmented Virtuality (AV) and Augmented Reality (AR). AV describes a technique wherein a completely virtual environment is overlaid with real objects to create the augmented scene. AR is the reverse of AV, and it involves a technique in which virtual objects are overlaid on the real world to create the augmented scene. A core component of this research involves the development of an HMI simulation platform based on MR. In the development of the MR simulation platform, the AR technique was used. Hence, the following sub-sections focuses on describing the concepts and technologies used in AR.

2.4.1 Definition and scope of augmented reality. A very popular definition of an AR system is the one postulated by Azuma (1997). He defined AR as comprising any system that:

1. combines both real and virtual objects

2. is interactive in real-time, and
3. is registered in three-dimensions (3D).

To breakdown the above definition further, first, combining real and virtual objects means that an AR system should allow digitally acquired real and virtual information to be blended into a single, augmented scene. Secondly, the system being interactive in real time means that users should be able to interact with the augmented scene, which should be continuously updating itself as data is being received. Finally, registration is an aspect of an AR system and refers to the accurate alignment of real and virtual objects. Without accurate registration, the illusion that the virtual objects exist in the real environment is severely compromised.

The basic goal of an AR system is to "enhance the user's perception of, and interaction with, the real world through supplementing the real world with 3D virtual objects that appear to coexist in the same space as the real world (Azuma et al., 2001)." Merging real and virtual worlds to provide system users with additional information for enhancing perception is what AR is all about (Figure 2.8), and what has established AR as an important technique for supporting user interaction and system design efforts.

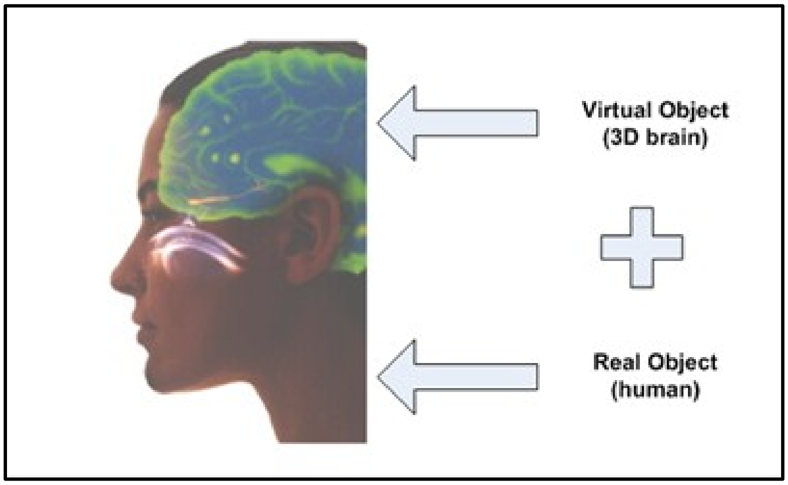
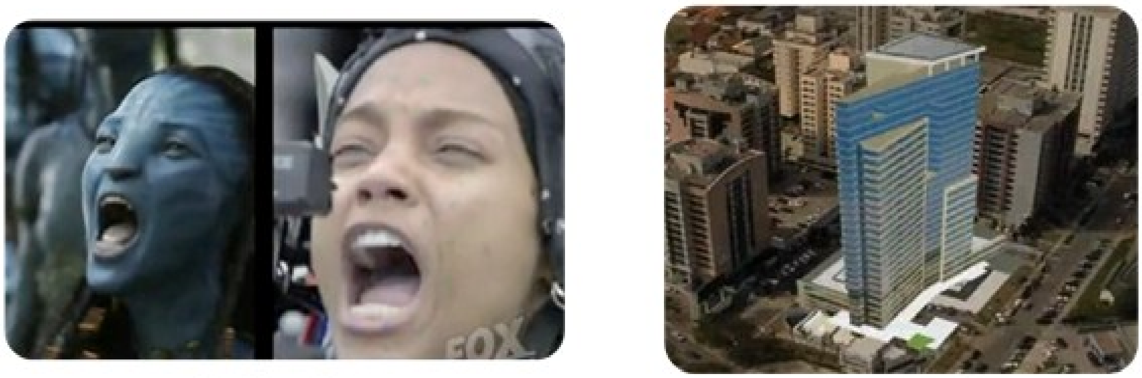


Figure 2.8. Augmented reality: mixing virtual and real worlds.

The scope of AR applications is enormous and has continued to grow rapidly over the years. The technology has been applied in a wide range of domains including, but not limited to, education, engineering, entertainment, medicine and the military. Familiar examples of AR applications includes: the virtual down lines that appears on the field during televised football games (Sung, 2004); the portrayal of virtual humans in movies such as Avatar (Cameron, 2009); driving-related information overlaid on the car windshield directly in the driver's line of sight (Boeriu, 2004); and the overlay of virtual buildings at a site to allow engineers, architects and customers to see how the buildings will look before they are built (Azuma et al., 2001; Haller, Billinghurst, & Thomas, 2007).

AR in Sports

AR in Navigation



AR in Filmmaking

AR in Construction

Figure 2.9. Examples of AR applications.

2.4.2 Components of an augmented reality system. Improvements in the capabilities of real-time video image processing, enhanced computer graphic systems and new display technologies are among the enablers that converge to make possible the development of AR systems. The architecture of any AR system comprises of four primary components namely: a graphics generation system, a display system, an interaction system, and a tracking system (Figure 2.10).

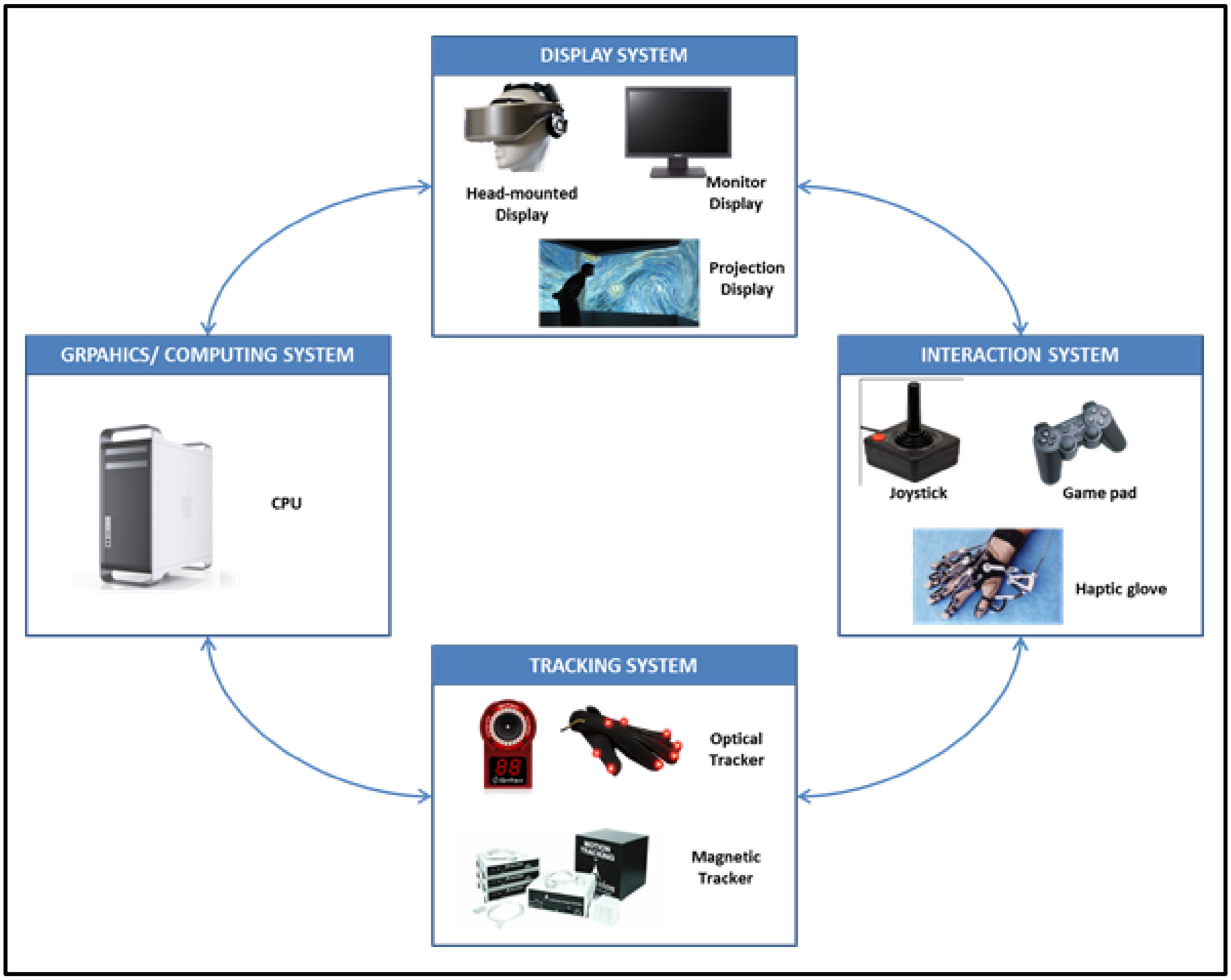


Figure 2.10. Components of an AR system.

2.4.2.1 Graphics generation system. The graphics generation system is usually a personal computer or other system such as a Silicon Graphic Inc. (SGI) computer equipped with a functional operating system and a computer-aided design (CAD) software to be used for generating the virtual objects. Some important requirements of the graphics generation system are that it must have a high-end video card to enable faster and efficient rendering of the virtual objects; it must have high processing capability to allow for quickly updating changes in the virtual objects; and it must have a minimum display resolution that is compatible with the resolution of the combination of video card(s) and the AR display.

2.4.2.2 Display system. The function of the display system is to allow the virtual objects to be registered to the real environment to create the augmented scene to be presented to the user. AR displays use a variety of objects representations to augment the real environment. The different types of virtual objects that can be used include texts, indicators, 2D images, 3D data, 3D wireframe, and rendered 3D objects (Wang & Dunston, 2007). The fidelity of the representation conveys information that can assist the user's comprehension ability, thus augmenting the user's cognitive process and activity.

The display used in AR systems is usually visual displays. Other classes of displays are non-visual displays including acoustic displays (i.e. displays with 3D localized sounds), and tactile displays (i.e. displays with force-feedback devices) (Wang, 2008). The main types of visual displays that are used for developing AR applications include head-mounted displays (HMD), projection displays (or spatial displays) and handheld displays. The HMD will be employed in this research, thus making it imperative to elaborate on this type of display. There are two kinds of HMDs – the video see-through and the optical see-through HMD. Video see-through HMDs are closed and do not allow the user to have any direct view of the real world. Video see-through displays present the augmented information (combination of virtual and real objects) to two small displays (either one or two) with lenses embedded in the HMD (Figure 2.11) (Arcane Technologies, 2012).

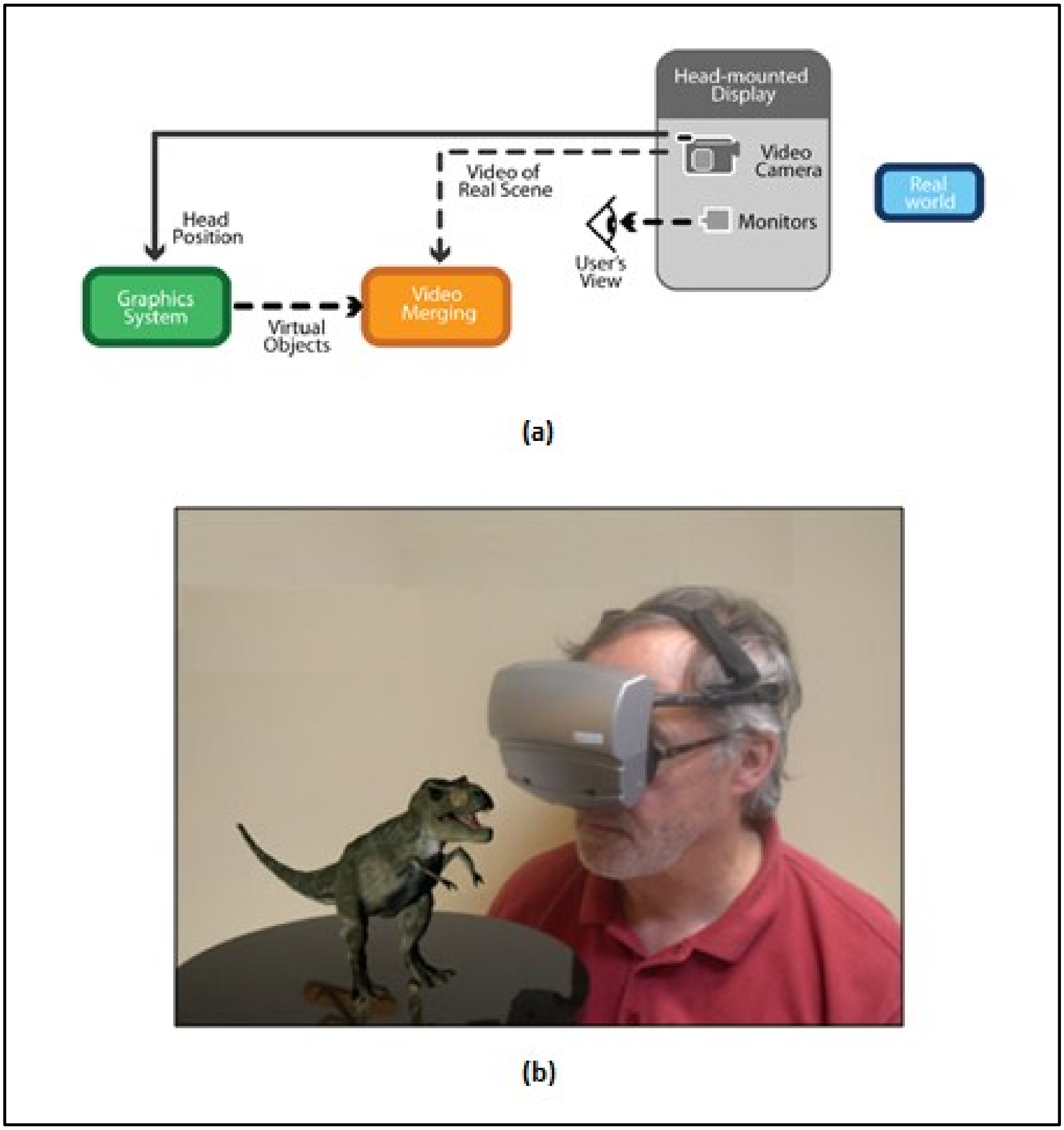


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Figure 2.11. Video see-through display: (a) configuration; (b) example HMD.

In contrast, the optical see-through HMDs work by placing optical combiners in front of the user's eyes. These combiners are partially transmissive and allow the user to look directly through them to see the real world (Figure 2.12) (Virtual Realities, 2012). The advantages and disadvantages of video-based see-through mixing and optical see through combination can be found in (Azuma, 1997).

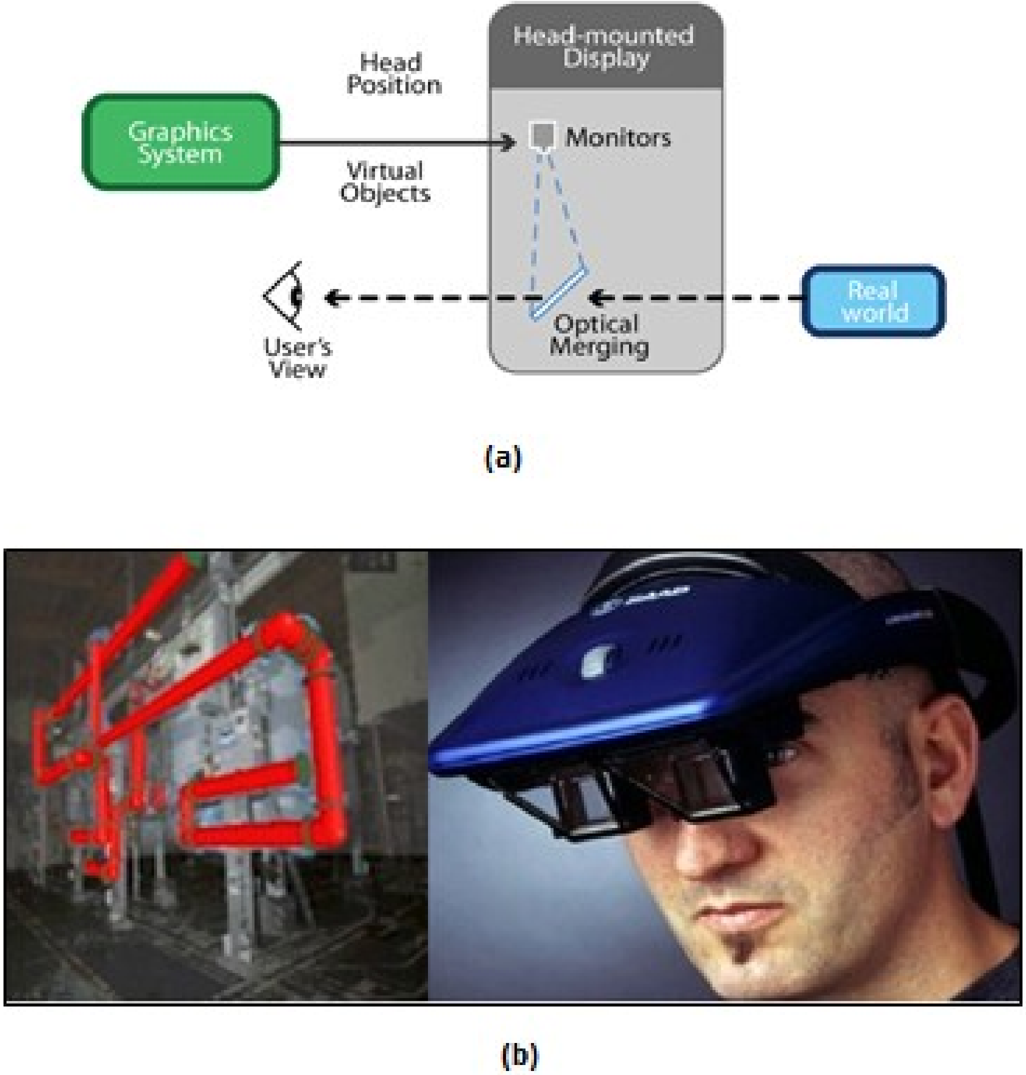


Figure 2.12. Optical see-through display: (a) configuration; (b) example HMD.

2.4.2.3 Interaction system. An important aspect of an AR system is its ability to allow users to interact with the virtual objects. An input device is typically used to manipulate the digital information displayed over the real environment. A variety of input devices can be applied in AR systems including – traditional input devices such as a mouse, 3D controllers, keyboard, and joystick; voice input, for a more direct, natural form of interaction; and also, haptic input devices. More information regarding input devices can be found in (Gabbard, 1997).

Markers, which serve as reference points for the registration (overlay) of the virtual objects, can also be manipulated and used for interaction. A comprehensive presentation of markers used in AR can be found in (Haller et al., 2007). Other advanced interaction techniques used in AR include collaborative AR, outdoor (mobile) AR, mobile phone AR, and tangible AR (Billinghurst, Kato, & Myojin, 2009; Billinghurst, Kato, & Poupyrev, 2008; Billinghurst, Poupyrev, Kato, & May, 2000; Feiner, MacIntyre, & Webster, 1997; Haller et al., 2007; Regenbrecht, M.T., & G., 2002).

***2.4.2.4 Tracking system*.** An AR system requires trackers to measure the position and orientation of the user in the environment. Typically, the motion of the user's head hands, and eyes are tracked. Tracking is important in order to ensure accurate registration and positioning of virtual objects as well as sensing the locations of other objects in the real environment. Most tracking technologies are context-aware approaches and the type of tracking technology to employ depends upon the application. Major trackers available include mechanical, inertial, magnetic, ultrasonic, optical, and infrared tracking systems (Azuma, 1997). Detailed surveys of tracking technologies have been widely published in open literature (Ferrin, 1991; Holloway & Lastra, 1995; Meyer, Applewhite, & Biocca, 1992).

2.4.3 Procedure for developing an AR application. The following steps outline how an AR application is developed.

1. The camera captures video of the real world and sends it to the computer.
2. The AR software on the computer searches through each video frame for markers. The markers serve as reference frames (or containers) for the virtual objects generated by the computer (also the graphics generation system).

3. If a marker is found, the software uses some algorithms to calculate the position of the camera relative to the marker.
4. Once the position of the camera is known, the virtual object is rendered (or drawn) from that same position. The virtual object is registered on top of the video of the real world and so appears stuck on the marker.
5. The final output is shown back in the display; so that when the user looks through the display they see graphics overlaid on the real world.

Figure 2.13 (ARToolKit, 2012) depicts the steps described above. For more information on the development of an AR application, see Billinghurst, Grasset, and Looser (2005).

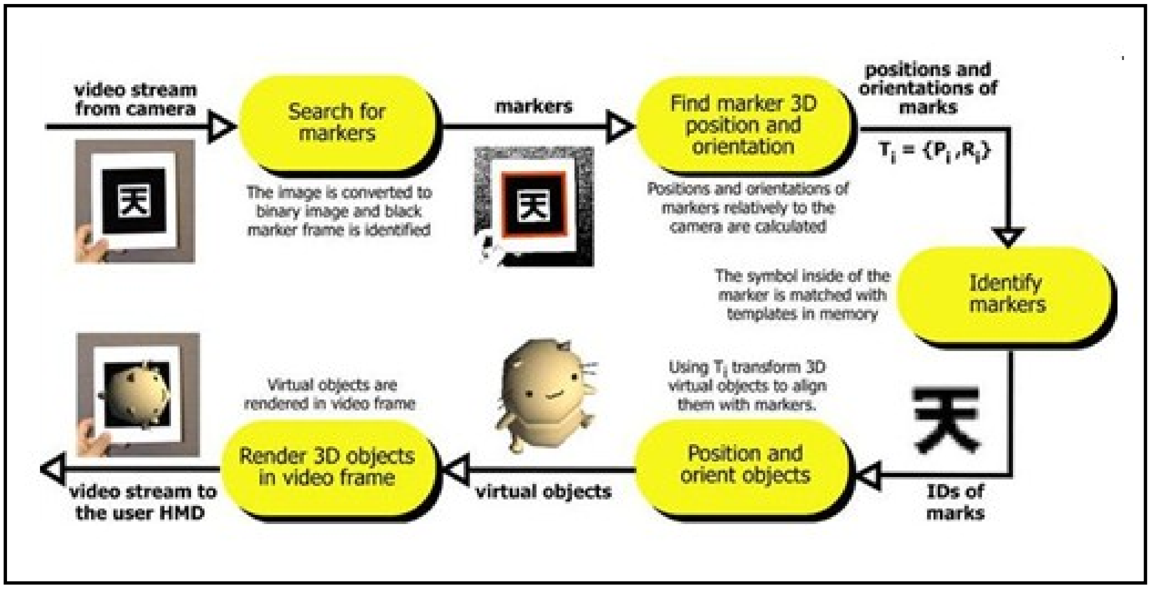


Figure 2.13. Steps for developing an AR application.

2.5 Related Work

A considerable amount of research has been published, documenting attempts to develop new HMI design strategies for hydraulic excavators. The majority of the published literatures present a multimodal HMI design strategy, with a focus on new control schemes. Some others have concentrated on HMI design strategies for enhancing operator training; and yet others have investigated HMI design solutions for teleoperation and autonomous excavation.

In general, multimodal HMIs provide a user with multiple modes of interacting with a system via the visual (sense of sight), haptic (sense of touch) and auditory (sense of hearing) sensory channels, and to a lesser extent, the olfactory (sense of smell) and gustation (sense of taste) sensory channels. Multimodal HMIs process two or more combined user input modes in a coordinated manner with multimedia system output to provide HMIs that are powerful, flexible, adaptable, and natural (Sharma, Pavlovic, & Huang, 1998). According to Sarter (2006), there are two classes of multimodal HMIs: multimodal input and multimodal output systems. Multimodal input includes speech, touch, manual gestures, gaze, and head and body movements. Multimodal input systems permit users the flexibility to use multiple input modes, that is, users can have a natural alternation between modes at any time. Multimodal output includes multimedia displays (visual displays), auditory cues (e.g. speech output), and haptic signals (e.g. vibratory turn signal lever of a car and aircraft stick shaker). Multimodal HMIs can be found in modern automotive systems, map-based navigation systems, and aircraft cockpits. The popularity of multimodal HMIs can be traced to two sources: the first stems from the reality that human cognitive processes and perceptions are built on multimodality as humans favor natural communication with multiple senses; the second springs from the continuous advances in technologies that support human-machine communication along multiple sensory dimensions. Some benefits of multimodal HMIs include synergy (i.e., the merging of information that is presented via several modalities and refers to various aspects of the same event or process), redundancy (i.e., the use of several modalities for processing the exact same information) and an increased bandwidth of information transfer. Multimodal HMIs have the potential to minimize user's cognitive workload as attentional resources will be drawn from different resource pools. They also have the potential to accommodate a broader range of users - including users of different ages, skill levels, native language, cognitive styles, sensory impairments and other handicaps (Oviatt, 2003; Sarter, 2006).

2.5.1 Multimodal HMI design strategies for the hydraulic excavator. Previous work on multimodal HMI designs for hydraulic excavators have been either based on conventional joysticks equipped with haptic feedback (Cemenska, Schneider, & Buege, 1989; DiMaio, Salcudean, Reboulety, Tafazoli, & Hashtrudi-Zaad, 1998; Ko & Choi, 2007; Mckinsey & Chiu, 2007; Ni, Zhao, & Ni, 2009; Parker, Salcudean, & Lawrence, 1993; H. Yamada & Muto, 2003) or a haptically-enabled coordinated control scheme (Elton, 2009; Hayn & Schwarzmann, 2010; Kontz, 2007; Lawrence et al., 1995; Torres-Rodriguez, Parra-Vega, & Ruiz-Sanchez, 2005).

In order to facilitate the testing and evaluation of control strategies and operator environments designed for heavy duty hydraulic machines, DiMaio et al. (1998) developed an excavator simulator for controller development and evaluation. The simulator comprised of an impedance model of the excavator arm, a model for the bucket-ground interaction forces, a graphical environment and a haptic interface consisting of a six degrees-of-freedom magnetically levitated (MagLev) force-feedback joystick for velocity control, and a twin pantograph device for position control. Their simulator was shown to be effective for the testing and evaluation of various control strategies (including those with interactive force-feedback) for applications including teleoperation, operator training, and excavation trajectory programming.

Aforementioned, the studies by Elton (2009) and Hayn and Schwarzmann (2010) are recent works on multimodal HMI design for hydraulic excavators which focused on the development of a haptically-enabled coordinated control scheme. Both works were very similar in that they both combined the coordinated controller with haptic feedback to provide a third modality that offers an in-vehicle assistance scheme for communication between the operator and the machine, and to demonstrate that operators performed better with haptic interfaces compared to standard interfaces without haptic feedback. The differences in their work lie in the design of the HMI, its implementation and evaluation. The work by Hayn and Schwarzmann (2010) was in an earlier section used to explain the haptically-enabled coordinated control scheme as part of the discussion on emergent HMI design concepts for hydraulic excavators. The presentation of these works again in this section seeks to highlight the technical implementation details of the proposed operational concept or HMI, as well as present the results obtained from tests conducted with the new operational concept. Their works are given special attention in this research because their proposed control concept yielded positive outcomes, and is therefore adopted in this research and combined with new display strategies to obtain an innovative interaction strategy that brings about greater improvement in the HMI design.

Elton (2009) developed an excavator simulator to test new HMI designs with coordinated haptic feedback control against standard designs. The simulator combines the actual cab of a Bobcat 435 mini-excavator with a full dynamic model of the excavator's hydraulic and mechanical systems that displays a simulated excavator arm and work environment on a 52" LCD television screen. The television was mounted vertically on the windshield of the cab. A prerecorded audio playback of sound from a construction site was used to simulate environment noise to give users a sense of being present at a construction site. A coordinated haptic input controller, the Sensable^{TM} Phantom Premium was used to provide the interface for operator input. Four control schemes, involving two different coordinated control schemes (position control and hybrid control) and two force feedback schemes (force feedback, and no force feedback) were developed and preliminary tests were run to measure increases in operator effectiveness and machine efficiency. A preliminary testing of both new and standard HMIs was conducting using six subjects. This preliminary testing was not designed to produce statistically conclusive results due to its simplicity, but to prove the viability of performing future conclusive tests and to show the viability of the tested control schemes. The preliminary results showed that the simulator can allow performance improvements to be measured for hydraulic excavator HMIs.

In the research done by Hayn and Schwarzmann (2010), an intuitive operational concept for a hydraulic excavator was proposed. This was a straightforward control method to manipulate a machine using an alternative operating device that resembles the front manipulator geometry of the hydraulic excavator. Their goal for the proposed concept was to improve the handling quality and to simplify the operation of the machine - especially for novice operators. In order to implement this concept on a test excavator, an internal model control (IMC) methodology with input constraints for a haptic device and a feedback control methodology for a master-slave system was applied. An anti-windup approach for models with pure integrators was used to implement the haptic feedback. With this implementation, the user is able to feel the inertia of the excavator's manipulator and thus get feedback on the interaction of the bucket with the environment. The application was tested in experiments using a Sensable^{TM} Phantom Omni device and a hydraulic test excavator. Twelve male test operators without any relevant experience with hydraulic excavators performed a predefined working task. The task was first performed using the standard joysticks, and after this, they performed the same tasks using the new control concept. They were filmed to analyze the working cycle times and operating errors, and were also surveyed using a questionnaire. The quantitative results of the test showed significant differences between both operational concepts; especially, the cycle time and the number of errors were significantly lower in the coordinated control concept. The survey also showed that the inexperienced operators subjectively benchmarked the coordinated control concept better than the standard control concept in terms of usability.

Another work that is closely related to this research is the augmented interaction strategy espoused by Spies, Ablaßmeier, Bubb, and Hamberger (2009). In their work, they envisioned augmented interaction as a new approach to interaction in the automotive domain in which real and virtual objects are fused together by means of a contact analog heads-up display and a haptic touchpad. The interaction allows a direct mapping of the displayed information on the touchpad with virtual objects represented by the contact-analog heads-up display. The driver interacts with the touchpad by sensing the corresponding environment (for e.g. a point of interest such as a historic building), selects the relevant sensed elevated objects on the touchpad and gets the real object highlighted contact-analog by the heads-up display. This simple direct cognitive mapping results in a reduction in mental workload. While this idea sounds great, it was only presented conceptually and has not been developed and tested.

2.5.2 HMI design strategies for hydraulic excavator operator training. Other researchers have also attempted using VR, AR and MR to develop interaction strategies for hydraulic excavator operator training. Their works have been based on the development of VR training simulators (Bernold, Lloyd, & Vouk, 2005; Engel, Alda, & Krzysztof, 2009; Fisher, 2008; Segura, Moreno, Brunetti, & Henn, 2007), and on MR training simulators (Akyeampong, Udoka, & Park, 2012; Wang & Dunston, 2007).

Ni et al. (2009), for example, developed a visual system for an excavator simulator with deformable terrain deformation for training operators and evaluating control strategies. In their system, the operator controls the excavator by means of a joystick while experiencing realistic operating sensations through force-feedback, graphical displays, and sound effects. They generated a dynamic deformable terrain mesh using the Real-time Optimally Adapting Mesh (ROAM) algorithm. By combining ROAM with realistic graphic rendering for the excavated region, and a particle system for managing the soil particles, they produced a dynamic interaction visual effect of a soil dumping operation. The visualization was realized using a PC, with a sustained frame rate of above 60 per second, which is the acceptable frame rate required of most real-time graphic applications. With this result, this system was purported to be apt for operator training.

(Wang & Dunston, 2007) presented the potentials of using AR in construction equipment operator training. In this light, they conceptualized an AR-based world training system (ARTS) for heavy equipment which included an AR-based interface for a hydraulic excavator to be used for operator training. Their visions of the mechanisms and strategies for the AR training system included using virtual objects to present operating procedures to operators, and providing virtual information about features and objects that do not have a constant configuration such as a specific haul road route and major destinations (e.g. loading and dumping sites).The goals they set for ARTS were to: (1) to provide a conceptual design of a wearable AR system that will allow a novice to try construction operations using heavy equipment with the support of digital information; and (2) explore how effectively the AR tool can support training compared with other training methods.

In a recent study, Akyeampong et al. (2012) extended the work by Wang & Dunston (2007) and developed a prototype AR system for simulating hydraulic excavator operator training – the Hydraulic Excavator Augmented Reality Simulator (H.E.A.R.S). The system features the overlay of virtual objects that describe the working parts of the hydraulic excavator, superimposed on the user's view of the workspace along with a simulated work environment to provide firsthand information on how each working part functions. The goal was to enhance the usability of the standard HMI by providing novices with information regarding control functions. This work was only preliminary, as it mainly sought to demonstrate the feasibility of constructing an AR simulator for operator training. Thus no conclusive usability tests were conducted to gain an objective measure of its effectiveness as a training tool.

2.5.3 HMI design strategies for autonomous excavation and teleoperation. Two other important areas that need to be mentioned where some considerable amount of work on HMI design for hydraulic excavators has been done are in autonomous excavation (Rowe, 1999; Yamamoto, Moteki, Shao, & Ootuki, 2009) and teleoperation (Barrientos, Luengo, & Mora, 1999; Hayashi & Tamura, 2009; Kim et al., 2009; Kim, Oh, Hong, Park, & Hong, 2008; Moon et al., 2009; H. Yamada & Doi, 2008).

Wang (2008), for example, proposed a conceptual MR-based visual HMI for remote excavation of dangerous materials in an unstructured environment. The goal of the proposed visual HMI was to improve the interface between the remote environment and the operator using MR and stereoscopic vision. The technical components of the visual HMI comprises a remote vehicle that mimics the design of commercial excavation platforms, mounted with cameras to acquire images of the explored environment; a position/tracking unit and a two-channel radio link for sending steering and manipulation signals. The remote machine is able to roam around a real space while sending video updates to a virtual world model of the real space. Steering is provided by means of a joystick controller from an operator station. The camera parameters (position and orientation) are tracked by a combination between GPS and mechanical tracking, and the video stream sent to the vision system for rendering a mixed scene consisting of virtual and real objects to the visual HMI.

2.6 Shortcomings of Previous Research

In general, a majority of the research contributions summarized in this chapter focused on design improvements for the control and very little or no contributions have been made regarding the design of the display, which is also critical for job performance. This can be attributed to the fact that the display reflects the visual modality which is already the most dominant modality in the HMI, and perhaps researchers wanted to explore 'sub-modalities' and their potential for bringing about performance enhancements. That notwithstanding, there are still great benefits that could be derived from further enhancing the design of the display. There was also the lack of proper usability testing to gain a better measure of the effectiveness and quality of the proposed operational concepts. Such partial research focus and oversights constrains the innovative prospects that may be brought about by considering a holistic design strategy that incorporates improvements in both display and control design.

2.7 Current Research Focus

The focus of this research is, therefore, to present a holistic design approach that involves an innovative interaction strategy - entitled augmented interaction - which employs advanced display (a heads-up display) and control schemes (coordinated control) for enhancing system usability and providing job-critical information needed by the operator to perform efficiently and effectively. In order accomplish this, perspectives in user-centered design, multimodal interaction and augmented reality which have all shown promise as proven techniques for aiding the design of HMIs that allow for a more enriched form of human-machine interaction were used to obtain a framework for guiding this research. This framework was used for deploying the augmented interaction strategy. The framework consists of three phases involving (1) the design, (2) the implementation and (3) evaluation of alternative HMIs for hydraulic excavators using a mixed reality simulated environment. The innovative augmented interaction strategy is thus proposed as an improvement on interaction methods currently being employed in practice; and promises to provide insights for designing futuristic HMI concepts for the next generation of hydraulic excavator designs, as well as HMI design of other heavy mobile equipment in the industry.

CHAPTER 3

Methodology

This chapter explains the methods adopted for this research including the research framework, the unit of analysis, the usability testing procedure which involves an experimental design, the data collection and data analysis procedure, and the ethical practices used in the research.

3.1 Research Framework

Augmented interaction strategy was developed on a framework consisting three major phases: Design, Implementation/Visualization and Evaluation (D.IV.E) (Figure 3.1). The framework shows the inputs (at the top) and outputs (below) of each phase.

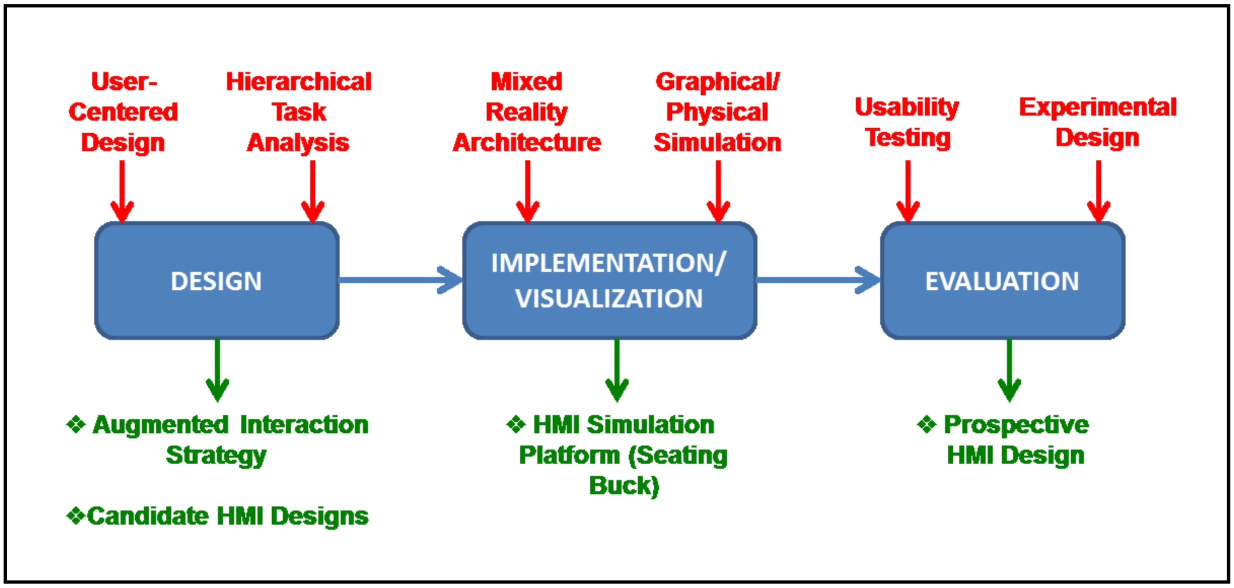


Figure 3.1. Research framework – D.IV.E.

In the Design phase, a user-centered design process supported by hierarchical task analysis was employed to design two alternative HMI design concepts that featured heads-up display and coordinated control (Design A), and heads-up display and joystick controls (Design B) respectively. These two alternative HMI designs were tested against the standard HMI design

(Design C), which served as the experimental control. Three candidate HMI designs were thus developed for implementation and evaluation.

The Implementation/Visualization phase involved the development of a mixed reality seating buck simulator, named the Hydraulic Excavator Augmented Reality Simulator (H.E.A.R.S), for simulating the three candidate HMI designs. H.E.A.R.S combined both virtual and physical components of the HMI elements of a hydraulic excavator. The virtual component included computer graphics and visualization of the three HMIs, combined with a work scene involving a rock excavation task. The physical components included the controls, and the operator's seat.

In the final phase, Evaluation, a usability study was conducted to examine the relative usability of the three candidate HMI designs. The usability study was characterized using quantitative and qualitative measures of the relative ease of use each of the HMI designs. The quantitative measures of usability were: task completion time and operating error; the qualitative measures were: subjected workload rating and subjective preference ranking.

3.2 Unit of Analysis

The unit of analysis of a research methodology defines what the object of the research is and so in the context of this research, the Human-Machine Interface of the hydraulic excavator is the unit of analysis. The analysis thus involves assessing the usability of new HMI concepts based on augmented interaction against the existing standard HMI design using objective and subjective measures of operator performance.

3.3 Equipment Setup

The mixed reality seating buck simulator, H.E.A.R.S, was used to provide the platform for simulating and evaluating the three HMI designs that were developed as a component of this research. H.E.A.R.S is a reconfigurable HMI evaluation platform that seamlessly combines computer-generated graphics (virtual objects) and physical devices that mimic the display and control elements of the HMI. It was comprised of five modules: *main module, graphics and computing module, display module, tracking module,* and *interaction module*. The main module served as the chassis or support structure for the seat and other hardware devices. The structure was made out of aluminium profiles and users were able to adjust the seat and supports for the controls in order to orient these elements to positions comfortable to them. On it, the two different controls (joysticks and coordinated control) were changed for each respective HMI being tested. The graphics and computing module consisted of computers for generating the virtual environment/task scenario and display visualizations, establishing the necessary communication protocols, and obtaining simulation output data. 3D models of an excavator and dump truck were created with a CAD software and imported into Virtools 5.0, which was the software used for generating the virtual environment for a rock excavation task scenario. An immersive mixed reality environment was provided with the display module. This was an open see-through head-mounted display – the nVisor ST60 (NVIS Technology, 2012). With this display, users were shown a forward view point of the windshield as would be experienced in a real cab. It was also used to present the visualization of the heads-up and monitor displays. The heads-up display was overlaid on the visor in the field of view of the user, but toward the right side of the virtual windshield. The monitor display was modelled as a 3D monitor and positioned at the bottom right side of the cab as would be seen in real life. The main difference between these two displays was in the type of visualization they provided. In addition to the traditional gauges that provided status information (i.e. oil and fuel level, engine temperature etc.), the heads-up display provided more information by including a bucket-integrated camera to provide a video feedback to enhance work visibility and information about environmental conditions (such as weather information).The tracking module used an Optitrak^{TM} VR100:R2 optical motion capture system (OptiTrak, 2012) equipped with 6 infrared cameras for accurately tracking and aligning user movements with updates in the virtual objects. The interaction module employed a Sensable^{TM} Phantom Omni haptic device (Sensable^{TM}, 2011)for simulating the coordinated control and a pair of Logitech^{TM} joysticks (Logitech™, 2012) for simulating the joystick controls.

3.4 Usability Evaluation

A usability evaluation involving a comparative assessment between three candidate HMI designs was conducted. The goal of the usability evaluation was to investigate the efficacy of the proposed augmented interaction strategy by gathering information to characterize the relative ease of use of each of the candidate HMI designs using quantitative (task completion time and operating error) and qualitative usability (subjective workload and user preference) metrics. The outcomes of these performance and subjective measures could then be used to predict the extent to which a prospective HMI design overcomes the gaps that currently exist in the standard HMI design. A design of experiments, described subsequently, was used for the usability evaluation of the candidate HMI designs.

3.4.1 Experimental design. A single-factor (HMI type), within-subject experimental design was used for analyses of experimental data. This yielded three experimental conditions based on the three HMI designs. The experiment was conducted with 20 participants. Each participant was made to interact with the three HMI designs in a completely randomized (counterbalanced) order. The independent variable was the HMI type. Both quantitative and qualitative responses were measured in the experiment as dependent variables. The quantitative dependent variables were task completion time and operating error. Task completion was defined as the elapsed time from the start to the end of the simulated task. The operating error was defined as the average number of errors that occurred during the task and this was estimated with two categories of error: ‘Error 1’ (termed error probability of collisions) and ‘Error 2’ (termed ‘error probability of misses’). The qualitative dependent variables were subjective workload ratings and subjective user preference rankings. Participants were asked at the end of the experiment to provide these responses using a computerized version of National Aeronautics and Space Administration (NASA TLX) and a Subjective Preference Questionnaire (SPQ) that was developed for this research (Appendix B). Analysis of Variance (ANOVA) was used to determine the statistical significance of the HMI type on the response variables. Tukey Honest Significance Difference test was used to examine the differences between the significant HMI types.

3.4.1.1 Experimental protocol. Each participant performed a simulated rock excavation task with the three HMI designs. The experiment was divided into four sessions and lasted a total of 90 minutes. The first session (5 minutes), was used to setup the seating buck. In the second session (10 minutes), the participant was invited to the study, his/her background information and consent to participate were requested, and a tutorial was given to familiarize him/her with the simulation. During the third session (60 minutes), the participant conducted the actual test by interacting with each of the three simulated HMI designs to complete the rock excavation task. The computing module of the seating buck was used to automatically obtain the quantitative response variables: a simulation clock was used to obtain task completion time data; while an error recorder was used to obtain Error 1 and Error 2 data. In the fourth, post-test session of 15 minutes, qualitative responses were collected by having the participants complete the NASA

TLX by rating the three HMI designs along five workload subscales – *Mental Demand, Physical Demand, Temporal Demand, Own Performance, Effort* and *Frustration Level*. Subsequently, the SPQ was administered to solicit information about participants' most preferred HMI across five usability attributes –*usefulness, satisfaction, accuracy, intuitiveness,* and *safety*.

3.4.1.2 Procedures for data and statistical analysis. For each participant, the quantitative and qualitative data from the simulator were collected and grouped by HMI type. These data were exported into an Excel spread sheet and the appropriate statistical methods were applied. Statistical analyses of the data, both descriptive and inferential, were computed using Minitab 15 (Minitab Inc., 2013). A single factor analysis of variance (ANOVA) was used to obtain empirical evidence of the relative usability of the three HMI designs by studying the effect of HMI type on operator performance.

3.5 Research Ethics

The researcher is aware of ethical standards of research. To this end, efforts were made to meet all professional, institutional and social standards for conducting research. This is a social behavioral research since it involves a usability evaluation of different HMI designs with a mixed reality simulator using human subjects. To ensure adherence to ethical standard of social behavioral research, approval was obtained for conducting this research study from the Institutional Review Board (IRB) of the Research Compliance Office at North Carolina Agricultural and Technical State University. All the requirements of the IRB were met, particularly by satisfying all three principles of human subjects research: informed consent, beneficence, and justice. For informed consent, all participants were made to conduct the test voluntarily, after having been adequately informed about the research, with full knowledge of relevant risks and benefits. It was emphasized to participants that they could stop the experiment if at any time during the experiment they felt uncomfortable. For beneficence, it was ensured that the research did not pose more than minimal risk to the participants. For justice, an equitable selection process was used to recruit participants and they were assured of the privacy and confidentiality of their information.

3.6 Phases of the Research

As depicted in Figure 3.1, this research will be developed in three phases. Chapter 4 presents the methodology that will be employed in the Design Phase. In Chapter 5, the methodology for the Implementation and Visualization Phase is presented, and finally the methodology for completing the Evaluation Phase is presented in Chapter 6.

CHAPTER 4

Design Phase

This chapter details the first phase of the research methodology – the Design Phase. It explicates a four stage user-centered design process used in designing alternative HMI design concepts that allow the new form of interaction, termed augmented interaction to be attained. To support the user-centered design process, hierarchical task analysis (HTA) was used in the second stage of the user-centered design process to establish requirements of the new HMI designs. HTA allowed the decomposition of complex tasks – such as the one involving the operation of a hydraulic excavator – into a hierarchy of goals and sub-goals so that the sequences of actions involved can be analyzed. The analysis was used to extract information about the physical and cognitive demands of an excavation task. This information was subsequently used to create the alternative HMI design concepts which were hypothesized to be an improvement over the standard HMI design. Two new alternative HMI designs in addition to the standard HMI design are obtained, yielding three candidate HMIs for implementation and evaluation. The two new alternative HMI designs featured two configurations of a heads-up display with coordinated control and joystick controls respectively; the standard HMI design features a monitor display and joystick controls.

4.1 User-Centered Design (UCD) Process

A user-centered design process was adopted for exploring the design of improved HMIs for hydraulic excavators. The four-stage user-centered design model from the ISO 9241-210:2010 standard (previously ISO 13407:1999) was used (Figure 4.1) (Usability Professionals' Association, 2012). The design activities performed at each stage are discussed in the subsections that follow.

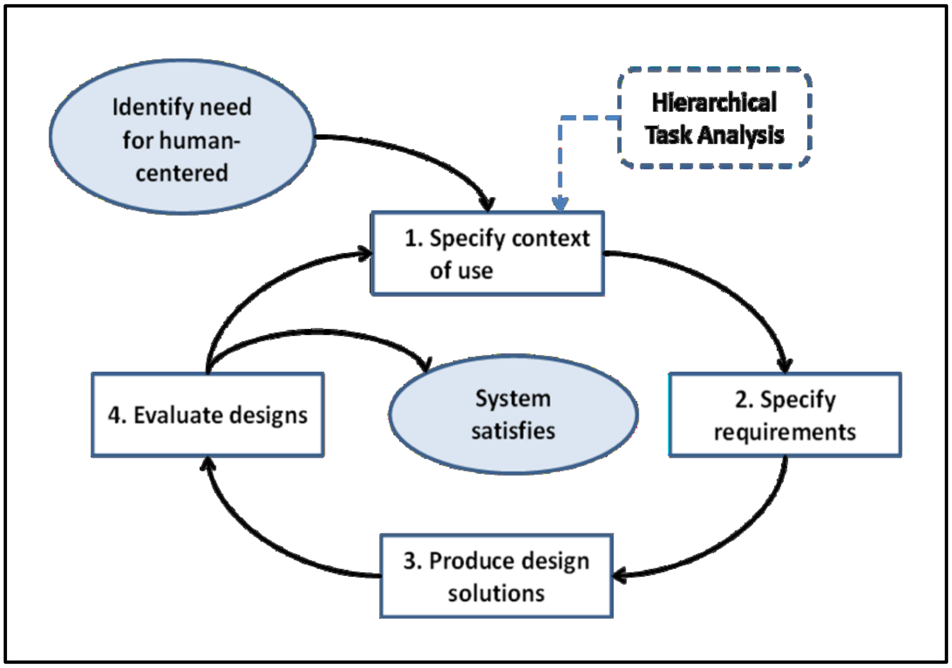


Figure 4.1. User-centered design process model (ISO 9241-210:2010).

4.2 UCD Stage 1: Specification of the Context of Use

Designing effective HMIs requires that context be taken into account. According to Dey, Abowd, and Wood (1999), and as defined by Uden (2007), context refers to any information that can be used to describe the situation of an entity – where an entity refers to a person, place or object that is reckoned to be relevant to the interaction between a user and a system; for this research, interaction between the operator and the hydraulic excavator. Thus, if any information or entity can be used to characterize the operator's actions while interacting with a system, then that information is the context. Context therefore plays an important role in understanding and designing the appropriate interaction for human use. Several contexts influence user actions in human-system interactions. These include: education and skills of the user, the environment, systems' goals, and organizational culture (Uden, 2007).

For hydraulic excavator HMI design, the environment where actual work processes take place is of paramount importance because there is a direct link between the environment and the

HMI since operators have to perform several actions to control the machine and also make numerous decisions via the HMI based on the environmental circumstances they encounter. The operator's actions cannot be separated from the environment in which they take place, and both operator and context must therefore be considered for effective HMI design. In light of this, the occupational profile of hydraulic excavator operators and the characteristics of their work environment were studied and are presented successively.

4.2.1 Occupational profile of hydraulic excavator operators. At the heart of every User Centered Design methodology are the users to whom the design is targeted. The users must be identified and be the focus at every stage of the design process. Their needs, wants and limitations must be considered and incorporated into the design. Hydraulic excavator operators are the users under consideration in this HMI design research. Their occupational profile was studied and a number of them were involved in the design process. They are classified as heavy equipment operators or construction equipment workers. Their occupation involves the operation and maintenance of heavy construction equipment, such as motor graders, bulldozers, backhoes, scrapers, cranes, shovels, front-end loaders, rollers, tractors, forklifts, compressors, pumps, and derricks. According to the Bureau of Labor Statistics (2010), heavy equipment operators fall into three categories of occupations: (1) operating engineers (OEs) and other construction equipment operators; (2) paving, surfacing and tamping equipment operators (PSTs); and (3) piledriver operators (PDOs).

Hydraulic excavator operators fall under OEs and other construction equipment operators whose primary work function involves clearing and grading of land to prepare it for construction of roads, buildings, bridges, airport runways, power generation facilities, dams, levees, and other structures; digging of trenches to lay or repair sewer and other utilities; and hoisting of heavy construction materials.

Hydraulic excavator operators are trained either through a formal apprenticeship program, on-the-job training, a paid training program, or a combination of these programs. Most of them are high school graduates. They are trained to obtain skills in such areas as hydraulics and electronics, automobile mechanics (for maintenance), mechanical drawing, and computerized controls and systems (especially in GPS enabled machines). Many operators are trained to operate different pieces of equipment, with operation of four to six pieces of equipment being common (Zimmermann, Cook, & Rosecrance, 1997).

In the 2010-11 Occupational Outlook Handbook, the Bureau of Labor Statistics (2010) reported that in 2008, there were an estimated 469,300 construction equipment workers. Of these, 404,500 (86%) were OEs, with median hourly wage of $ 18.88; 60,200 (13%) were PSTs, with median hourly wage of $16; and 4,600 (1%) were PDOs, with median hourly wage of $23. The projected job growth rate for construction equipment operators is 12%, estimated between 2008 and 2018. This will be spurred, among other things, by increased federal government spending on infrastructure to improve roads and bridges, railroads, the electric transmission system, and water and sewer systems; an expected rise in energy production which will increase work on oil rigs, smart grids, windmill farms, pipeline construction, and other types of power-generating facilities; and increased output of mines, and rock and gravel quarries.

4.2.2 Work environment. Hydraulic excavator operators work in outdoor environments in nearly every type of climate and weather condition. Some operators work in remote locations on large construction projects, such as highways and dams, offshore oil rigs, or in factory or mining operations. The types of terrains they work on include sand, gravel, clay, rock and concrete. They often get dirty, greasy, muddy, or dusty. They sometimes work at irregular hours because work on some projects continues around the clock or must be performed late at night or early in the morning.

4.3 UCD Stage 2: Specifying Requirements

Hierarchical task analysis (HTA) was used to identify sources of improvements in the standard HMI design and based on that to specify new requirements for designing an improved HMI. HTA was adopted because it offers a flexible, exhaustive and systematic task analysis method that provides a means of identifying the behaviors that occur during a task. According to Stanton (2006), HTA was developed by Annett and Duncan (1967) to provide a systematic basis for understanding the component skills required in complex non-repetitive tasks such as those in process control industries. It has since been extended to a range of applications including interface design and evaluation, job aid design, error prediction, and workload assessment.

HTA is used to decompose a high-level, complex task into a hierarchy of goals and sub-goals. The goal represents the motive of the task, which is accomplished by means of operations. Operations are the conditions relating to the specific actions that must be performed to attain the goal. At its core, HTA is based on a theory of performance (goal-directed behavior) with three governing principles. These three governing principles were described by Annett, Duncan, Stammers, and Gray (1971) as follows:

1. *At the highest level we choose to consider a task as consisting of an operation and the operation is defined in terms of its goal. The goal implies the objective of the system in some real terms of production units, quality or other criteria.*

2. *The operation can be broken down into sub operations each defined by a sub-goal again measured in real terms by its contribution to overall system output or goal, and therefore measurable in terms of performance standards and criteria.*
3. *The important relationship between operations and sub-operations is really one of inclusion; it is a hierarchical relationship. Although tasks are often proceduralized, i.e. – the sub-goals have to be attained in a sequence, this is by no means always the case.*

These three principles can be summarized as indicating that HTA is a goal-based analysis of a system. The ultimate goal is a function of system objectives, and the achievement of sub-goals and the overall system goal can be evaluated in terms of measurable performance criteria. In order to satisfy the goal in the hierarchy its immediate sub-goals also have to be satisfied.

4.3.1 Hierarchical task analysis for hydraulic excavator. Proctor, Dunston, So, and Wang (2012) used HTA to conduct the analysis of a trench digging task involving a hydraulic excavator. By employing HTA to decompose such a complex excavation task into a hierarchy of goals and sub-goals, they identified the skills requirements needed to operate the machine. Their goal was to use such information to improve training of operators during both simulator and real equipment training phases. In this research, HTA was used to decompose an excavation task to extract information for specifying new requirements for HMI design improvement. Additionally, input from experienced operators, as well as proper consideration of the physical and cognitive demands of the task were used to extract additional information for obtaining the new design requirements.

The starting point of the HTA for the hydraulic excavator was to establish the task for the analysis. The selected task is excavation. Excavation is often used as a broad term which includes cuts (trenching) and fills (embankment). Cuts involve removing material to lower the elevation of an area. Fills involve placing material to raise the elevation of an area. Other forms of excavation include material handling such as the picking and placing of rocks and prefabricated materials on a construction site. A trench digging task was considered in the analysis. This task was selected because it is the most commonly performed with the hydraulic excavator.

In order to conduct a practical analysis using HTA, information about excavation tasks was extracted from published literature (Proctor et al., 2012), and performance manuals such as the Caterpillar Performance Handbook (Caterpillar, 2004) and the American Pipeline Contractors Association's manual on "Excavation and Trenching Best Practices for Operators" (APCA, 2008). To obtain further insight about the task, the information gathered was refined by observing an operator perform a trench digging task on a drainage system construction project at North Carolina A&T State University (Figure 4.2).

Figure 4.2. Typical excavation work at a construction site.

In the construction of HTA diagrams the notation of Annett, Cunningham, and Mathias-Jones (2000), as adopted by Proctor et al. (2012), was also adopted in this research. While the HTA diagram constructed by Proctor et al. (2012) showed only the 'steady state cycle of the operations' (i.e. the working stage where the hydraulic excavator is positioned at a fixed work location and the operator uses front manipulator to perform a series of dig and dump cycles), the HTA diagrams constructed here are extended to include the 'start-up' and 'finish' operation states of the task. Thus, the task was divided into three states: initiation, working and termination states respectively in the analysis (Figures 4.3, 4.4 and 4.5). Each state is described by its overall goal and sub-goals. The cognitive and physical demands of the task in each state are extracted to understand their impact on task performance, since these demands can be linked to the effectiveness of the HMI design.

In the HTA diagrams, the goals and sub-goals in the boxes are numbered in an outline structure. Thus, the overall goal (0) is at the top of the hierarchy. The first level sub-goals are numbered in a numerical order (1, 2, 3 etc.) and located directly below the overall goal. Additional sub-goals are decomposed into a second level of sub-goals (e.g. 1.1, 1.2, 1.3 etc.). The 'Plan' specified in the ovals shows the conditions under which each of the sub-goals are triggered. The ">" notation is used to describe subtasks that are performed sequentially, and the "+" notation is used to describe subtasks that are performed concurrently (Proctor et al., 2012).

4.3.1.1 Initiation state. During the initiation state (Figure 4.3), the goal of the task is to prepare the work site and position the machine for starting the job. This goal is supported by the following sub-goals: (1) conducting a walk-around check to assess the external physical conditions of the machine and ensuring the environment is safe from obstacles; (2) recording initial ground level and marking-out the work area or envelope (i.e., drawing out the trench lines); and (3) positioning the machine at the work location. The decision point illustrated in the diamond shape for Plan 1 refers to the requirement that, for ‘sub-goal 1’, the work environment must be checked for safety before starting the task. If the environment is safe (Yes), then the operator proceeds with ‘sub-goals 2 and 3’; if the environment is not safe (No), the operator must complete ‘sub-goal 1’ before proceeding with ‘sub-goals 2 and 3’. ‘Plan 3’ shows that the third sub-goal is decomposed into lower-level sub-goals and it also describes the sequence of the tasks which include: mounting the cab (3.1), turning on the ignition (3.2), checking the gauges and the controls (3.3), setting the work modes (3.4), and moving the machine to the work location (3.5). ‘Sub-goals 3.2, 3.3 and 3.4’ are performed concurrently.

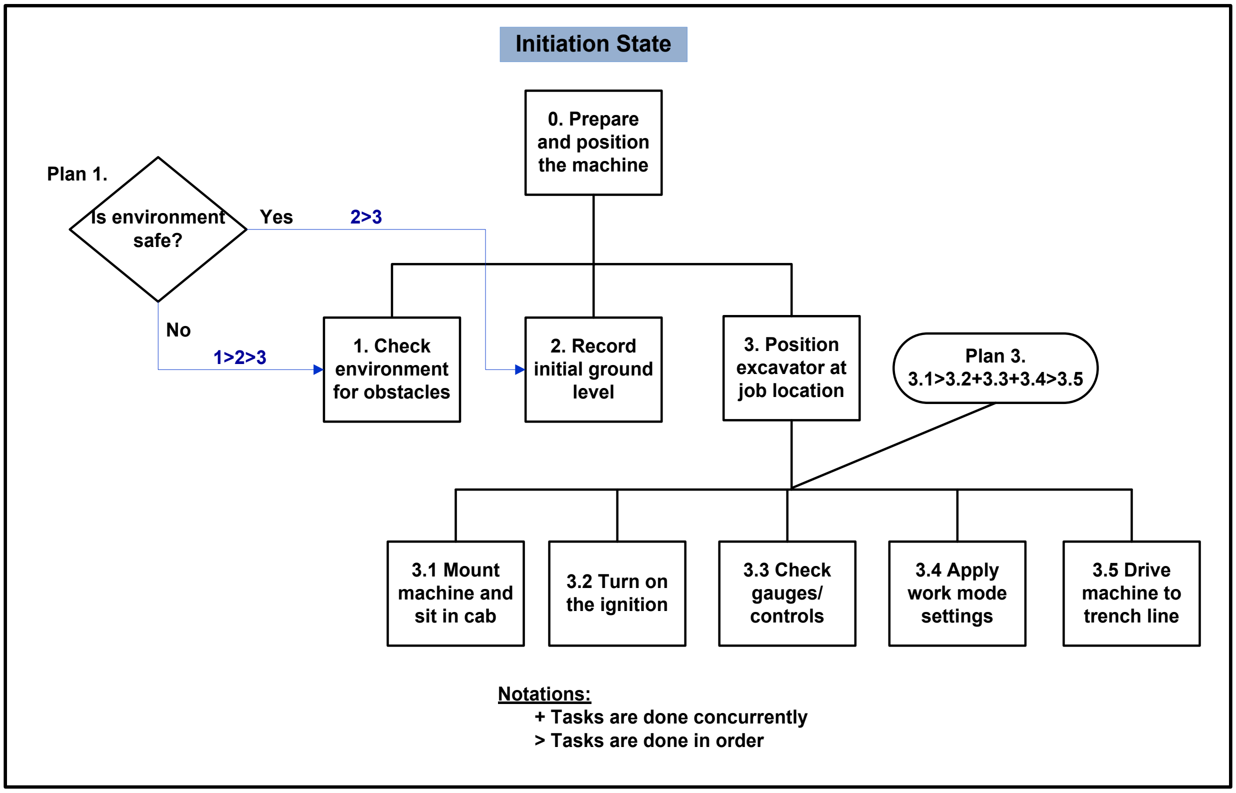


Figure 4.3. HTA diagram for initiation state of excavation task.

The tasks performed in this state place both cognitive and physical demands on the operator. Cognitive demands arise from checking of the gauges, obtaining status information from the monitor display, setting the work mode, obtaining the ground level, and determining how to position the machine near to the trench. To meet such cognitive demands, the operator draws heavily on declarative knowledge of standard operating procedures as learned through training. Physical demands stem from extending the arms to turn the ignition on and manipulating the controls to move and position the equipment.

4.3.1.2 Working state. During the working state (Figure 4.3), the physical action of digging the trench is performed. The set goal is to dig a trench by making a cut in the ground, and loading the excavated soil into a dump truck bed. With the machine positioned in line with the trench, the operator uses the joysticks to control the front manipulator, which usually involves lowering the boom, and stick to bring the bucket to cut through the soil, then curling the bucket to scoop the soil. With the soil contained in the bucket, to dump it into the dump truck bed, the operator swings/rotates the cab and positions the bucket above the dump truck bed, uncurls it and releases the soil. The operator then re-positions the machine for the next digging cycle. The decision point illustrated in the diamond shape for “Plan 0” refers to the periodic requirement that the excavator back up along the trench line to obtain an optimal reach for digging the trench. These five operations and their associated sub-operations are repeated until the trench is completely dug.

The working state of the task induces a significant amount of cognitive and physical workload. To form the trench, the operator uses the two joysticks to perform a series of lowering, raising, curling and swinging of the working parts, and occasionally uses the levers and pedals to drive the machine to position/reposition it near the trench. The operator checks the monitor display to ascertain the status of the system such as fuel level and engine temperature. The operator also looks at the ground to check whether the trench is being dug to the desired depth.

Depending on the skills level of the operator, their behavior toward the task may be skill-, rule-, or knowledge-based. For experienced operators, the amount of mental effort required on their part is typically less since the performance of task evolves into a skills-based behavior over time, that is, one that has been overlearned and becomes automatized. On the contrary, for novices, the mode of behavior may be either rule-based, which requires more effort and the retrieval of explicit rules about what actions to take in specific circumstances; or knowledge-based, which is the most effortful and time consuming, requiring diagnoses of problem situations and selection of action to achieve the desired outcome. A significant amount of physical workload is also induced due to the repetitive use of the controls and awkward body postures the operator is subjected to in the effort to accomplish the task goals.

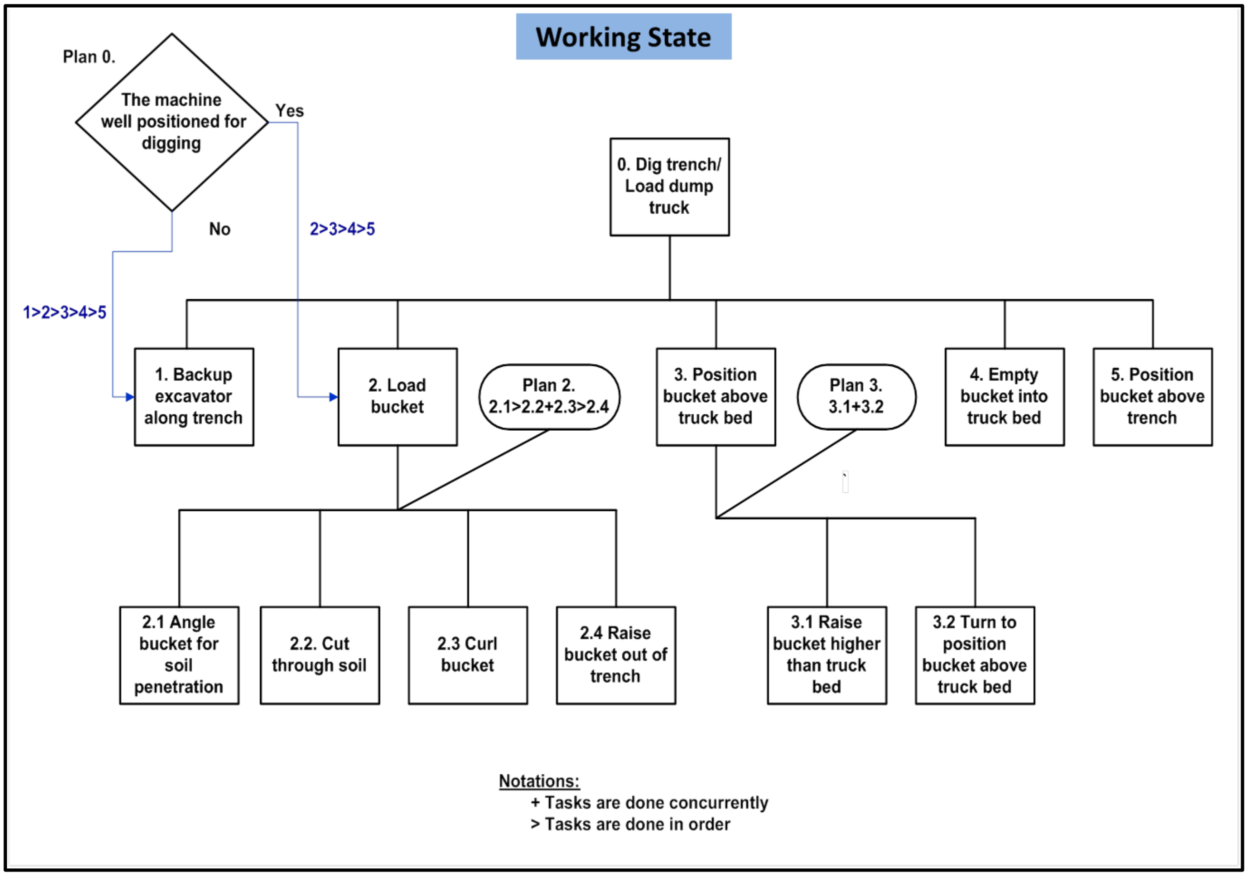


Figure 4.4. HTA diagram for working state of excavation task.

4.3.1.3 Termination state. This is the final state where the trench digging task is brought to an end (Figure 4.5). The operator's goal is to close-out the task. The key operations that are performed in this state are those that involve using the controls to reposition the machine to the "home" position, and the key switch to shut down the machine. Other operations done in this state such as refueling, removal of materials/debris generated in the process of work activities, repairs and maintenance work are left out because they typically do not require the use of the HMI.

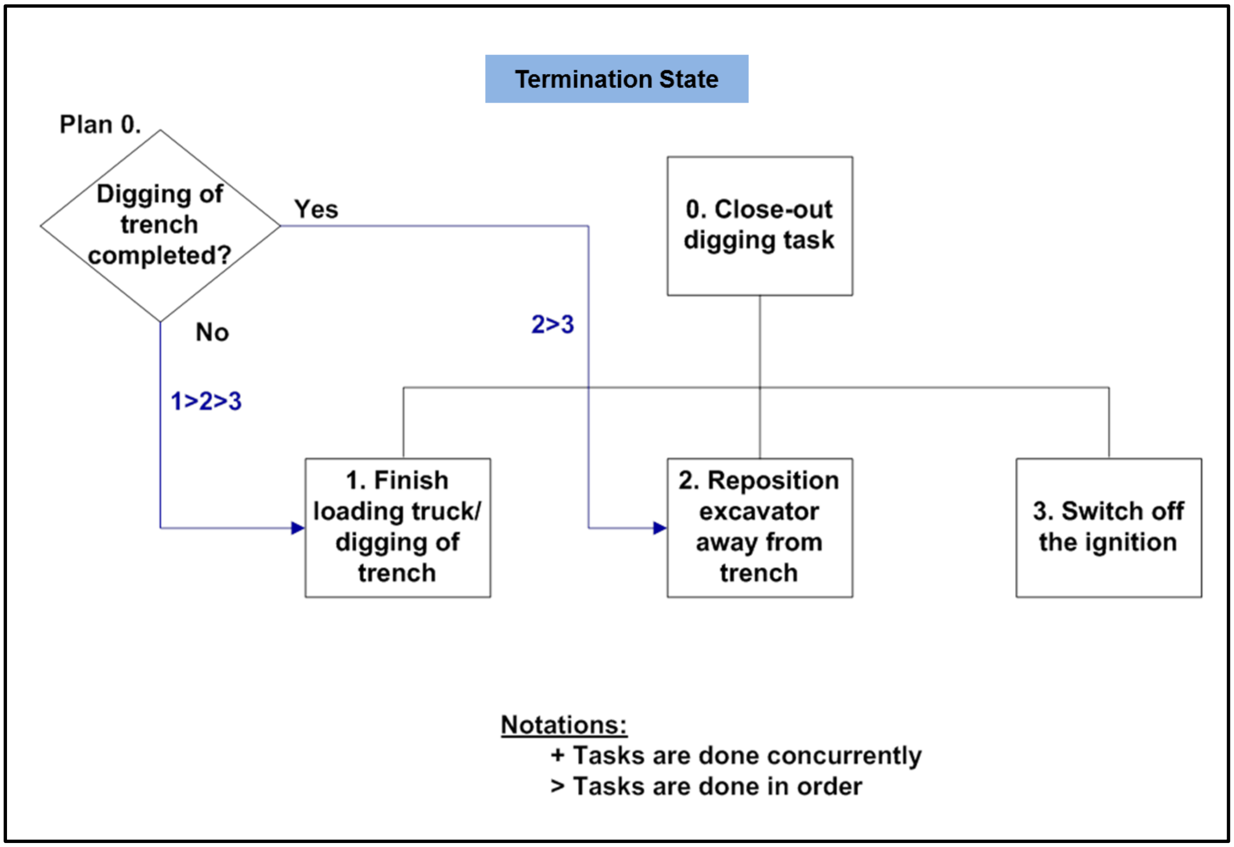


Figure 4.5. HTA diagram for termination state of excavation task.

This state induces very little cognitive and physical workload. The operator uses the controls to reposition the machine and key switch to shut it down. He/she also checks the HMI to record the final states of the machine such as the amount of fuel consumed, oil level, and work mode settings and uses that information to determine the system demands for the next job.

4.3.2 Analyses of the HTA diagrams. The analyses of goal hierarchies for the hydraulic excavator trench digging/dump truck loading task as shown by the structure of the task in the different states illustrates the usefulness of HTA is decomposing tasks into goals and sub-goals, and extracting the specific cognitive and physical demands for the execution of each sub-task. From the HTA diagrams, it can be seen that the working state of the task required more sub-tasks than the other two states, and consequently required a greater use of the elements of the HMI to accomplish the goal of the task. This suggests unsurprisingly that cognitive and physical task demands are more pronounced during the working state. It can be seen from Figure 4.4 that the sub-tasks are higher during the loading of the bucket and when positioning it above the dump truck bed. These sub-tasks therefore represent the major sources of mental and physical workload of the task. During the performance of these sub-tasks, in order for the operator to control the front manipulator effectively, the operator must move the joystick controls in a repetitive pattern to control the boom, stick and bucket, and swing the cab. Such repetition induces significant amount of physical stress. It was also observed that, in terms of utility, while the controls were more useful and afforded the operator a means to control the machine, the monitor display on the other hand was limited to displaying only information about the state of the machine, and operators seldom used it when performing the excavation task.

Decomposing the task using HTA and using it to extract the cognitive and physical requirements accounted for two potential sources of design improvement of the standard HMI design in terms of both control and display design. First, for the controls, as noted by (Proctor et al., 2012), although the HTA diagrams may characterize the goal structure for both novices and experts, it is possible that some of the subtasks performed sequentially by novices may become proceduralized in experts to allow them to perform the task concurrently. To reduce this imbalance in control skills between experts and novices, a control design that bridges the skills gap between them and allows for smooth, coordinated control becomes essential for facilitating task performance. Secondly, to become more useful, the display can be designed to capture additional information beyond machine status to include such job-critical information as ground visibility (depth and elevation), and environmental conditions (weather, soil characteristics, obstacles in the ground, etc.).

4.3.3 Operator involvement and feedback. To further refine the analyses of the HTA to obtain a better sense of the feasibility and potential benefits in the proposed design improvements, three excavator operators with an average of ten years working experience were interviewed to validate the analyses and obtain feedback as to the modifications that need to be made to improve the design of HMI. To this end, questions were posed to them and their responses were noted. These questions and responses are summarized in Appendix K.

The collaboration with the operators and the responses they provided a deeper insight of the gaps present in the existing HMI design, and led to the creation of a shared vision for an innovative solution for addressing those gaps. From analyzing the HTA diagrams and obtaining the operators' feedback it became evident that the complex and data rich work environment subjects the operator to considerable cognitive and physical demands. The operator must process lots of information and maintain high situational awareness, which results in the high workload. Under high workload situations, the current interaction modalities employed in the standard HMI design are not sufficient to adequately support effective task performance, making it imperative that other ways of augmenting the interaction be considered. An innovative interaction technique (dubbed augmented interaction in this research) employing advanced work visualization and interaction schemes was therefore envisioned as a solution to addressing the usability gaps in the existing standard HMI design. New HMI design requirements for attaining this new form of interaction were therefore defined. The new design requirements are subsequently presented below.

4.3.4 New HMI design requirements for attaining augmented interaction. Based on the analyses performed and the feedback obtained from the interviewed operators, new design requirements were defined for designing new HMIs with augmented interaction. The design new requirements include:

1. A display that provides additional, job-critical information that is easy to access and understand.
2. A control that is intuitive, easy to use and learn.
3. An HMI that is ergonomic and safer to operate with.

Providing HMI design solutions that meet these new requirements gives rise to an innovative form of interaction which has been termed augmented interaction. *Augmented interaction is thus defined as a form of interaction which involves the use of advanced display and control schemes employing heads-up display and coordinated control that allows job-critical information to be presented to the operator for quick, easy and safe access, as well as providing an effective means of system control.* An HMI designed to incorporate this type of interaction promises to provide enhanced usability, while allowing operators to successfully accomplish their task goals with significantly less mental and physical effort.

These new requirements place important demands on the design of the display and control elements of the HMI. The first requirement for display design, emphasizes that the HMI be designed with technologies that not only allow status information to be presented to the operator, but that the information must also be augmented, i.e., it should provide additional information that cannot easily be sensed by the operator and must be easily accessible. The second requirement for control design demands that the control for operating the front manipulator be intuitive, providing novices especially with less difficulty in learning how to use it. The third requirement demands that the design of both the display and control should reduce as much as possible the sources of physical workload such as awkward postures and overexertion, in order to obtain an HMI that is safer to operate with.

4.4 UCD Stage 3: Producing Design Solutions

To obtain HMIs with augmented interaction therefore, an advanced form of visualization via the display and an intuitive type of interaction via the control is essential for the design of the HMI. To this end, the following technical solutions have been identified as the enablers for designing this type of interaction for hydraulic excavators:

1. *Display*: A heads-up display for providing all the job-critical information needed in one place with proper visualization to reduce the operators cognitive workload.
2. *Control*: A coordinated control device whose segments resemble the geometry of the front manipulator (boom, stick and bucket).

4.4.1 Display scheme for augmented interaction (heads-up display). Heads-up displays originated with jet fighters to provide flight information – as shown in Figure 4.6 (Google Images, 2012) – to pilots without requiring them to look away from their usual viewpoints. It also sought to ease information overload and to make the instrumentation less complicated. Since then, heads-up display technologies have advanced and become common in many commercial aircrafts, and quite recently, they have been implemented in some cars (Spies et al., 2009; US Department of Transportation, 1995). Adopting heads-up display technology for hydraulic excavators will provide the operator with centralized, critical information within the operator's field of vision. This would increase the operator's scan efficiency and reduce task saturation and information overload. Unlike the traditional monitor display in current hydraulic excavator models, the heads-up display will have all the information needed in one place for the operator to work faster and more accurately, eliminating the need to turn the head to view the already information deficient traditional monitor display.

Figure 4.6. Heads-up display – aviation.

For the hydraulic excavator, the following considerations were made for developing the information visualization schemes that need to be provided to the operator via the heads-up display in order to attain augmented interaction. Such information includes:

- ***System Status Information***: Real-time information about the status of the machine such as engine rpm, oil temperature, fuel level, an eco-gauge; machine position and orientation via GPS; and previous and current positions of the components of front manipulator to give an indication of the operator's trajectory for the current digging/loading pass.

- ***Work Visibility Information***: A video display of real-time depth, sloping, elevation and reaching information of obscure work zones. This will be in the form of a bucket-integrated camera that tracks the position of the bucket and sends a video feedback of such obscure work zones to the heads-up display.
- ***Environment Information****:* Information about the weather, terrain characteristics, and user-friendly safety alerts (e.g. an alarm notifying of presence of obstacles in work zone)

4.4.2 Control scheme for augmented interaction (coordinated control). Coordinated control is proposed for providing the control scheme for meeting the requirements of augmented interaction. The coordinated control in itself is intuitive since the controller geometry emulates that of the front manipulator of the hydraulic excavator. Additionally, it can be equipped with haptic feedback to allow operators to feel the digging forces from the ground via the controller, which enhances their cognition by giving them a sense that they are getting the job done. However, haptic feedback control was not considered in this research, since considerable investigations have been conducted about haptic feedback in some previous research work that have been presented earlier (see Section 2.8).

Although there are currently no industrially-made coordinated controls for operating the hydraulic excavator, there are some commercially available force-feedback controllers that have been employed in research to investigate the feasibility of using the coordinated control scheme for a hydraulic excavator. These include the Sensable^{TM} Phantom Omni and Phantom Premium haptic controllers (Sensable^{TM}, 2011) (Figure 4.7).

Figure 4.7. Sensable^{TM} haptic controls: (a) Phantom Omni; (b) Phantom Premium.

4.4.3 Candidate HMI designs. Based on the technical information presented above, three candidate HMI designs were developed for implementation and evaluation. The first design, Design A, combines the heads-up display with a coordinated control device (referred to as the phantom). In order to test the viability of the heads-up display concept with the traditional joysticks, a second design, Design B was created. The third design, Design C, maintains the standard design which combines a monitor display with the joystick controls. Based on these display and control combinations, each of the three designs was classified as offering a certain type of augmented interaction style. Design A was described as employing "*full augmented interaction*," Design B employed *"partial augmented interaction*," and Design C was used as the experimental control and therefore considered to employ "*no augmented interaction*." The three candidate HMI designs and their technical descriptions are shown in Table 4.1.

Table 4.1

Candidate HMI Designs

HMI Element	**Alternative Solutions**		
	HUD/haptic HMI		***Traditional HMI***
	Design A	***Design B***	***Design C***
Display	*Heads-up display*	*Heads-up display*	*Monitor display*
Control	*Phantom Control*	*Joystick Controls*	*Joystick Controls*

4.5 UCD Stage 4: Evaluation of Alternative Designs

Evaluation of the alternative HMI designs directly follows their implementation. Implementation involved simulating prototypes of the candidate HMI designs. A mixed reality seating buck was developed to simulate prototypes of the candidate HMI designs, as well as provide the evaluation platform for testing them. Details of the development of the seating buck are presented in the next phase, the Implementation Phase, of this research in Chapter 5. To evaluate the candidate HMI designs, a usability testing aimed at determining the relative usability of the three HMIs along quantitative and qualitative performance measures including task completion time, operating error, subjective workload, and subjective user preference was conducted. This is presented in the Evaluation Phase of this research in Chapter 6.

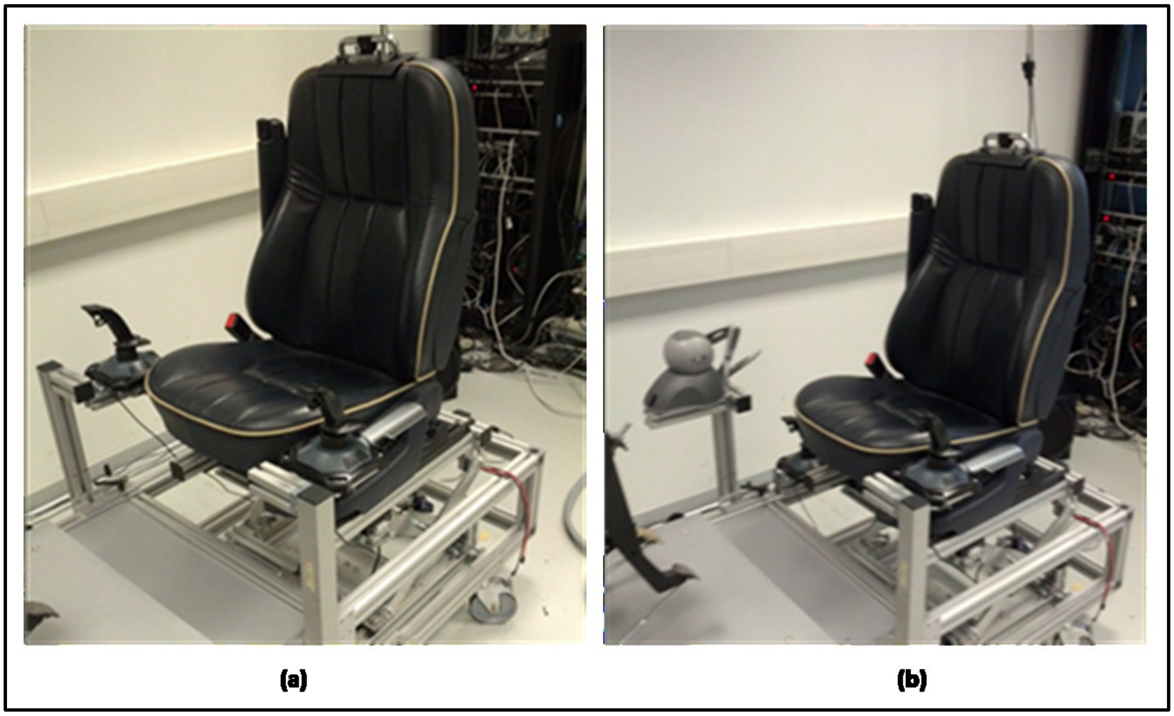
CHAPTER 5

Implementation/Visualization Phase

This chapter describes the second phase of the research methodology. The implementation of the three candidate HMI designs are presented herein. The outcome of the work done in this phase is the development of prototypes of the three HMI designs using H.E.A.R.S, the seating buck mixed reality simulator. A description of the architecture of H.E.A.R.S, and its soft and hardware components are presented. Subsequently, the technical details about how the virtual and physical simulations of the HMI designs were developed are presented.

5.1 Development of the Seating Buck (H.E.A.R.S)

The implementation of the augmented interaction strategy required a platform for easily and effectively simulating the three different HMI configurations. To accomplish this, a mixed reality seating buck simulator named the Hydraulic Excavator Augmented Reality Simulator (H.E.A.R.S) was used (Figure 5.1). The original seating buck was developed by Bordegoni and Caruso (2012) for evaluating virtual prototypes of automobile HMIs. It was modified in this research to provide simulation platform for simulating hydraulic excavator HMIs. The seating buck was constructed out of standard alloy profiles and integrated with augmented reality technologies, thus providing a mixed reality system. This type of mixed reality system allows users to see and interact with both the physical and the virtual components in a natural way. For simulating the candidate HMI designs of the hydraulic excavator, the physical components of the seating buck consisted of the operator seat and a set of joystick and phantom controls; and the virtual components consisted of the display visualization schemes (i.e. the heads-up display and monitor display visualizations).


(a)

(b)

Figure 5.1. The seating buck (H.E.A.R.S) with: (a) joystick controls; (b) phantom control.

5.1.1 H.E.A.R.S system architecture. The system architecture on which H.E.A.R.S was based consisted of four modules namely: the *main module*, *graphics/dynamics computing module*, *tracking module*, and *interaction module* (Figure 5.2). Based on the architecture described above, a simulation network consisting of the software and hardware devices selected for running the mixed reality simulator for evaluating the three HMI designs is shown in Figure 5.3.

The *main module* includes the skeleton of the structure, the pedals mechanism, supports for the joystick and phantom controls, and the support for the operator seat. The supports for the controls were made of two (left and right) vertical rectangular alloy profiles with a horizontal resting base at the top onto which the controls were held firmly in place. Attached to the bottom of the vertical supports were rails that fit into grooves at the bottom left and right sides of the skeleton structure to allow for adjustability. The resting bases are adjustable to three degrees of freedom (vertical, horizontal and rotational) so that the desired position and angle for the controls can be chosen by the operator.

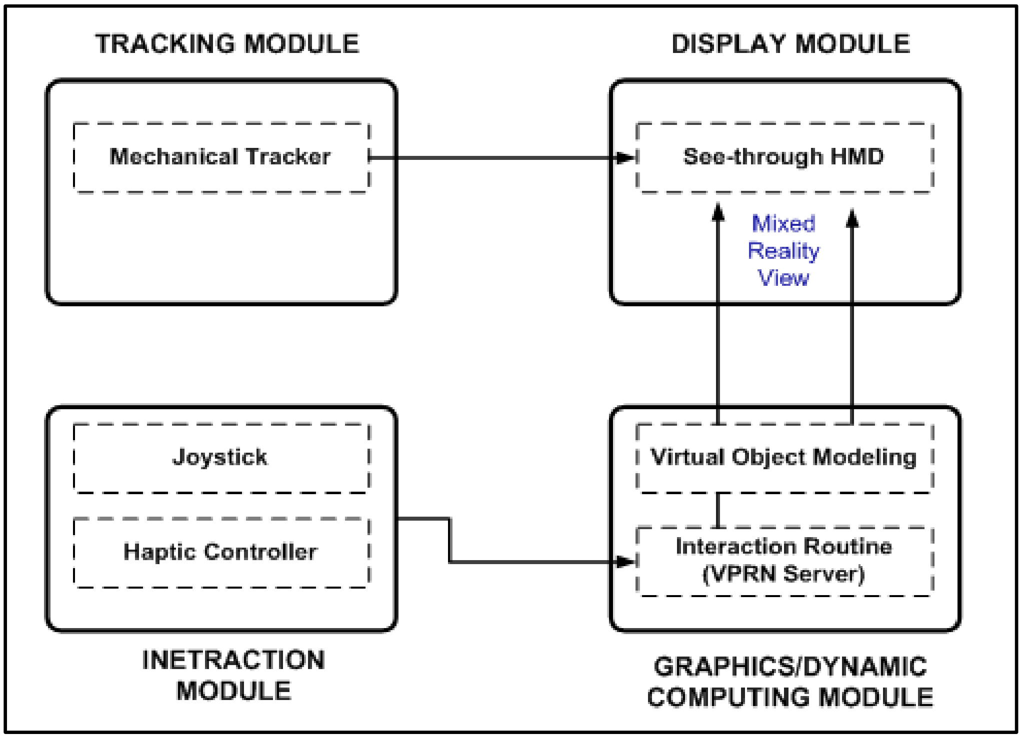


Figure 5.2. H.E.A.R.S system architecture.

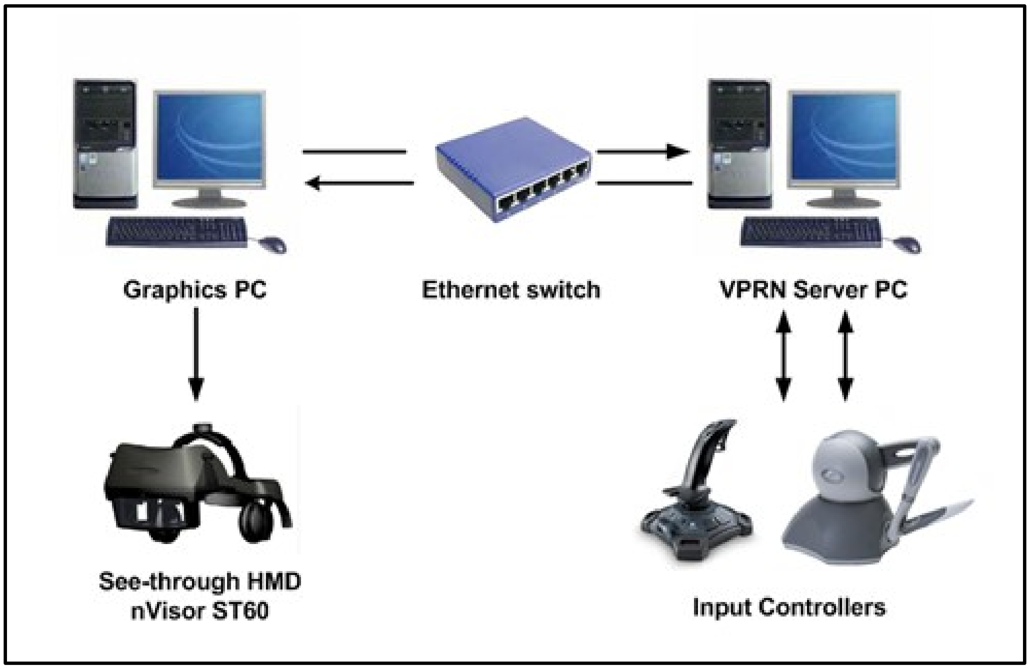


Figure 5.3. Simulation network.

The *graphics/dynamics computing module* consisted of a graphics computing system for rendering the virtual objects of the simulator and a dynamics computing system for establishing the physical relationship of the hardware/control devices with the graphics. For simulating the HMI displays (heads-up display and monitor display), virtual objects in the form of descriptive texts, 3D solid models, photo images, and animations were used. The type of graphical media used for a particular HMI type depended on the type of information needed to be presented. Two desktop personal computers (PC), dubbed Graphics PC and Virtual Reality Peripheral Network (VRPN) Server PC, networked via Ethernet cards were used to implement the graphics/dynamics computing module. The Graphics PC was a custom PC running a Windows 7 operating system with an Intel Core i7 processor, 12 GB RAM and a Quadro FX 3800 video card. It employed the software, 3DVIA ™ Virtools 5.0 Software Development Kit (SDK), to draw and render the display visualizations and virtual environment, play audio sounds, and write the simulation output data to a file. The Virtools SDK afforded a script-based application development interface that allowed the virtual world to be built using a set of object modules (e.g. box, rectangle) and building blocks (e.g. rotate, transform etc.). The building blocks were used to add behavior to the objects; behaviors were built by creating a script on an object and linking the associated building blocks to them. The Virtools SDK also provided resources for interfacing the hardware components with the graphics to develop the mixed reality simulator. The VRPN Server PC was an IBM PC running a Windows operating system with a Pentium 4 processor, 1.5GB RAM and a Quadro4 XGL video card. It was used to solve the dynamics of the excavator’s moving parts. It was also used to run the code for managing the tracking system. The final output of the graphics/computing module was sent to the display module.

The *display module* handled the display of digital information in the mixed reality simulator. This module received the virtual information from the graphics/dynamics module for providing visualizations of the HMI display elements and virtual work environment to the user. The visualizations of the HMI display elements and virtual work environment were provided by means of an nVisor ST60 optical see-through head-mounted display. This display allowed the simultaneous visualization of both virtual and physical objects. Users were able to see themselves in the scene, thereby introducing a sense of presence within the environment. The nVisor ST60 was equipped with the following technical specifications: a proprietary optical design that provides users with 1280x1024 pixels per eye across a 60 degree field-of-view; and high efficiency optics incorporating reflective-transmissive polarizers that increase light-throughput and present a high-contrast virtual image while allowing 40% light transmission from the environment (NVIS Technology, 2012).

The *interaction module* allowed the user to manipulate the virtual environment graphics. This was accomplished by developing an interaction routine – a code that runs on the VRPN Server PC and affords the software interface that facilitates communication between the controls and the graphics. A pair of Logitech ™ Attack Pro joystick controls (Logitech™, 2012) were used to simulate the standard joystick controls, and the Sensable™ Phantom Omni (Sensable™, 2011) was used to simulate the coordinated control. The interaction routine obtains the command position and velocity data from these controls via user input and sends this command to the graphics of the simulator (including graphical representations of the bucket, arm, and boom) to allow them to be manipulated.

The *tacking module* allows the point of view of the user to be tracked so that the virtual objects are always coherent with the user's viewpoint. To avccomplish this, the Optitrak™

VR100:R2 optical motion capture system was used for tracking user movements (OptiTrak, 2012).

5.2 Implementation Details

The mixed reality seating buck simulator, H.E.A.R.S, required a combination of both virtual and physical aspects of the HMI designs. Therefore, these two aspects were carefully developed to allow for the implementation of the HMI designs. The technical implementation details of the virtual and physical aspects of H.E.A.R.S are thus presented in the following sub-sections.

5.2.1 Virtual simulation. The virtual elements of the simulator consisted of generic three-dimensional (3D) computer-aided design (CAD) models of a hydraulic excavator (Figure 5.4) and dump truck (Figure 5.5), the display elements, and the virtual work environment (or work site). All of these were developed with the Graphics PC. The cab of the hydraulic excavator was designed to the 95th percentile population. The 3D-CAD models were imported into Virtools and specific virtual constraints were applied to establish the proper kinematics for the joints of the front manipulator. A virtual task scenario was also created. This consisted of five rocks, which the user was required to interact with during the testing session. In order to allow the interaction with the rocks, it was necessary to add a physical characteristic to each rock. To this end, the physics pack of the Virtools SDK was used to set physical features such as mass, friction, and inertia to the rocks.

5.2.1.1 Display design. The visualization schemes for the heads-up display (Designs A and B) and monitor display (Design C) were graphically modeled and integrated into the virtual environment. For Designs A and B, the heads-up display visualization included information about system status; a bucket-integrated camera that follows the bucket to provide work visibility information in real time, and information about environmental conditions (Figure 5.6).

For Design C, the monitor display (Figure 5.7) was modeled as a 3D monitor as the operator would see in reality, and only presented information about system status using gauges along with function keys for selecting and setting other system options such as work mode, time, and type of front manipulator work attachment. It is important to note, however, that apart from the gauges that indicated system status, the functional keys were made static merely to represent the design concept of the monitor display interface. Animation of the keys was not developed, since selection and setting of those system options with the keys were not necessary for the task scenario.

Figure 5.4. Rendered SolidWorks model of a hydraulic excavator.

Figure 5.5. Rendered SolidWorks model of a dump truck.

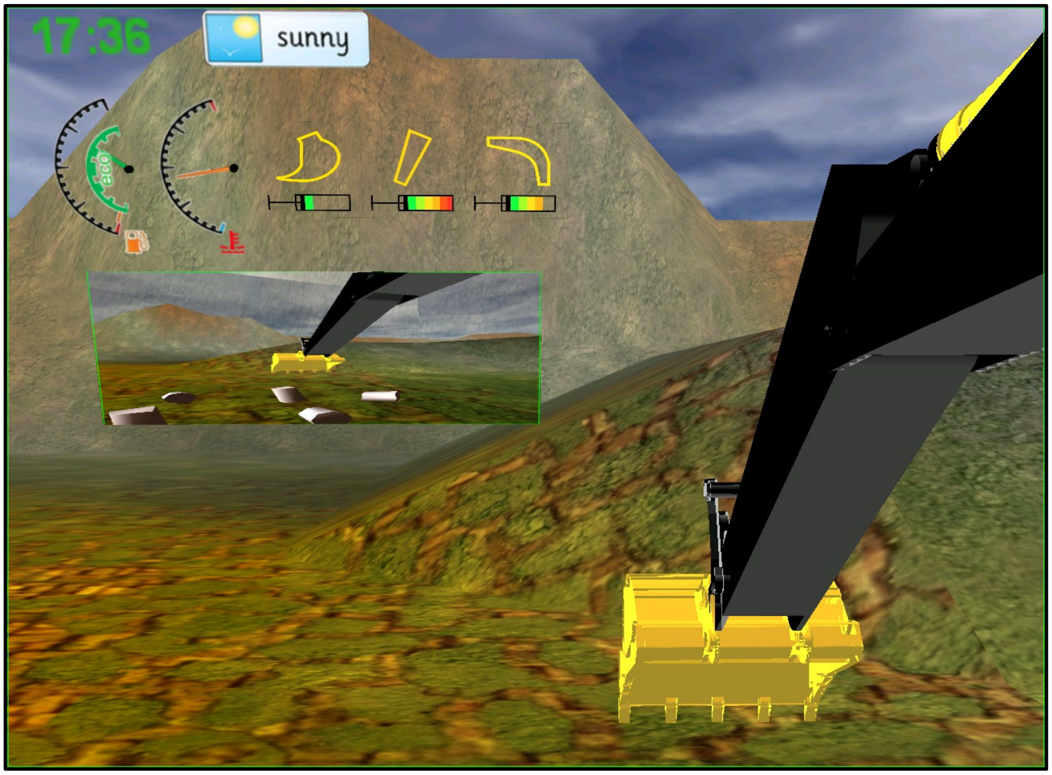


Figure 5.6. Heads-up display visualization of proposed HMI design (Designs A and B).

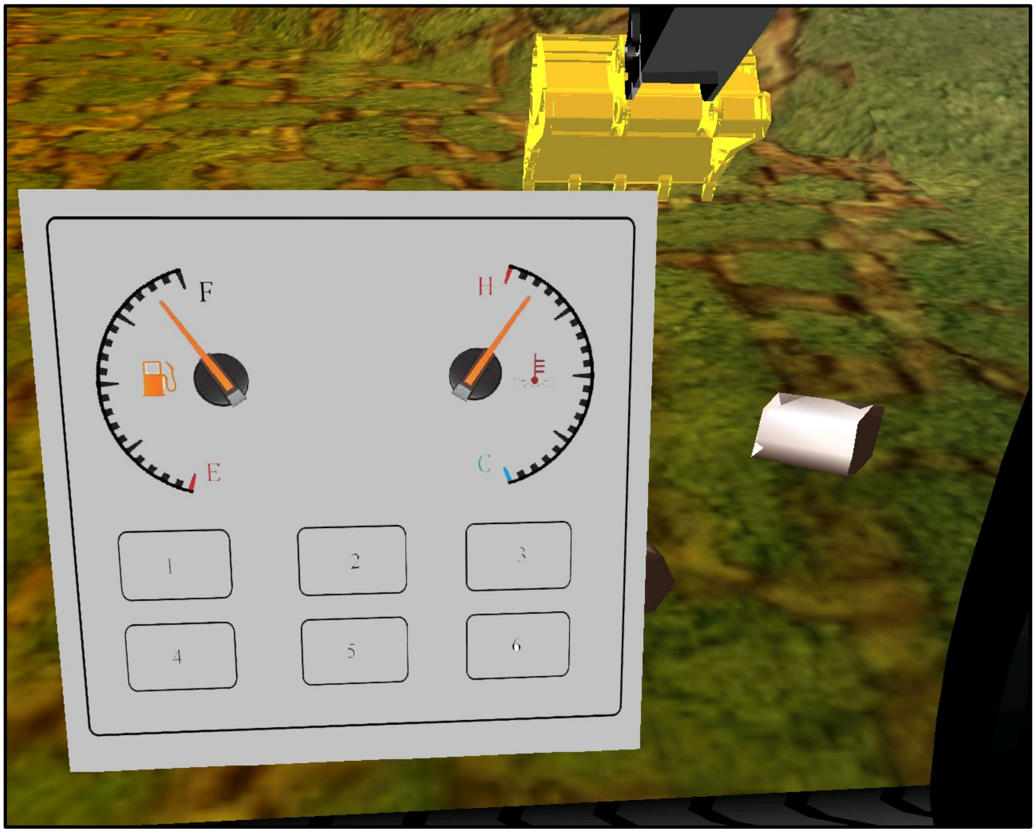


Figure 5.7. Monitor display visualization of the standard HMI (Design C).

5.2.2 Physical simulation. The physical elements of the simulator via the seat and the controls were used to replicate the main components of the hydraulic excavator cab, and to enable the subject to feel a real physical feedback during the test. The functionality of the joystick controls was natively managed by the Virtools SDK. The mapping between the joystick controls and the virtual representation of the front manipulator is shown in Figure 5.8. The trigger button on the joystick controls were programmed to be used for motion.

The phantom was partially managed by the Virtools SDK and also partially supported externally using a C++ program written as an extension to the VRPN library. The program obtained the joint angles (J1 – swing; J2 – boom, J3 – arm; and J4 – bucket) from the phantom's encoders and these were assigned to the joints of the virtual representation of the front manipulator. The mapping between phantom and front manipulator joints is described in Figure

5.9. The joint angular values were conveniently scaled to enable the user to perform natural movements during the digging simulation. For instance, since the configuration of the phantom does not allow a 360^o rotation along the waist joint (J1), a rotational scale was applied to control the swing movement of the excavator to allow for a 360^o swing of the virtual cab.

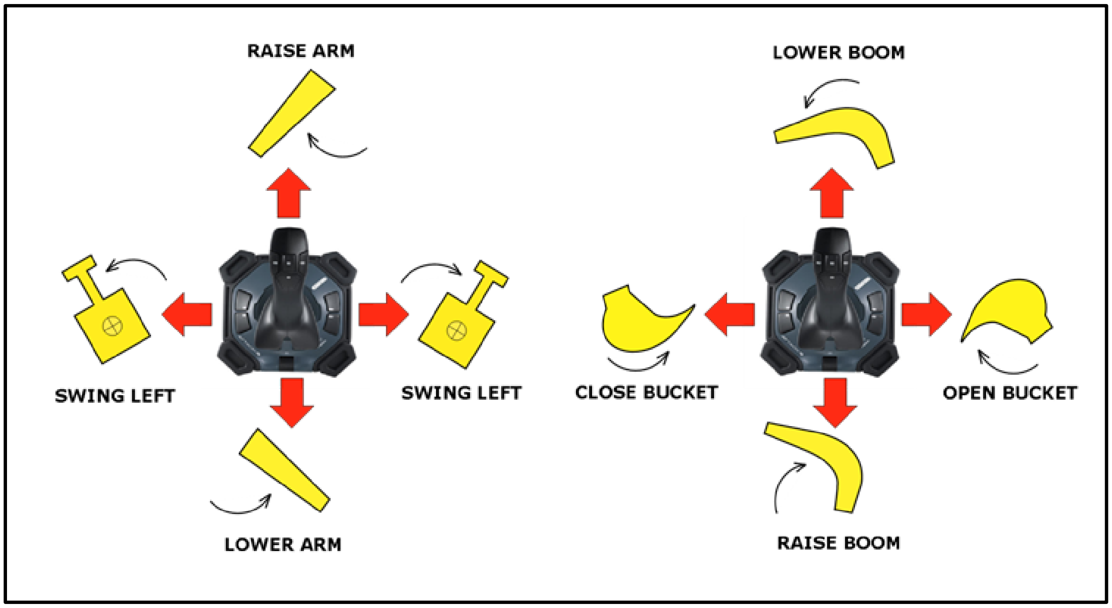


Figure 5.8. Mapping between joysticks control functions and virtual front manipulator.

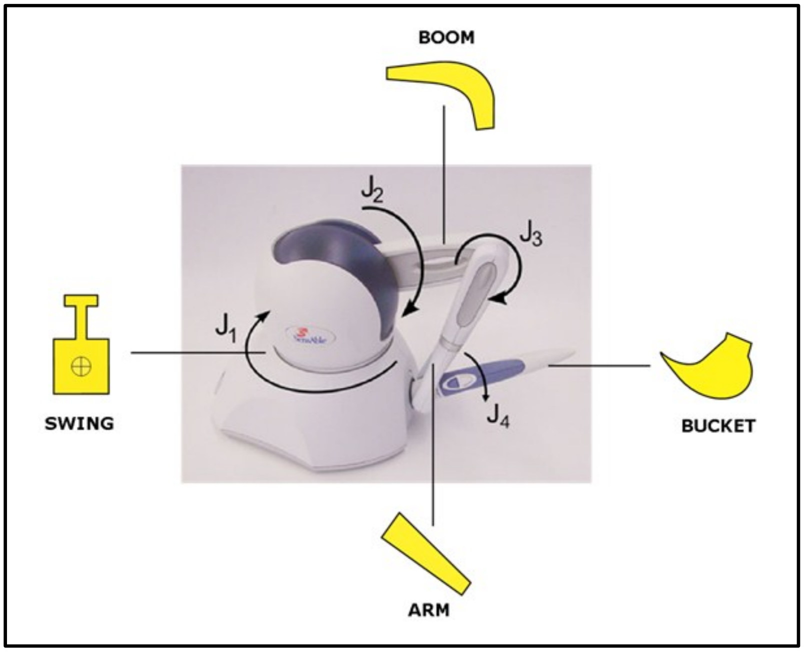


Figure 5.9. Mapping between phantom joint angles and virtual front manipulator.

CHAPTER 6

Evaluation Phase

The Evaluation Phase presents the final phase of the research methodology. Because this research seeks the design of a more usable HMI for a hydraulic excavator, a usability evaluation was done. This chapter presents the usability evaluation of three candidate HMI designs, aimed at determining whether the newly proposed HMI designs based on augmented interaction are more usable compared to the standard HMI design. First, the goal of the usability study is stated. Next, the quantitative and qualitative usability metrics used in the evaluation are discussed. Subsequently, the research question, the usability testing methodology, the experimental design, and the data collection and analysis procedures are presented.

6.1 Statement of Usability Testing Goal

The usability testing goal is to assess the relative ease of use of three candidate HMI designs for a hydraulic excavator and determine how well the newly proposed HMI design involving the augmented interaction strategy was able to address the design gaps identified in the standard HMI design.

6.2 Usability Metrics

According to Rubin and Chisnell (2008), for a product or service to be usable, it must be useful, efficient, effective, satisfying, safe, and intuitive (learnable). These six metrics were considered in this research. Efficiency and effectiveness were used as quantitative (objective) measures of the relative usability of the candidate HMI designs; whereas usefulness, satisfaction, safety, and intuitiveness were used as qualitative (subjective) measures. These six metrics are discussed in the following section.

6.2.1 Quantitative metrics. Quantitative measures of the relative usability of the three candidate HMI designs were assessed with objective performance scores based on time (measure of efficiency) and operating error (measure of effectiveness or reliability). These two metrics provide good measures of usability because ease of use and successful user performance with a system are a reflection of both timely completion and correct behavior.

6.2.1.1 Task completion time. Task completion time was used to measure how quickly a user was able accomplish the task goal with a given HMI type. Using this metric, the relative efficiencies of the three candidate HMI designs under consideration were tested. A candidate HMI was thus considered to be more efficient (hence, usable) if it takes a relatively shorter amount of time to meet the demands of a given task.

6.2.1.2 Operating error. Operating error was used to obtain a measure of the extent to which the user was able to perform the intended task goals with a given HMI type accurately, i.e., without making mistakes. This metric was indicative of the reliability of the user, as well as the relative effectiveness of the candidate HMI designs. While many factors can be identified with human operator errors (Dhillon, 1986), two categories of operating error based on two critical sub-tasks to be performed by users with each of the candidate HMI designs were deemed essential to operator performance in this research. These were 'sub-tasks 3 and 4' from the HTA diagram of Figure 4.4. The two errors that were associated with these sub-tasks were: 'Error 1'– failure to avoid accidents (collisions); and 'Error 2' – failure to accurately dig and dump the rock (misses). Each of these errors was computed using the human error probability equation extracted from Dhillon (1986) which was defined by Green and Bourne (1972) as:

$$human\ error\ probability = P_{he} = \frac{E_n}{O_{pe}}$$

$$\dots (Equation\ 1)$$

Where P_{he} is the probability that a human error will occur when a task is carried out with a system; E_n is the number of committed errors of a given type; and O_{pe} is the total number of opportunities for the error.

For Error 1, the human error probability was termed the error probability of collisions (P_{ER1}); and for Error 2, it was termed the error probability of misses(P_{ER2}). The equations for P_{ER1} and P_{ER2} are defined as follows:

$$P_{ER1}(error\ probability\ of\ collisions) = \frac{E_c}{O_{pc}}$$

$$\ldots (Equation\ 2)$$

$$P_{ER2}(error\ probability\ of\ \ misses) = \frac{E_m}{O_{pm}}$$

$$\ldots (Equation\ 3)$$

Where P_{ER1} is the probability that a collision will occur when carrying out the task with a given HMI type; E_c is the number of collisions recorded; and O_{pc} is the total number of opportunities for collisions. Similarly P_{ER2} is the probability that a miss will occur when carrying out the task with a given HMI type; E_m is the number of misses recorded; and O_{pm} is the total number of opportunities for misses.

The operating error (O_{ER}) was, therefore, obtained as the product of the two probabilities above. A candidate HMI was thus considered less usable if it yields in a high amount of operating error.

6.2.2 Qualitative metrics. Qualitative measures of performance were assessed with subjective data from the National Aeronautics and Space Administration’s Task Load Index (NASA TLX) and a Subjective Preference Questionnaire (SPQ) that was developed for this research. The NASA TLX was used to determine the subjective workload demands that each

HMI type subjected to the user. The NASA TLX was chosen because it is the most widely used subjective workload estimation tool and has achieved some reliable goals in human factors research. It provides a multidimensional rating procedure that allows for collecting subjective workload score based on a weighted average of ratings of six subscales. The six subscales include: *Mental Demand (MD)*, *Physical Demand (PD)*, *Temporal Demand (TD)*, *Own Performance (OP), Effort (EF)*, and *Frustration Level (FL)*. The first three of the six subscales relates to the workload demands imposed on the subject; and the remaining three relate to the subject's interaction with the task. The definition of each of the six subscales is provided in Appendix A. The SPQ was used to ascertain the degree of user preference for each candidate HMI design by asking users to rank each of them across five usability attributes – *usefulness, satisfaction, accuracy, safety,* and *intuitiveness*. These metrics were drawn from Rubin and Chisnell (2008). For a definition of each of these metrics, see Appendix B.

6.3 Research Hypothesis and Questions

In a quest to obtain a more usable HMI design for a hydraulic excavator, this research hypothesizes that the HMI designed with augmented interaction will significantly enhance operator performance via reduced task completion time and operating error, lower subjective workload and high subjective preference. To this end, the research searched for answers to the following questions:

1. What is the relative efficiency of each of the three HMI designs?
2. What is the relative effectiveness of each of the three HMI designs?
3. Which of the three HMI designs yields in the least subjective workload?
4. Which of the three alternative HMI designs is the most preferred by users?

6.4 Usability Testing Methodology

The methodology that was used for usability testing was the comparative assessment test. This test examines the relative usability of designs by evaluating how well a user can actually perform realistic tasks and in identifying specific usability deficiencies in the designs (Rubin & Chisnell, 2008). With this test, the above research questions are brought into focus, and the relevant test hypotheses developed for answering them. To test each hypothesis, an experiment was designed in which functional prototypes of the three HMI designs were presented to users for them to interact with. From the interaction, the empirical evidences of the relative usability (based on the metrics identified above) of each of the HMI designs were determined.

6.5 Experimental Design

6.5.1 Participants. Twenty participants were recruited for the experiment: sixteen males, four females; ages 23–35 years, average height 5.7 ± 0.3 ft., and average weight 156.9 ± 32.4 lbs. The participants were selected among the university community at Politechnico di Milano University, Milan, Italy. The prerequisite for participation was that the participant should have no visual and musculoskeletal health problems. Approval for testing was obtained from the Institutional Review Board of the Office of Research Compliance at North Carolina A&T State University, and permission to conduct the tests was obtained from the College of Engineering at Politechnico di Milano University, Milan, Italy. Prior to conducting the test, participants were asked to sign a consent form, and also provide their personal information including: age, gender, height, and weight.

6.5.2 Type of design. A completely randomized, within-subject design was employed. With this design, each participant was made to test all three candidate HMI designs in a randomized order. A randomization technique was used to vary the order of the test runs in order to reduce transfer of learning effects (Appendix C). A single factor analysis of variance (ANOVA) was used to determine the effect of the HMI type on the response variables. Tukey Honest Significance Difference test was used to examine the differences in the HMI types that showed a significant effect on the response variables.

6.5.3 Sample size determination. Power analysis for an ANOVA: fixed effects, omnibus, one-way test was conducted in G*POWER 3 software (Erdfelder, Faul, & Buchner, 1996) to determine the sample size using the following parameters: alpha = 0.05, power = 0.95, and large effect size, *d* = 0.8. Based on these parameters, the sample size obtained was 20.

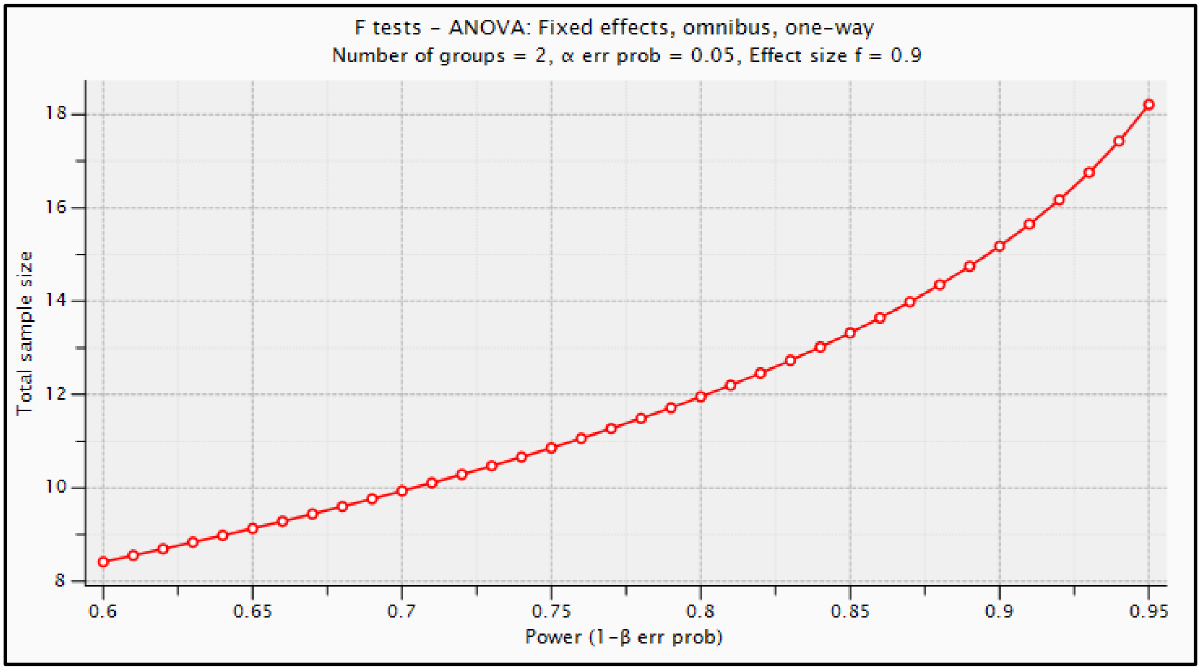


Figure 6.1. Sample size estimation plot.

6.5.4 Design variables. The independent variable was: the HMI type (Design A, Design B, and Design C) (Figure 6.2). For the objective measures, the dependent variables were: task completion time, denoted by TCT; and operating error, denoted by O_{ER} . For the subjective measures, the dependent variables were: the NASA TLX workload ratings, and the subjective preference rankings.

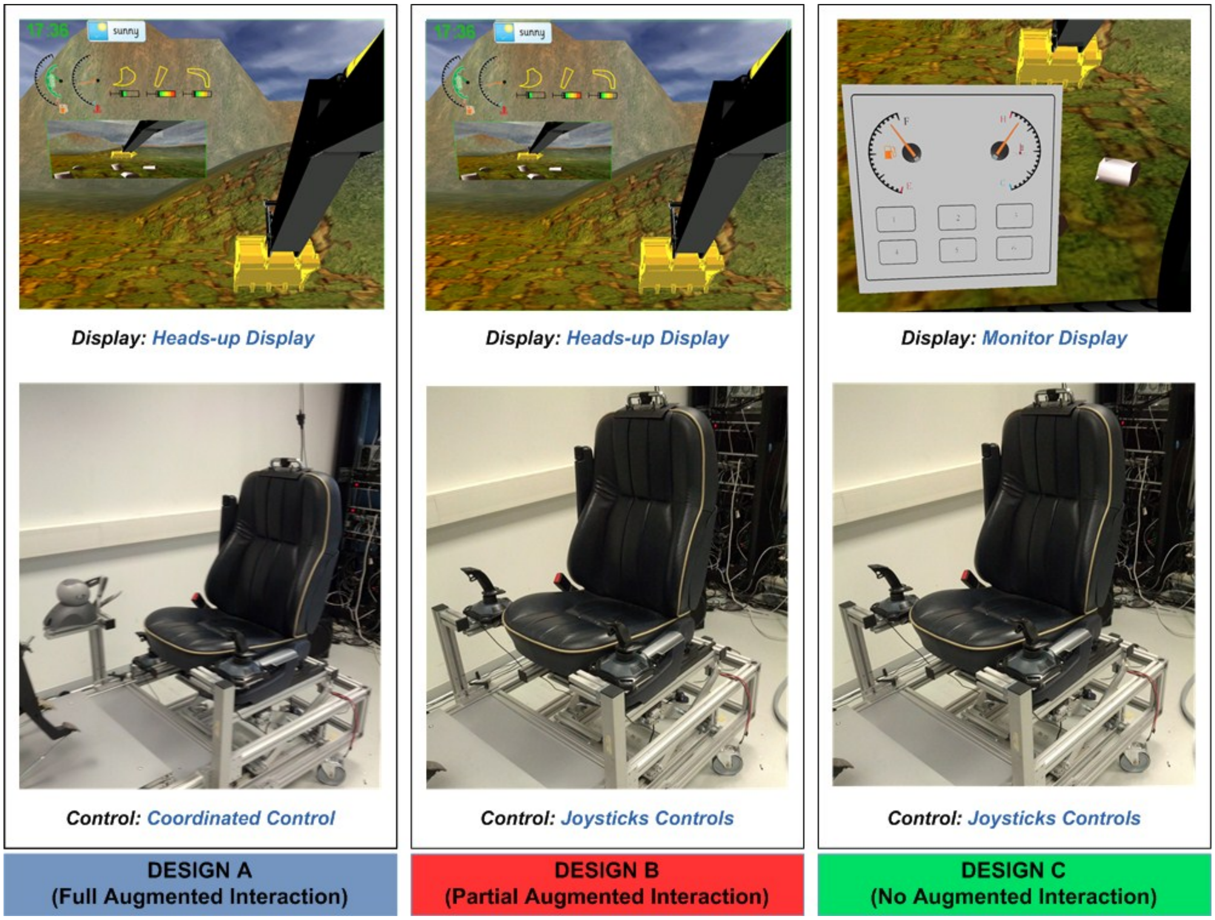


Figure 6.2. Candidate HMI designs.

6.5.5 Task description. The task scenario that was simulated involved the excavation of rocks. The goal of this task was to dig up rocks placed at vantage locations on a work site, and dump them into a dump truck bed (Figure 6.3). To accomplish the task goal, the test participants were required to perform a *move-dig-move-dump* work cycle just like the excavation task described in the HTA diagrams in Section 4.3.1. The subject must first move the excavator to the rock, dig it up, and move the excavator with the dug rock to dump into the dump truck located at a fixed position on the worksite. Five rocks were randomly placed in the scene within an arbitrary work envelope. Participants were thus required to perform five replications of the task. The location and distance of the rocks from the dump truck was unknown to the subject. This was done to introduce some degree of difficulty and judgment, by requiring the subject to do several manipulations of the controls, combined with cognitive processing of displayed information in order to accomplish the task goal. In order to locate the rock, the participant was required to use the motion control buttons on the joystick to drive towards the rock. In order to dig and dump the rock, the participant was required to apply the necessary combinations of the joystick movements to control the boom, arm and bucket.

Figure 6.3. Task scenario.

6.5.6 Experimental protocol. The twenty participants who volunteered for the study conducted the usability evaluation of the three HMI designs in random order over a two-week period. The seating buck was used to conduct the usability testing under the supervision of a test moderator. The entire experiment, which was divided into four sessions, lasted a total of 90 minutes. In the first session, prior to inviting the participant to conduct the testing, the seating buck was prepared. All the modules of the seating buck were set in proper working condition to ensure that there were no hitches during the HMI simulation runs. For each run, the platform was configured to fit the HMI design to be tested. The total duration for this session was 5 minutes. In the second session, the participant was welcomed to the study and asked to provide their informed consent and background information including: age, gender, height and weight. Next, a tutorial was given to familiarize the participant with the testing procedure, including how the display and controls of the HMI designs worked. Subsequently, the participant performed an initial test run. The total duration for this session was 10 minutes. In the third session, the actual test was conducted. The participant was presented with simulations of each HMI design in a random order, with which they were required to complete the rock excavation task. The five rocks to be excavated were presented in the scene during each HMI simulation run. A maximum allowable task completion time of 15 minutes was established as the benchmark time for completing the task. This time was obtained in a pilot test with three testers who were not part of the twenty participants who performed the evaluation. It was based on an average task completion time of 10 minutes plus an allowance time of 5 minutes. After one HMI simulation run had been completed, the participant was given 5 minutes to rest and to recover from any mental and physical workload before starting the next HMI simulation run. This time was also used to reconfigure the seating buck for the next HMI design to be tested. During this session the quantitative outcomes of each HMI simulation was obtained. Task completion time and operating error were automatically recorded with a "simulation clock" and "error recorder" respectively, both of which were built into the computing module of the seating buck. The total duration for this session was 60 minutes. In the fourth and final session, the qualitative measures for each HMI design were collected. The NASA TLX and the SPQ were used to obtain the subjective workload ratings and subjective preference rankings respectively for each of the three HMI designs. The total duration for this session was 15 minutes.

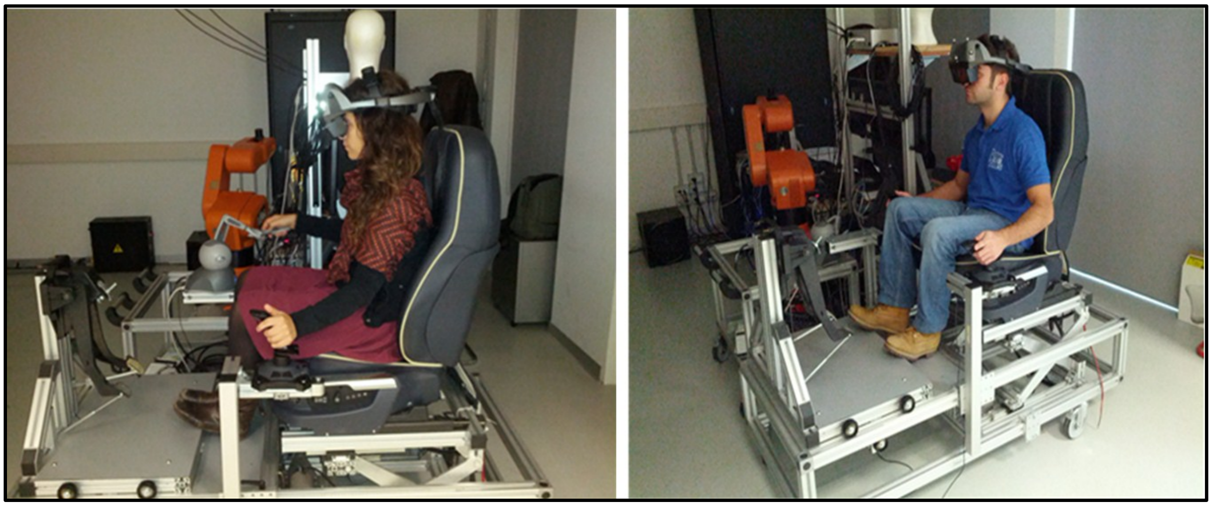
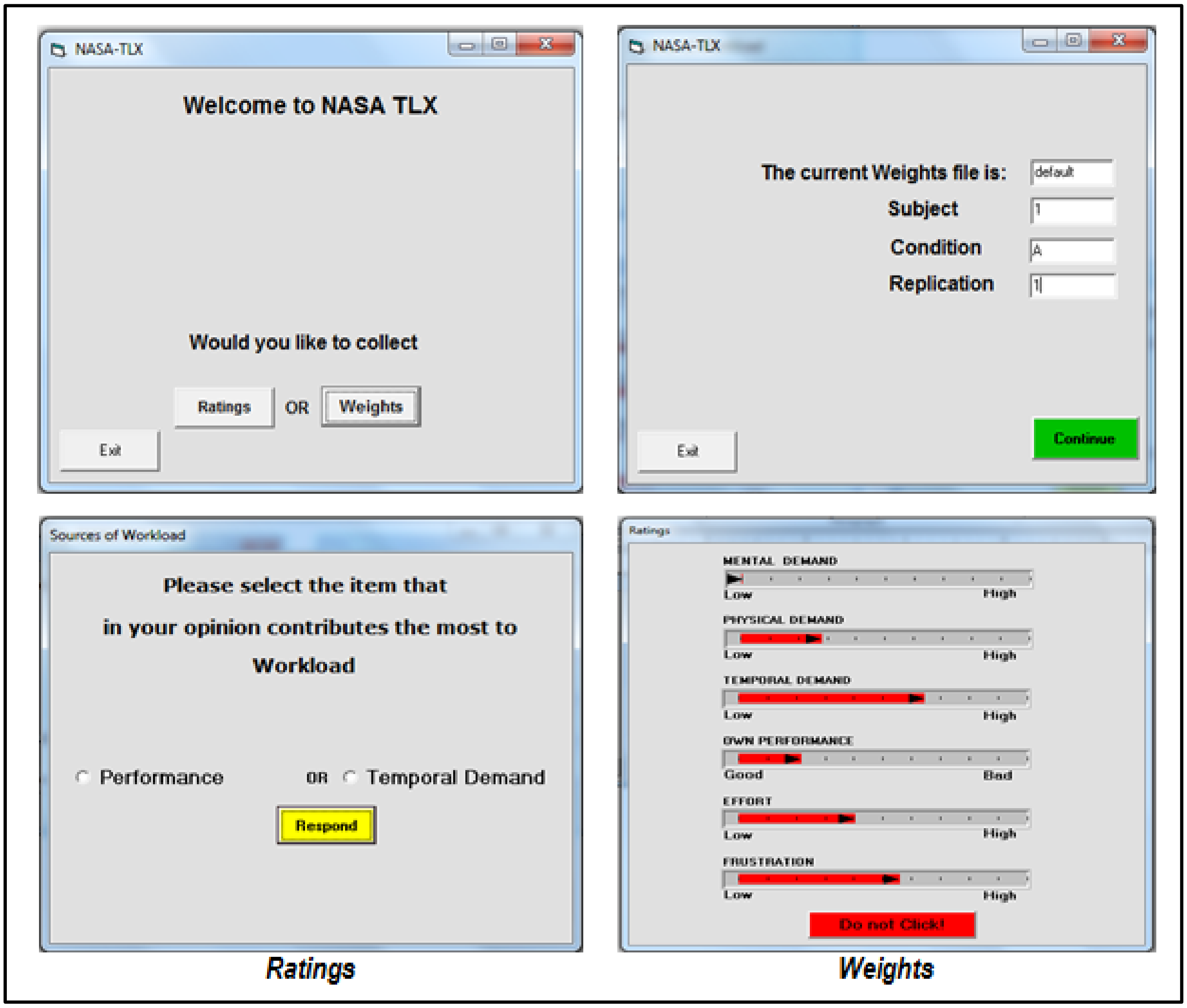


Figure 6.4. Female and male test participants.

6.6 Data Collection Procedures

6.6.1 Quantitative data collection. A simulation clock and an error recorder built into the computing module of the mixed reality seating buck simulator were used to obtain the quantitative user performance data. The simulation clock recorded the average time spent on completing the rock excavation task. The error recorder logged the number of collisions (E_c), and the number of misses (E_m). Both task completion time and operating error responses were written to an output text file (.txt) for each HMI design for all twenty participants and stored in a database.

6.6.2 Qualitative data collection (NASA TLX and SPQ). A computerized version of the NASA TLX (Figure 6.5) was used to obtain the subjective workload scores for each of the three HMI designs along the six sub scales. Before scoring, each participant was trained on the connotation of the six sub-scales of the NASA TLX method, and also familiarized with how to use the computer version for scoring.



Welcome to NASA TLX

Would you like to collect

The current Weights file is: default
Subject 1
Condition A
Replication 1

Please select the item that in your opinion contributes the most to Workload

Figure 6.5. The NASA TLX – computerized version.

The scoring with the NASA TLX involved a two-part evaluation procedure consisting of weights and ratings. In order to obtain the weight of each scale, participants were asked to provide responses to 15 possible pair-wise comparisons among the six subscales, to collate the degree to which each of the six subscales contributed to their workload. The weight was determined by tallying the number of times the participant circled a particular sub-scale on the pair-wise comparison. For the magnitude ratings, participants responded by marking each subscale on a 5 in. line anchored at the ends by bipolar descriptors (i.e. *Low* on the left end and *High* on the right end). The line for each subscale was divided into 20 equal intervals by 21 vertical tick marks ranging from 0 to 100 in increments of 5. Each subscale was rated by moving the needle on the line to a tick mark location, which was based on the participant's perspective of the contribution of the given subscale to the workload of the task. The ratings and the weights were written to an output text (.txt) file.

After completing the NASA TLX, the SPQ (Appendix B) was administered to all participants to rank the relative usability of each of the three HMI designs across the five qualitative usability attributes stated earlier.

6.7 Data Analyses Procedures

6.7.1 Quantitative data analysis. The simulation output data collected for task completion time and operating error were exported and pre-processed in a Microsoft Excel spreadsheet. There were 60 data values for task completion time – organized into twenty independent responses for Design A, Design B, and Design C (Appendix D). For operating error, there were 120 data values: organized into two tables for each category of error, with each table having 60 data values (Appendix E).

The error probabilities P_{ER1} and P_{ER2} were computed using equations 2 and 3. The parameters E_c and E_m were obtained from the simulation output as indicated earlier. The total number of opportunities for collisions(O_{pc}) was established by normalizing to the total number of collisions recorded across all three HMI designs. The value of $O_{pc}$was obtained as 25. The total amount of opportunities for misses(O_{pm}) was obtained as the total number of rocks that were required to be excavated – i.e., $O_{pm} = 5$. In order to obtain the overall operating error, the probability tree method, adopted from (Dhillon, 1986) , was used. The branches of the tree represent the subtasks 3 and 4 (Figure 4.4) with opportunities for the two categories of operating error, collisions and misses respectively. Each branch was assigned a probability:

$P_{ER1}: (p_i, q_i: i = 1)$ and $P_{ER2}: (p_j, q_j: j = 2)$ indicating that the subtask was performed correctly with no errors ($p_1 = 1$ and $p_2 = 1$) or incorrectly with errors ($q_1 < 1$ and $q_2 < 1$).

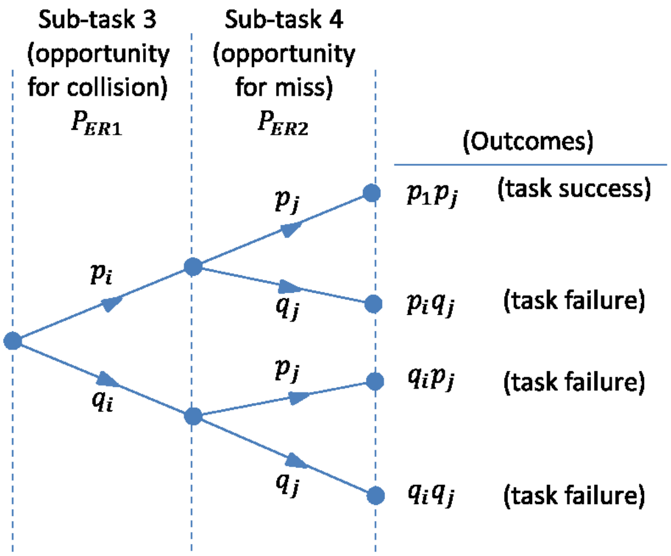


Figure 6.6. Probability tree diagram with subtasks 3 and 4 of working state HTA diagram.

From the tree there exist four possible outcomes, three of which represent task failure. Since the operating error response variable is indicative of task failure it was calculated as the probability of task failure. Thus the operating error for each individual participant (n) for a given HMI type was obtained as follows:

$$Operating\ error = O_{ER,n} = P_{ER1} \times P_{ER2} = p_{i/j} \times q_{i/j} \quad (For\ i, j=1,\ 2;\ n=\ 1\ to\ 20) \qquad \ldots(Equation\ 4)$$

The overall operating error for all twenty participants ($N = 20$) for a given HMI type was obtained as:

$$O_{ER,N} = \frac{\sum_{n1}^{n=20} O_{ER,n}}{N} \qquad \ldots(Equation\ 5)$$

For statistical analysis, the pre-processed data was exported into Minitab 15 (Minitab Inc., Cary, NC, USA). For inferential statistics, One-way ANOVA was used. This type of statistical model was used because only one factor, HMI type, was being investigated. A p-value < 0.05 was considered statistically significant.

6.7.2 Qualitative data analysis. For the NASA TLX, the output files of the weights (W) and ratings (R) were exported into Microsoft Excel for pre-processing. Based on the outcomes of the weights and ratings, the *adjusted rating* for each subscale was computed by multiplying the weight obtained for that subscale with its corresponding rating; this was computed for each of the three HMI designs tested by each participant. The *adjusted rating* was then summed across all six sub scales, and then divided by the total sum of the weights (15) to obtain the *weighted workload score* for each HMI design. An overall weighted workload *score* was obtained by calculating the mean of the *weighted workload scores* across all twenty participants for each HMI design as shown in equation 6.

$$Weighted\ workload\ score = \sum_{n=1}^{n=20} \frac{\sum_{s=1}^{s=6}(W \times R)}{\sum W}$$

$$\dots (Equation\ 6)$$

Where n represents a participant; s is the subscale; W is the weight; and R is the rating.

Similarly, the responses from the SPQ were summarized in a Microsoft Excel spreadsheet. The responses were then tallied and used to determine participants' collective preference for each of the three HMI designs across the five usability attributes.

CHAPTER 7

Results

This chapter presents the experimental results obtained from the usability evaluation of the three candidate HMI designs. The results presented herein include: the descriptive and inferential statistics of the quantitative and qualitative measures of usability of the three HMI designs. One-way analysis of variance (ANOVA) was used to determine the statistical significance of the experimental factor (HMI type) and Tukey Honest Significance Difference (HSD) test was used to perform a post-test pairwise comparison between the HMI types to examine the significant differences.

7.1 Quantitative Results

The quantitative responses, task completion time(TCT) and operating error(O_{ER}), were analyzed in Minitab. A complete table of the results for task completion times and operating errors for the three HMI designs are presented in Appendix D and Appendix E respectively.

7.1.1 Task completion time. The task completion time data (the amount of time used by each participant to complete the rock excavation task) was obtained with a simulation clock. All twenty test participants completed the simulated rock excavation task within the 15 minutes benchmark time that was established. The descriptive and inferential statistics of the data are presented subsequently.

7.1.1.1 Descriptive statistics. A comparison of the task completion times between Design A and Design B, between Design A and Design C, and between Design B and Design C are shown in Figures 7.1, 7.2 and 7.3 respectively. The mean task completion time decreased from 8.22 minutes in Design C to 5.980 minutes with Design A and to 7.798 minutes with Design B. In other words, the statistics showed that participants performed 2.24 minutes faster with Design

A over Design C and 0.43 minutes faster with Design B over Design C. This is shown graphically by the boxplot in Figure 7.4.

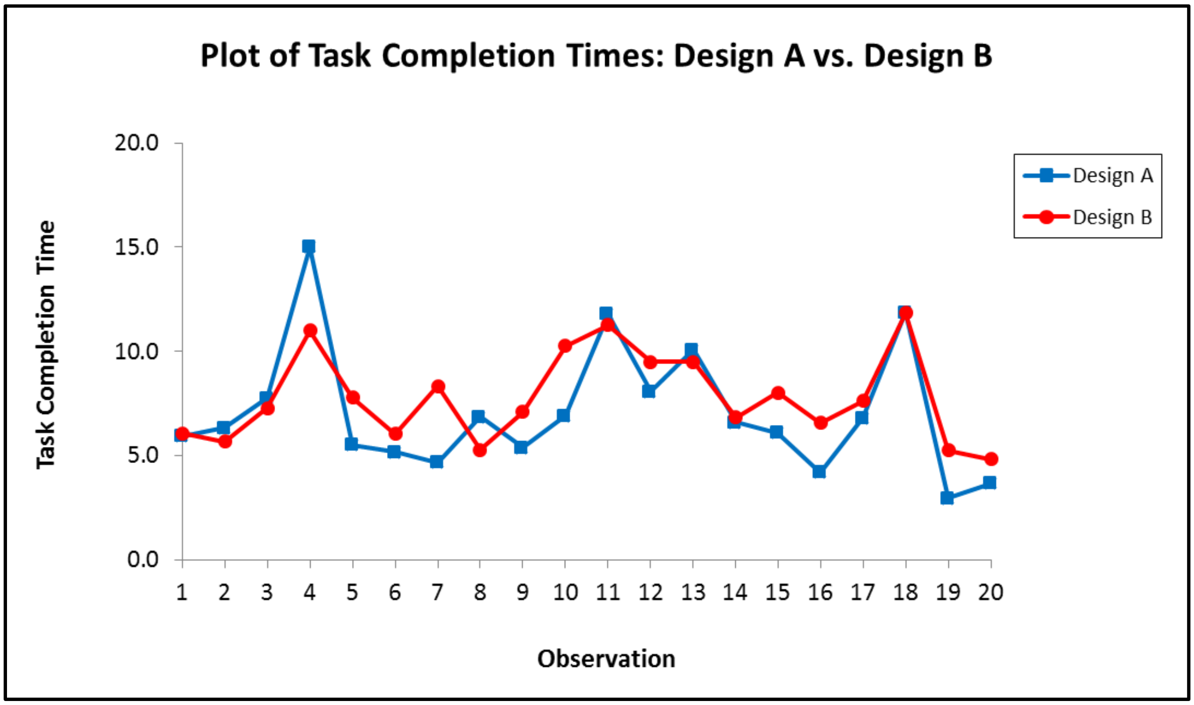


Figure 7.1. Task completion times for twenty participants: Designs A vs. Design B.

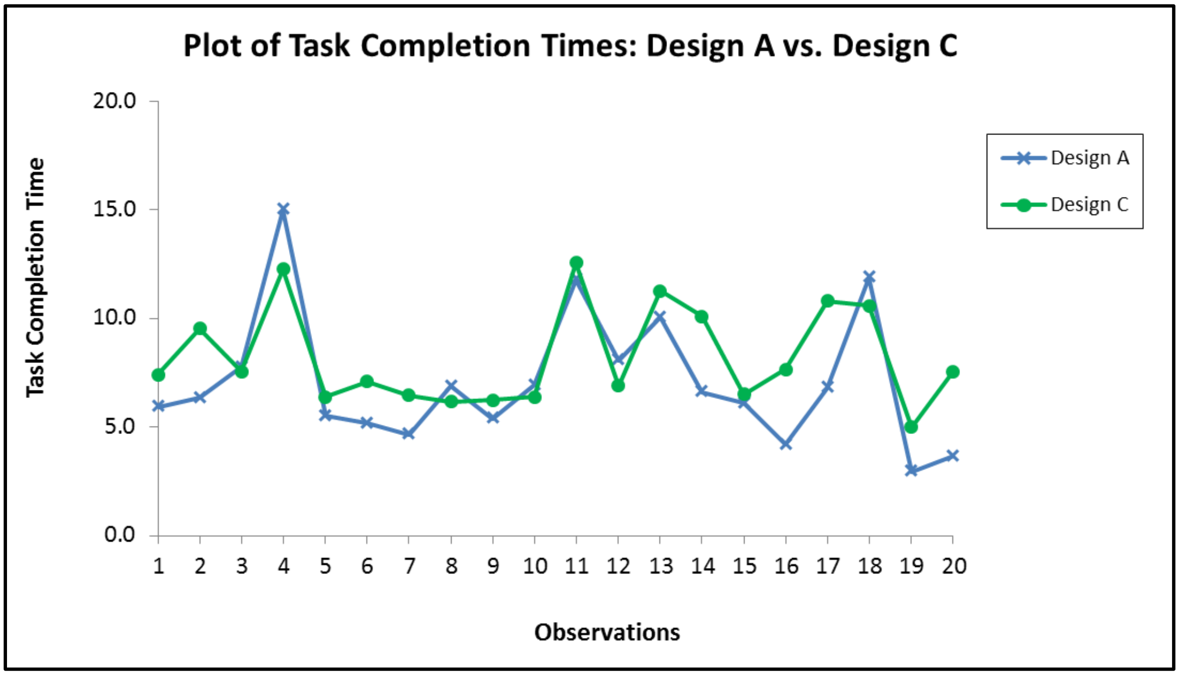


Figure 7.2. Task completion times for twenty participants: Designs A vs. Design C.

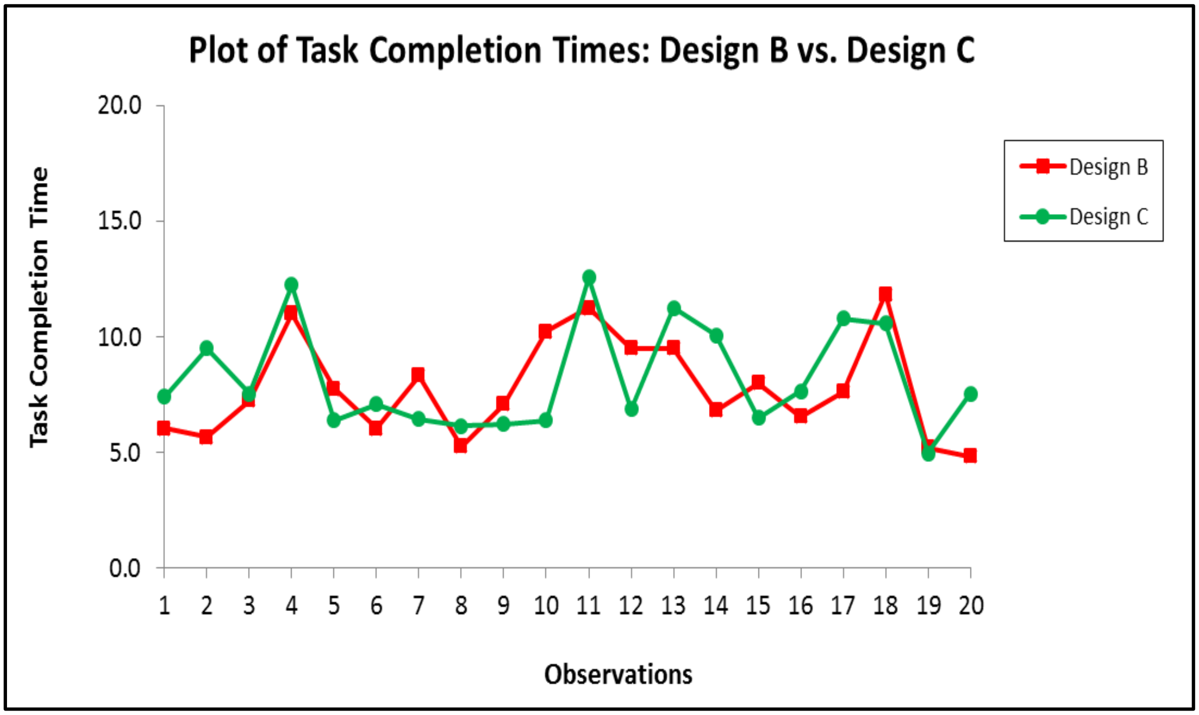


Figure 7.3. Task completion times for twenty participants: Designs B vs. Design C.

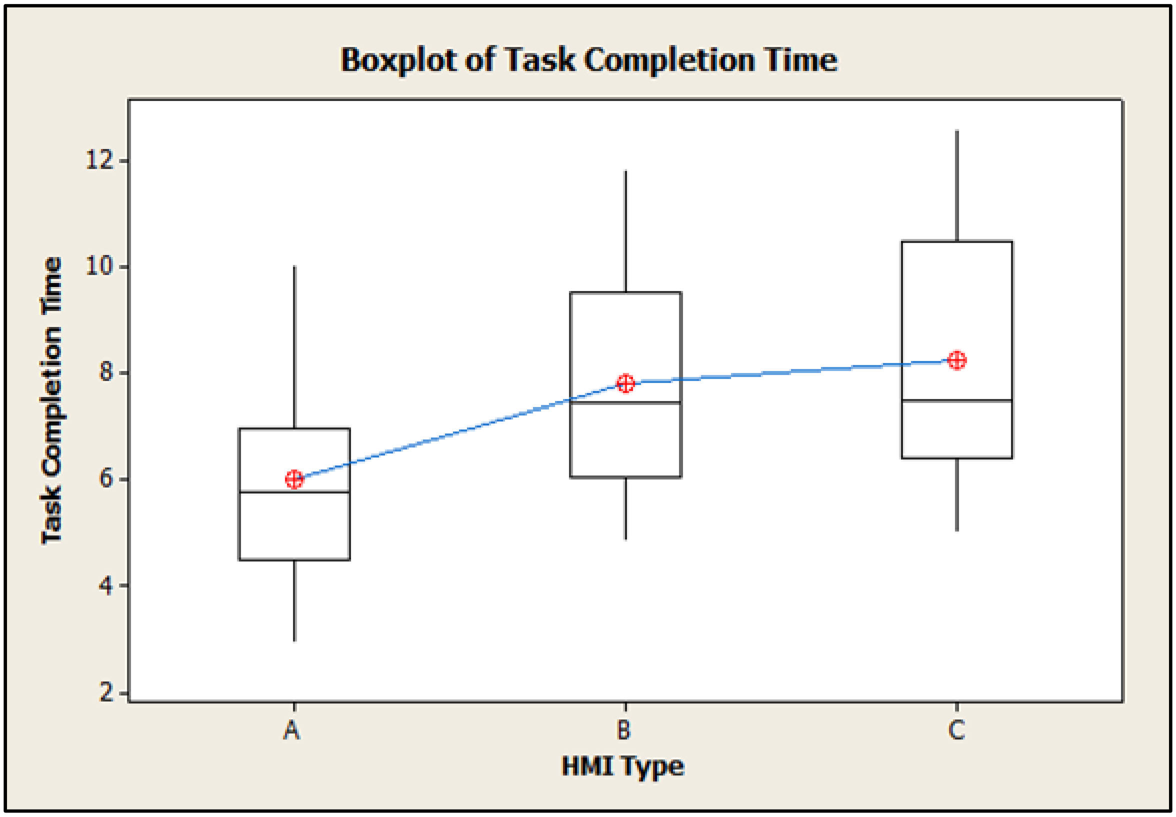


Figure 7.4. Box plots of task completion time for Designs A, B and C.

7.1.1.2 Inferential statistics. The impact of the type of HMI type on the mean task completion time was tested using a hypothesis test of efficiency as described below:

- ***Hypothesis test for efficiency*$(\boldsymbol{TCT})$**

$H_0: \mu_{TCT,A} = \mu_{TCT,B} = \mu_{TCT,C}$

H_1: At least one mean is different

A one-way, omnibus ANOVA was used for performing inferential statistics. Using this type of analysis requires that certain basic assumptions be met in order to present an exact test of hypothesis of no difference in treatment means. These assumptions were investigated by performing a model adequacy check, which involved examining the residuals for normality, independence and homogeneity of variance (Montgomery, 2009).

A check for the normality assumption requires that the residuals should be normally and independently distributed with a mean of zero and a constant but unknown variance, expressed mathematically as $NID(0, \sigma^2)$. This check is made visually by developing a normal probability plot of the residuals. If the residuals approximate a straight line, then it can be said that the errors are normally distributed. Based on this, a normal probability plot of the residuals of the data was generated as shown in Figure 7.5(a). By visualization, since the plot resembles a straight line, the errors are normally distributed; hence the normality assumption is satisfied.

The independence assumption requires that there should be no correlation between the residuals. This check was made by plotting the residuals in a time order of data collection to detect if any correlation existed between the residuals. From Figure 7.5(b) it can be seen that there is no correlation between the residuals; hence, the independence assumption is satisfied.

The homogeneity of variance assumption requires that the residuals should be structureless, that is, they should not reveal any obvious pattern. In particular, they should not be related to any other variable including the predicted response. This assumption was therefore checked with a plot of the residuals versus the fitted or predicted response (Figure 7.5(c)) and showed no unusual structure; hence the homogeneity of variance assumption is satisfied.

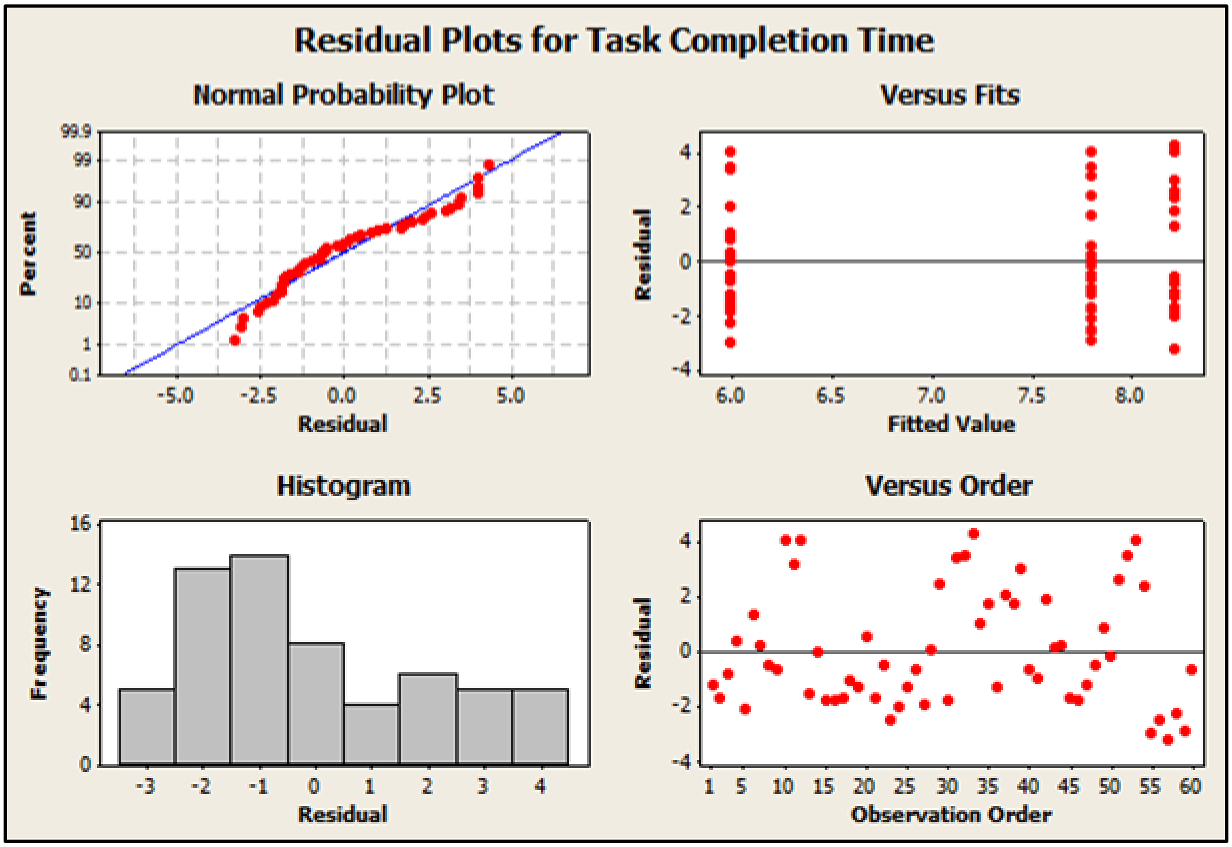


Figure 7.5. Model adequacy plots of task completion time: (a) normality; (b) independence; (c) homogeneity.

Having met all the assumptions of ANOVA, the F test static for investigating the statistical difference in the means was computed. The results indicated that HMI type had a significant impact on task completion time (*F (2, 59) = 6.20, p = 0.0037*). There was a significant difference between Design A and Design B, as well as between Design A and Design C (Figure 7.6). Bars shown in the figure with the same letter are not significantly different from each other (Tukey HSD test,∝= 0.05). The complete ANOVA results are provided Appendix F.

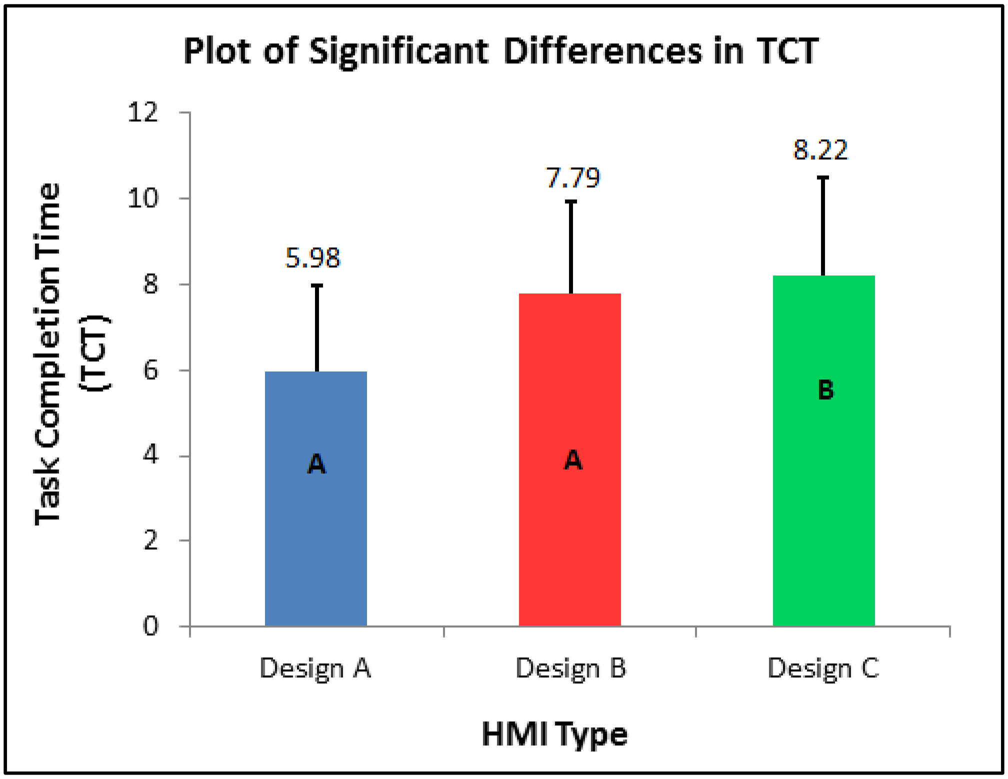


Figure 7.6. Plot of significant differences in task completion time.

7.1.2 Operating error. The level of effectiveness of the three HMI designs was assessed with the two categories of operating error defined earlier as: Error 1, P_{ER1} (error probability of collisions); and Error 2, P_{ER2} (error probability of misses). These errors were obtained using an error recorder built into the mixed reality simulator. The analyses of the data obtained yielded the following descriptive and inferential statistics.

***7.1.2.1 Descriptive statistics*.** ForP_{ER1}, the mean error probability due to collisions reduced from 11.4% in Design C to 9.2% for Design B, but increased to 27.2% for Design A. The differences in the mean error probabilities among the three HMI designs are shown by the boxplots of Figure 7.7.

In terms of P_{ER2}, the mean error probability due to misses was 12% for Design A, 18% for Design B, and 20% for Design C. This is shown by the box plots in Figure 7.8.

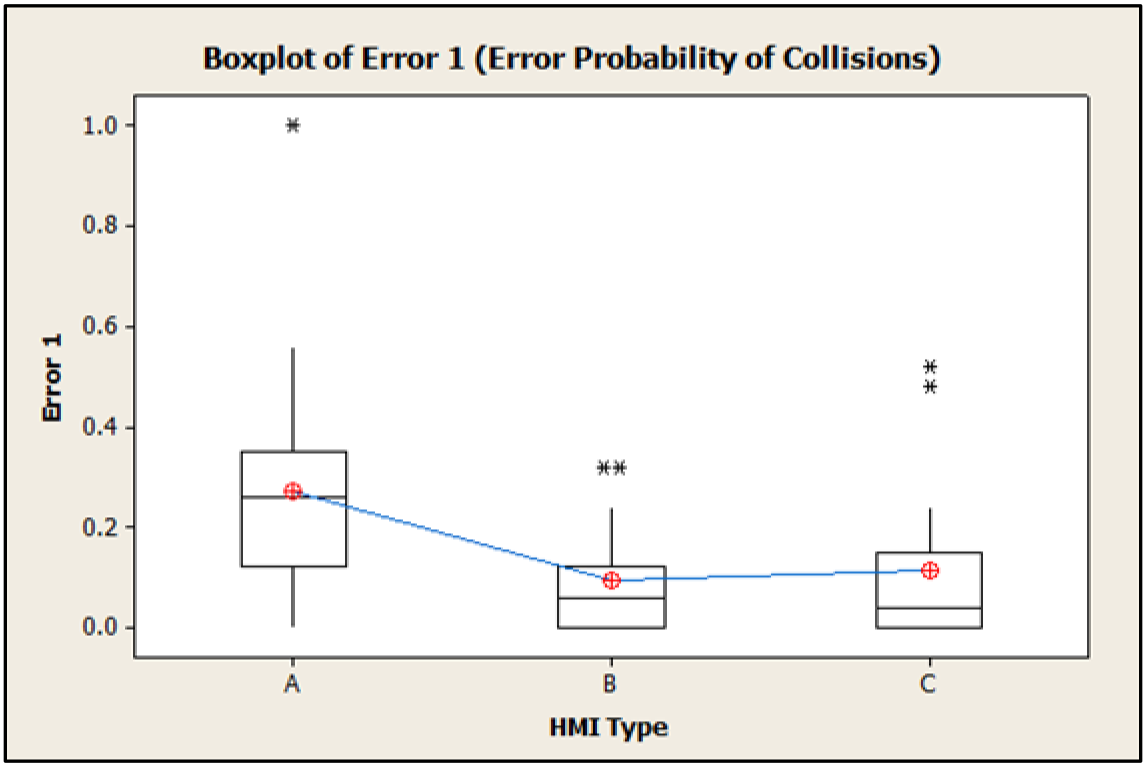


Figure 7.7. Box plots of Error 1 (error probability of collisions) for Designs A, B and C.

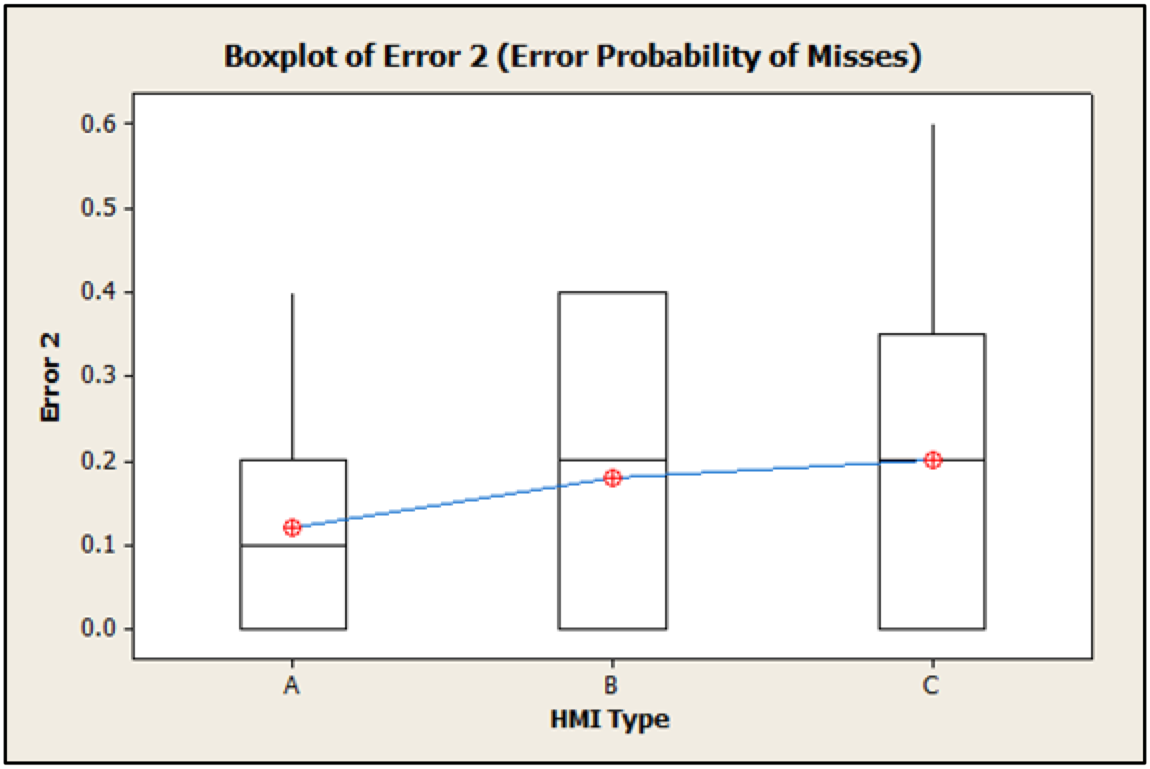


Figure 7.8. Box plots of Error 2 (error probability of misses) for Designs A, B and C.

7.1.2.2 Inferential statistics. The impact of the type of HMI design on task effectiveness as measured by operating error was tested using two hypothesis tests based on the probabilities of the two error categories:

- ***Hypothesis testing for effectiveness*** $(\boldsymbol{Error\ 1 -\ P_{ER1}})$

$H_0: \mu_{P_{ER1},A} = \ \mu_{P_{ER1},B} = \mu\ _{P_{ER1},C}$

H_1 = *At least one mean is different*

- ***Hypothesis testing for effectiveness*** $(\boldsymbol{Error\ 2 - P_{ER2}})$

$H_0: \mu_{P_{ER2},A} = \ \mu_{P_{ER2},B} = \mu\ _{P_{ER2},C}$

H_1 = *At least one mean is different*

A model adequacy check was performed on the operating error response variables as well. For P_{ER1}, analyses of the residuals indicated that all the three model assumptions – normality, homogeneity and independence – were met (Figures 7.9 (a), 7.9 (b), and 7.9 (c)). The ANOVA results showed that HMI type had a significant impact on P_{ER1} (*F (2, 59) = 6.49, p<0.0003).* Figure 7.10 shows the HMIs that were significantly different from each other. Bars shown in the figure with the same letter are not significantly different from each other (Tukey HSD test, $\propto = 0.05$). The complete ANOVA results are provided in Appendix G.

For P_{ER2}, analysis of the residuals indicated a violation of normality. However, the homogeneity and independence assumptions were met (Figures 7.11 (a), 7.11 (b), and 7.11 (c)). An attempt to normalize the data with a "square root transformation" showed a marginal impact. However, as noted by Montgomery (2009), because ANOVA is generally robust to violations of normality, the results can be relied upon since the deviations do not have a substantial effect on the F-statistic. The ANOVA results showed that P_{ER2} was not significantly affected by HMI type (*F (2, 59) = 1.16, p<0.321).* The complete ANOVA results are presented in Appendix H.

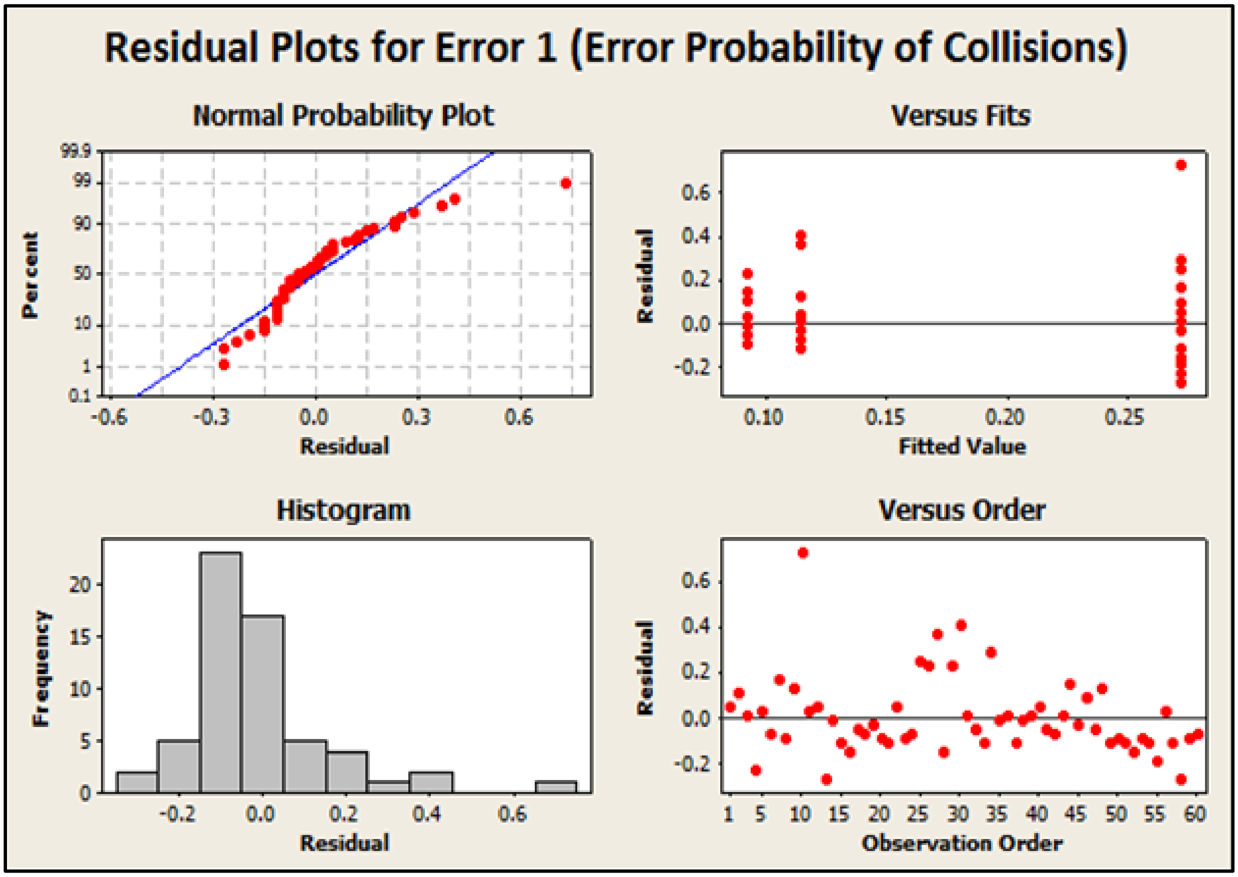


Figure 7.9. Model adequacy plots for Error 1 (error probability of collisions): (a) normality; (b) independence; (c) homogeneity.

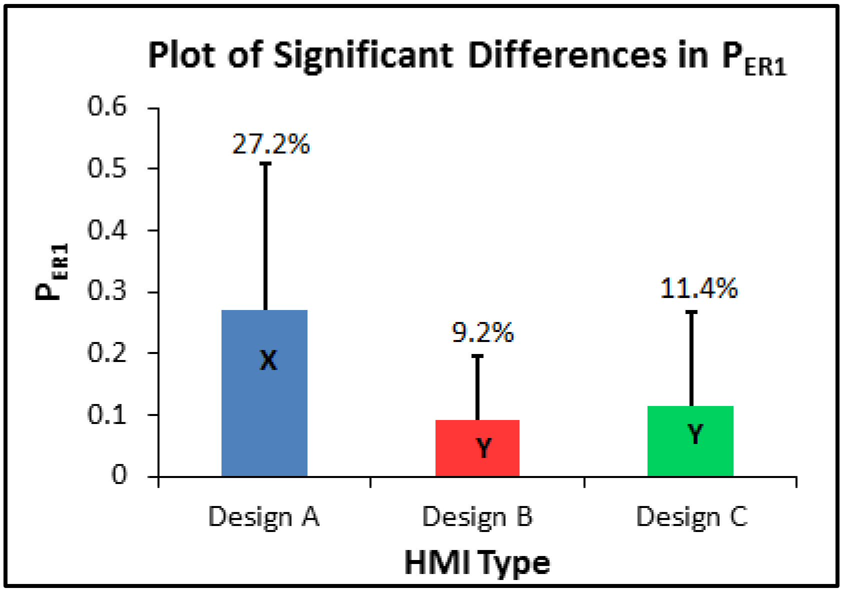


Figure 7.10. Plot of significant differences in Error 1 (error probability of collisions).

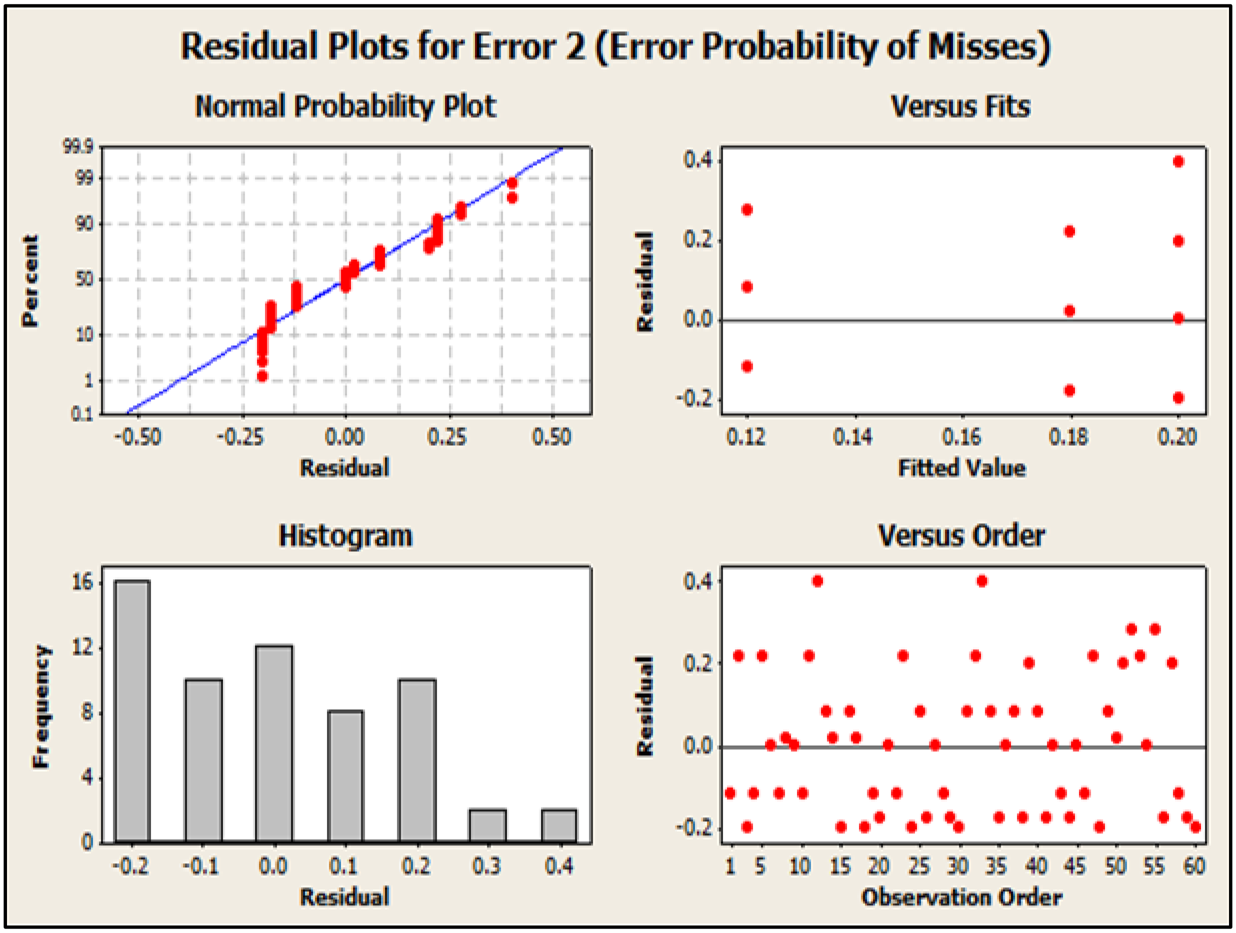


Figure 7.11. Model adequacy plots for Error 2 (error probability of misses): (a) normality; (b) independence; (c) homogeneity.

7.1.2.3 Calculation of operating error. Based on the outcomes of the error probabilities, P_{ER1} and P_{ER2}, the O_{ER} was calculated using equation 4 (see section 6.7.1). Table 7.1 below provides a summary of the mean O_{ER} obtained for each of the three HMI design types. The given error probabilities for each HMI design type is the mean for all the twenty test participants.

As can be seen from the table, the O_{ER} yielded only slight differences between the three HMI designs. In decreasing order, the O_{ER} was 3.26% for Design A, 2.3% for Design C and 1.7% for Design B.

Table 7.1

Summary of Operating Errors for Designs A, B and C

HMI Type	Mean Error Probability of Collisions (P_{ER1})	Mean Error Probability of Misses (P_{ER2})	Mean Operating Error $O_{ER} = (P_{ER1} \times P_{ER2})$
Design A	0.272	0.12	0.0326
Design B	0.092	0.18	0.017
Design C	0.114	0.20	0.023

7.2 Qualitative Results

The qualitative responses that were measured in the usability evaluation of the three HMI designs – i.e., the subjective workload ratings using the NASA TLX and the subjective preference rankings using the SPQ – were analyzed using Microsoft Excel and the results are presented below. A summary of the workload ratings data for the three HMI designs is presented in Appendix I.

7.2.1 Mean weighted workload ratings. The mean subjective workload rating for each of the NASA TLX subscales for Designs A, B and C are shown in Figures 7.12, 7.13 and 7.14 respectively. Overall, the Mental Demand (MD) recorded the highest mean workload score across all the three HMI Designs. This was followed by Own Performance (OP), Effort (EF), Frustration (FL), Temporal Demand (TD) and Physical Demand (PD) respectively. The weighted ratings are shown as the dependent measure on the y-axis and the six workload subscales are shown as the independent measures on the x-axis. The width of the subscale bar reflects the weight (or the relative importance) assigned to it, with the value of the weight on top of the bar; the height of the bar represents its rating. The adjusted workload rating is, therefore, the area of the subscale bar obtained as the product of the weight and the rating.

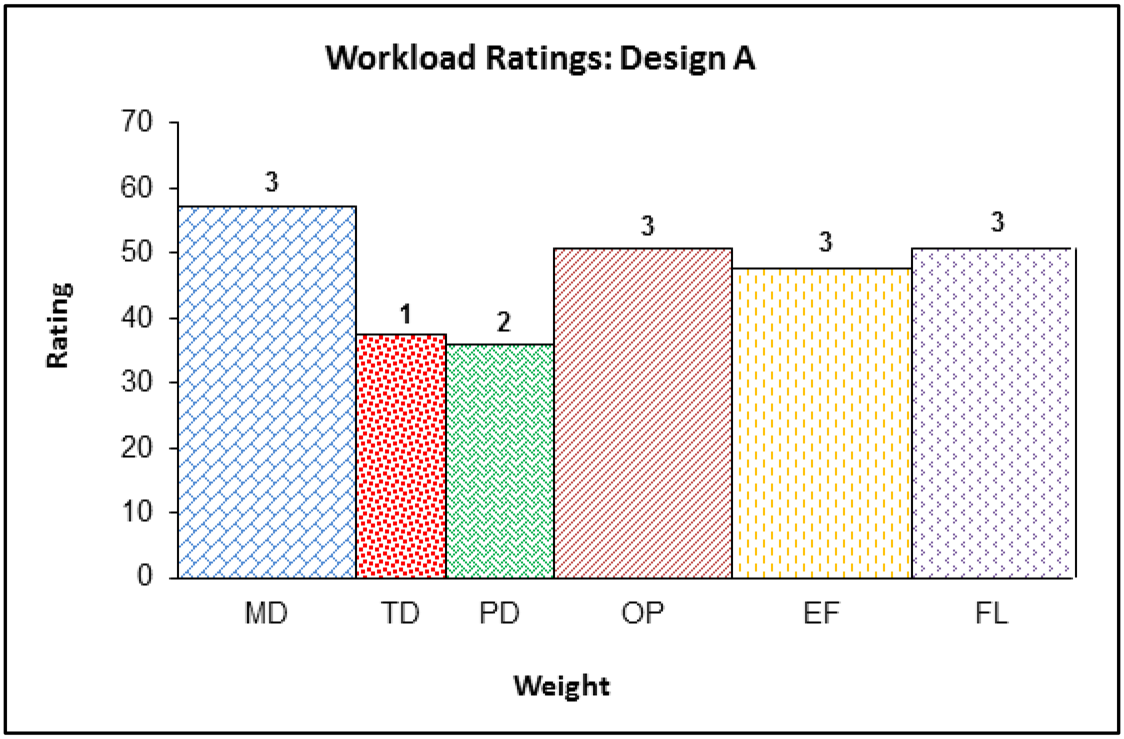


Figure 7.12. Plot of NASA TLX workload ratings for Design A.

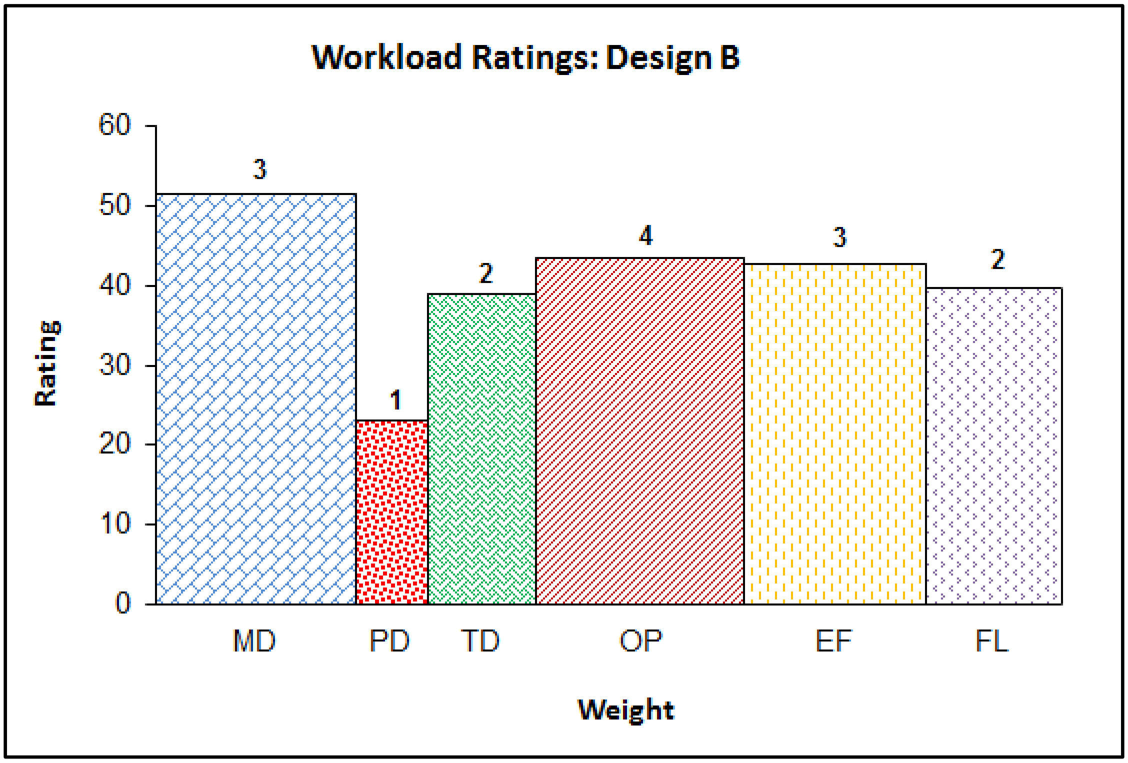


Figure 7.13. Plot of NASA TLX workload ratings for Design B.

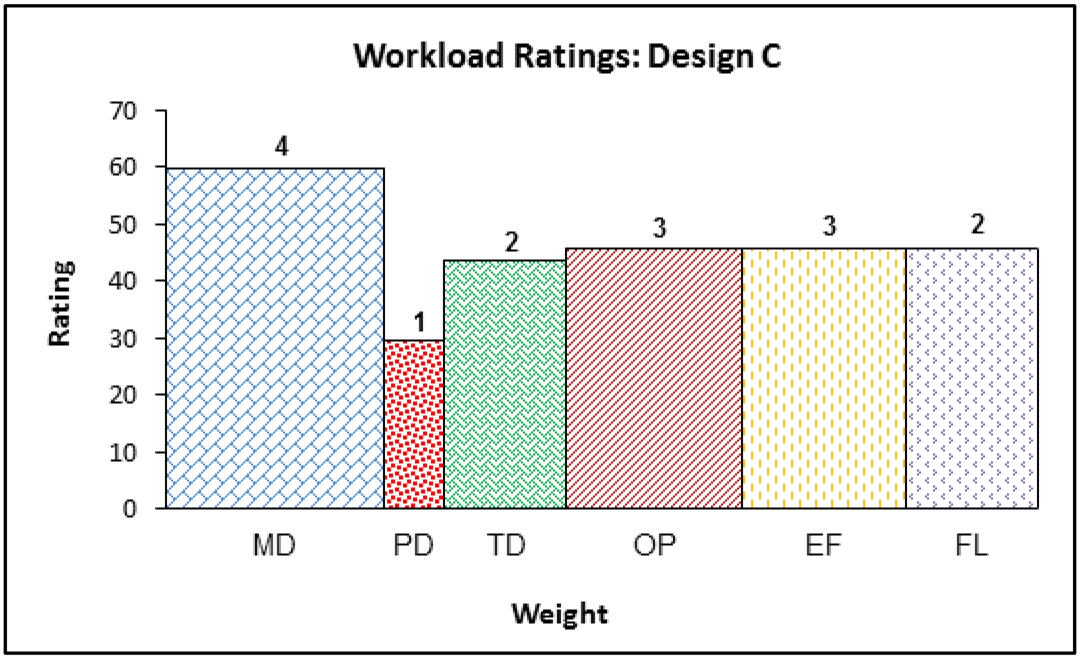


Figure 7.14. Plot of NASA TLX workload ratings for Design C.

7.2.1.1 Overall subjective workload. The overall weighted rating for each HMI design was obtained by dividing the sum of the adjusted workload rating across the six subscales by 15 as explained in Section 6.7.2. The result is shown graphically in Figure 7.15. Design B had the least overall workload score.

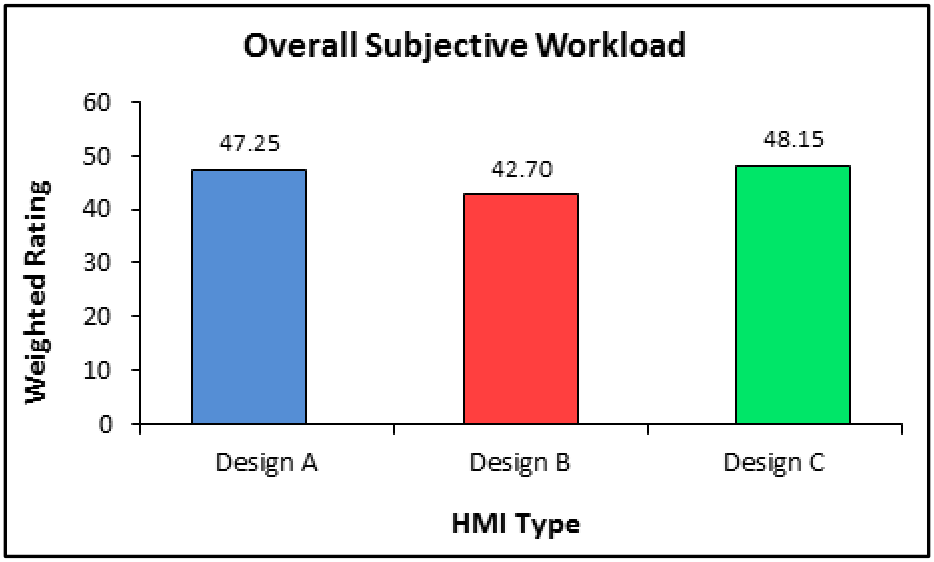


Figure 7.15. Plot of overall subjective workload ratings for Designs A, B and C.

7.2.2 Subjective preference rankings. In order to measure the degree of preference for a particular HMI design, the participants ranked the three HMI designs across the five subjective usability attributes. For the *usefulness* attribute, seven (35%) participants ranked it for Design A, ten (50%) ranked for Design B, and three (15%) ranked for Design C. Along the *satisfaction* attribute, three (15%) participants chose Design A as more satisfying, fifteen (75%) chose Design B, and two (10%) chose Design C. In terms of *accuracy*, three (15%) participants thought Design A was more accurate, fifteen (75%) thought Design B was more accurate, and two (10%) thought Design C was more accurate. In terms of *safety*, 1 (5%) participant felt Design A was safer, 17 (85%) felt Design B was safer, and two (10%) felt Design C was safer. With respect to *intuitiveness,* 9 (45%) participants found Design A to be more intuitive, 8 (40%) found Design B to be more intuitive, and 3 (15%) found Design C to be more intuitive. These results are graphically shown in Figure 7.16. A summary of the participants' responses is also presented in Appendix J.

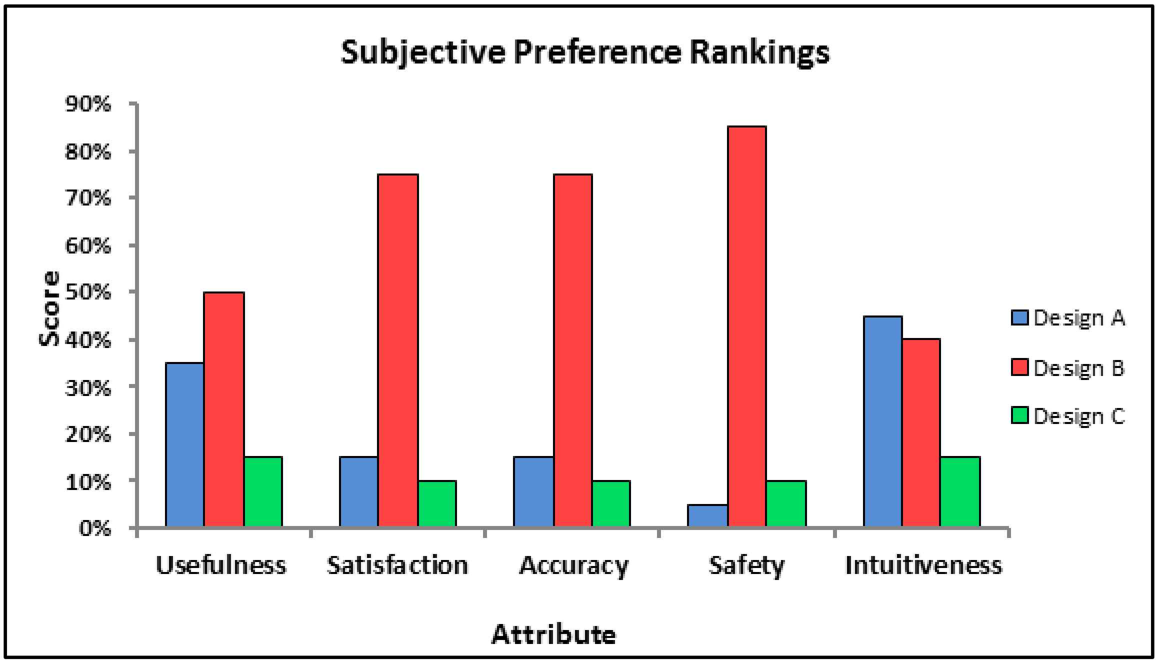


Figure 7.16. Plot of subjective preference rankings of Designs A, B and C.

CHAPTER 8

Discussion

A detailed explanation of the results obtained from this research is presented in this chapter. The chapter is introduced with a general discussion on the importance of a well-designed HMI. Following this, the results of the hypotheses that were tested and how they were supported or not supported are interpreted and presented. Specifically, the impacts of HMI type on the usability measures – i.e., efficiency, effectiveness, subjective workload and subjective user preference – are examined. To end the chapter, the implications of the results for system designers are summarized to bring to light how the results ought to be interpreted and used.

8.1 The Significance of a Usable HMI Design

Generally, HMI solutions that are easier to use are becoming functionally critical to major industry sectors including automotive, heavy mobile equipment, electronics, telecommunications and medical. These solutions have become one of the major selling points for the products made by these industries. The HMI serves as the principal point of contact between the user and the system (machine), and provides the controls and information used to operate the machine. Its goal is to manifest the technology that makes up a system to the users of the system, allowing them to interact with the system to perform the functions for which it was designed. Because the interactive aspect of the system via the HMI is as important as its functionality, how the HMI is designed is therefore crucial for ensuring effective user and system performance. A well-designed HMI makes the interaction seem intuitive; whereas a poorly designed HMI can alienate users, encourage users to circumnavigate the system, or result in poor or unsafe system performance. A well designed HMI fits the user's mental image to the task; it must perform the functions that the user requires and carry out prescribed tasks with a minimum of expended effort while improving productivity. A well-designed HMI provides the user with prompts of the actions to perform, feedback on the results of those actions, and information on the system's performance. Furthermore, a well-designed HMI is judged by its usability, which includes its learnability and productivity. The degree of usability of the HMI can affect the acceptance of the entire system. In fact, in many applications it can impact the overall success or failure of a product (Panone, 2010). The HMI therefore directly represents the core system's quality and value. This quality and value are the preeminent reason why its design should be well-conceived (with the proper user considerations) in order to ensure the user's satisfaction as well as the effectiveness of the system.

The research is based on the premise, confirmed by published research, that a majority of the current HMI designs employed in hydraulic excavators are not well-conceived, as revealed through the usability gaps present in existing HMI designs. These gaps create complex interaction problems that negatively impact both operator and system performance. Expediency in development of a sophisticated form of interaction that enhances usability via efficacy and efficiency is paramount to the advancement in operation of the hydraulic excavator. To this end, an augmented interaction strategy which is anchored on user-centered design principles and mixed reality technologies was envisioned for the development of advanced display and control schemes for hydraulic excavators. These schemes take the form of a heads-up display and a coordinated control device for designing the HMI for a hydraulic excavator. The goal of such an interaction strategy is to obtain a more usable HMI design, and this is achieved through the implementation of such advanced visualization and control schemes which will seek to provide job-critical information to operators for fast, precise and intuitive operation. Some literature provide evidence that advanced interaction schemes via sophisticated mix of design considerations, such as contemporary style, aesthetics, intuitive information visualization, and automation coupled with satisfactory ergonomics, create HMI designs that elevate a user's experience and lead to increased levels of user satisfaction and productivity (Norman, 2002; Panone, 2010). Such are the benefits inherent in the proposed augmented interaction strategy. In order to demonstrate the augmented interaction strategy, three candidate HMI designs were developed and tested, and their relative usabilities were measured. The outcome of the usability studies are discussed in the sections that follow.

8.2 Discussion of Experimental Results

8.2.1 Impact of HMI type on efficiency. In order to investigate the degree of usability in terms of efficiency, it was hypothesized that HMI type has a significant correlation with task completion time. Task completion time metric measured how quickly the simulated rock excavation task was performed. This is influenced by the design of both display and control sub-systems in terms of the information feedback that the operator obtains via the display and his/her dexterity with the control. The adequacy of the information provided and the ability of the user to easily manipulate the control influences how quickly or slowly the task can be completed. It was predicted that with the heads-up display (specifically the introduction of the bucket-integrated camera video feedback) and the coordinated control scheme, the operator will receive adequate information and will therefore perform faster.

The results of the statistical analysis supported the initial hypothesis as it indicated that HMI type had a significant impact on task completion time. As expected, the new HMI designs inspired by the augmented interaction strategy, Design A (featuring the heads-up display and phantom control; referred to as *full augmented interaction*) and Design B (featuring heads-up display and joystick controls; referred to as *partial augmented interaction*), recorded shorter mean task completion times when compared to Design C (the standard HMI with monitor display and joystick controls; referred to as *no augmented interaction*).

Furthermore, there was only a slight difference in the mean task completion times between Design A and Design B, with the former having the fastest task completion time. This difference in mean task completion time is attributed to a more intuitive form of control provided by Design A via the phantom that made it easier for users to understand and manipulate during completion of the prescribed task. The type of display and control design thus played a significant role in how efficient the HMI can be. With full augmented interaction, Design A was found to be more efficient. This confirmed that the augmented interaction strategy, even if partially employed as in Design B, promises better performance compared to the standard HMI, Design C.

8.2.2 Impact of HMI type on effectiveness. In order to assess the effectiveness of the HMI designs, it was hypothesized that HMI type will have a significant impact on the operating error. The degree of effectiveness of a given HMI type was thus characterized by the operator's ability to accurately perform the task with a minimum number of (or ideally without) collisions and misses. To this end, the two categories of operating error, Error 1 (error probability of collisions) and Error 2 (error probability of misses), were defined as indicators of the degree of effectiveness of each of the three HMI designs. Thus, two hypotheses tests of effectiveness were performed. The first hypothesis test based on Error 1 sought to establish that operator error due to collisions, which implies the operator's failure to avoid accidents by hitting the front manipulator against the dumptruck, will be significantly affected the type of HMI being used. Similarly, the second hypothesis based on Error 2 sought to establish that given the type of HMI design being operated with, there would be a significant difference in operator error due to misses – which implies failure to accurately dump the rock into the dumptruck bed.

The statistical results from the hypothesis test of effectiveness indicated that HMI type had a significant impact on Error 1. This category of error not only assessed the accuracy of user behavior but also examined how safely users were able to operate with each HMI type without encountering or minimizing accidents. For this metric, Design B recorded the least error probability of 9.2%. This was followed by Design C with 11.4% and Design A with 27.2%. These results clearly indicated that the control was the source of the error. The joysticks tended to be more accurate compared to the phantom even though the latter seemed more intuitive. This is attributable to the sensitivity and degrees of freedom (flexibility) in the joints of the phantom. Unlike the joysticks which were stiffer and allowed only translational movements in the vertical and horizontal planes, the phantom allowed spatial movements in its links as well as rotational movement at the base, making it too free to maneuver. Such flexibility led to irregular movements which resulted in the high number of collisions recorded, thereby affecting task accuracy. Participants recommended that some weight be introduced in the links of the phantom to increase its stiffness in order to reduce control sensitivity and flexibility.

Error 2, on the other hand, showed no significant effect with HMI type. In other words, albeit the mean error probability of misses was lower for Designs A and Design B as compared to Design C, none of the three HMI designs was less accurate than the other in accomplishing the task goal of dumping the rock onto the dumptruck bed. Error 2 assessed the ability of the operator to accurately pick the rock, contain it and successfully dump it onto the dumptruck bed. As was observed during the experiment, this metric was associated with user behavior; more careful participants behaved more accurately and were therefore successful at achieving the task goal.

Overall, the operating error which was obtained as the interaction of Error 1 and Error 2 showed that Design B was a more effective solution for enhancing operator performance compared to Designs A and C. This was mainly due to a relatively less number of collision errors committed with Design B.

8.2.3 Impact of HMI type on subjective workload. The results of the subjective workload scores from the NASA TLX indicated that Mental Demand (MD) induced the highest workload across all three HMIs. This partially confirms the research problem statement that the operation of the hydraulic excavator is a mentally demanding job. Within the scope of this research was the goal to achieve a reduction in the operator's mental workload, afforded by an improved HMI design that enhances cognition through providing richer work-space information for accomplishing task goals. To this end, the heads-up display was proposed as a vital component for providing a potential solution to the mental workload problem. The results of a simulated concept of the heads-up display as reflected by Designs A and B indicated that users experienced less mental workload with this type of display. Overall, there was an improvement in the mental workload with the new designs. When compared to Design C, the mental workload was reduced by 28.38% for Design A, and 35.39% for Design B.

In addition to MD, Own Performance (OP) and Effort (EF) also received high ratings in contributing to the workload of the operator across all three HMIs. The high scores translated to users feeling that they performed poorly and had to exert a substantial amount of effort to accomplish the goals of the task. The reason that can be attributed to this outcome is that all the users who tested the three HMI designs were novices and did not have relevant experience with operating a hydraulic excavator. Nevertheless, since they were all able to complete the task within the allowable time without prior knowledge or exposure implies that when given time to completely develop the skills needed to operate a hydraulic excavator (as in training), their performance can be significantly enhanced and the level of effort required can also be significantly reduced. Only marginal differences were recorded in OP workload between the new HMI designs. When compared to Design C, the workload due to OP increased by 4.68% for Design A, and by 26.51% for Design B. The contribution of EF to workload increased by 4.05 % with Design A compared to Design C, and decreased by 6.57% with Design B compared to Design C.

Workload due to Frustration Level (FL) was highest for Design A with a 65.9% increase over Design C, and lowest for Design B with a 13.22% decrease. It was observed that, during task performance, users seemed to be stressed because they found the sensitivity in the phantom frustrating in attempts to use it to accomplish the task goal, and this provides explanation for a higher workload score associated with Design A.

The results also indicated that Physical Demand (PD) had a remarkable impact on the operator's workload. This also serves to partially confirm the research problem that the standard HMI design subjects operators to some undue amount of physical workload. Much of the physical of workload comes from repetitive use of the joysticks and long operating hours (typically 6 -8 hours) (Kuijt-Evers, Krausea, & Vinka, 2003). Due to the simulation time being short in this study, the duration spent on performing the simulated task could not be attributed to PD workload. However, the physical exposure to the controls was linked to PD workload. It was revealed that the phantom, despite its sensitivity, was effective in reducing the PD as compared to the joystick controls. There was reduction in workload due to PD for both Design A (17.36%) and Design B (10.69%) when compared to Design C.

The Temporal Demand (TD) exhibited the least contribution to operator workload. TD is influenced by such things as time pressure and speed of the task. These variables were not simulated in the task, hence the low ratings. However, the TD workload decreased in Design A (9.31%) and Design B (10.49%) when compared to Design C.

Finally, in terms of the overall workload reduction from Design C, Design B exhibited the least overall workload with an 11.32% change, whereas Design A exhibited a 1.87% improvement. The results of the NASA TLX thus provide support for augmented interaction as an effective solution for reducing the usability gaps in terms of mental workload, and to a lesser extent the physical workload that operators are subjected to by the standard HMI design.

8.2.4 Impact of HMI type on subjective preference. The subjective preference questionnaire (SPQ) administered at the end of the experiment revealed some important details about the qualities of each of the three HMIs from the user's perspective. The users' experience with the three HMIs was characterized using five usability attributes - usefulness, satisfaction, intuitiveness, accuracy, and safety. The goal of this aspect of evaluation was to gage which HMI was most preferred by users – as preference is to a large extent dependent on the perceived quality of the HMI. It was anticipated that Design A would, on average, emerge as the most preferred design since it is the HMI that fully reflects the proposed augmented interaction strategy. Contrary to this expectation, Design B, which partially reflected the augmented interaction strategy, emerged on average as the most preferred by users. Users ranked Design B highest on four of the five attributes. These four were: usefulness, satisfaction, accuracy, and safety. For Design B to be more useful than Design A implies that if a proposed system is perceived to be intuitive (as is the case of Design A), but does not achieve the specific goals of the user, it will not be used. Design B also afforded more satisfaction due to the shortcoming in the phantom control (i.e., its sensitivity) used in Design A. Furthermore, the high accuracy and safety rankings for Design B were consistent with the results of the objective test of hypothesis for task effectiveness (operating error metrics: Error 1 and Error 2) and the subjective workload assessment using the NASA TLX. Design A was, however, ranked higher than Design B in terms of intuitiveness - which became obvious from the type of control it offered. Overall, 23 % indicated preference Design A, 65% for Design B, and 12% for Design C.

8.3 Implications for Design

The objective of this research was to demonstrate the viability of using an augmented interaction strategy, which features heads-up display and coordinated control for the design of the HMI for hydraulic excavators. From the results of the experiment, it became evident that the augmented interaction strategy is a viable solution for addressing the usability problems with the standard HMI design. Both variants of the augmented interaction strategy (i.e., Design A and Design B) showed promise when compared to the standard HMI design (Design C). In terms of quantitative performance metrics, Design A was found to more efficient whereas Design B was more effective. Qualitatively, Design B yielded lesser workload and was also highly preferred by users. Based on this, it cannot be concluded that either design is the ultimate design since both HMI designs proved to be feasible solutions. The major strength in both HMIs was the heads-up display concept. The weakness was the control type. The phantom control of Design A did not show much promise. Although users found this control type to be more intuitive and performed relatively faster with it, with respect to task accuracy, they performed better using the joysticks controls of Design B.

This work has demonstrated the viability of these two newly proposed HMI concepts by showing that innovative modalities for information presentation (heads-up display) and control (coordinated/ joystick control) for a hydraulic excavator makes a significant difference in the level of performance attainable by both the operator and the system. Designers are therefore provided with the empirical evidence that lays the foundation for them to explore these new designs. These new designs provide several benefits via enhancements in operator and system performance. For the operator, operating with an HMI that allows the job to be done accurately on shorter number of cycles translates into increased productivity and enhanced job satisfaction; for the system, efficiency and effectiveness translates into efficient machine utilization, reduced fuel consumption among others. In light of this, system design efforts geared toward advancing the newly proposed designs are encouraged in order to attain improved HMI designs for the hydraulic excavator as envisioned by this research. Recommendations for such future work are highlighted in Section 10.4.

CHAPTER 9

Conclusion

This chapter concludes the dissertation. The sections that follow start with a high-level summary of the research which highlights the problem, the solution approach, and the results. The remaining sections present the research contribution, limitations and recommendations for future work.

9.1 Research Summary

The need for a more usable HMI design that enhances both operator and system performance in the operation of hydraulic excavators was the challenge that motivated this research effort. This need was driven by the presence of design gaps in the HMI – such as lack of adequate information feedback and repetitive use of controls – that make operation difficult and unsafe. These gaps serve as barriers that negatively impact operator and system performance. To this end, expedience in examination of human-machine interaction strategies became imperative to address the design gaps towards HMI ease of use.

To address these gaps, therefore, this work proposed an innovative interaction strategy for designing HMIs for hydraulic excavators, termed augmented interaction, which involves the use of advanced display and control schemes in the form of heads-up display and coordinated control. The goal of the augmented interaction strategy is to enhance the usability of the HMI for the next generation of hydraulic excavators; and by extension allow for more efficient, effective, intuitive and safe operation of the hydraulic excavator.

A framework consisting of three phases - Design, Implementation/Visualization, and Evaluation (D.I.V.E) was used to develop the augmented interaction strategy. In the Design phase, a user-centered design process supported by hierarchical task analysis was employed to obtain two new HMI design concepts. These concepts sought to provide adequate information and work visibility. The two new HMI design concepts featured a heads-up display (in lieu of the standard monitor display) paired with a coordinated control device (popularly known as the phantom), and joystick controls respectively. In the Implementation phase a mixed reality simulator, the seating buck, was built to simulate prototypes of the new HMI designs as well as that of standard HMI design. In the Evaluation phase, a usability study was conducted with twenty novice users to evaluate the impact of HMI type on two quantitative performance measures (task completion time and operating error), and also on two qualitative measures (subjective workload ratings and subjective preference rankings).

The results from the usability study indicated that the type of HMI design had a significant effect on task completion time and operating error. Also, the type of HMI design had a significant effect on subjective workload scores and subjective preference rankings. It was determined that the two new HMI designs offered a viable HMI solution for addressing the usability gaps in the standard HMI design. It was therefore concluded that, the proposed interaction strategy lent itself as a feasible solution for solving the research problem. However, the results cannot be taken to be conclusive for choosing one of the new HMI designs as the ultimate design; instead, designers should consider both in parallel as candidate solutions. Most importantly, to determine which of the two HMI designs is best suited for the hydraulic excavator, future investigations geared toward improving the quality of the newly proposed HMI designs is essential.

9.2 Research Contribution

To begin with, this research sought to address some major usability gaps present in the current HMI of hydraulic excavators. These include gaps related to mental and cognitive workload such as lack of adequate information feedback and poor work visibility, and fatigue due to repetitive use of non-intuitive controls. It is worthy to note that some previous research efforts such as those by Elton (2009) and Hayn and Schwarzmann (2010) have preceded this research in addressing several aspects of the problems identified with the HMI. This research sought to complement such efforts in overcoming the aforementioned gaps. In so doing, two major contributions were added to the field by this research, and these are described below.

9.2.1 An innovative interaction strategy. This research sought to demonstrate that an augmented interaction strategy - which involves the use of a heads-up display and a coordinated control scheme - provides an innovative approach for enhancing the HMI usability of a hydraulic excavator. The D.IV.E framework provided the guidance for investigating the feasibility of the proposed strategy. It allowed three candidate HMIs with different combinations of display and control elements to be assessed for their relative usability, thus laying down a solid foundation for exploring advanced interaction strategies for hydraulic excavators. Such an advanced interaction strategy as augmented interaction, showed promise as a viable solution for addressing the usability gaps that negatively impact operator and system performance in the standard HMI design. Below is presented the benefits of the proposed strategy and how it addresses the usability gaps in the standard HMI.

- **Increased information feedback:** The use of the heads-up display (with augmented information visualization) provides all the job-critical information needed in one place for the operator's consumption. With the heads-up display, a bucket camera has been introduced which provides visibility of obscure work zones via video feedback.
- **Mental and physical workload reduction:** The information provided via the heads-up display offers the operator adequate work visibility and feedback cues which seek to reduce

the operator’s mental workload. The cognitive processes of perception, attention, memory and execution thus become easier. The intuitiveness of the coordinated control provides a single control solution that eliminates the use of both hands thereby reducing repetition. Its intuitiveness also significantly reduces the learning required to operate the machine. Together both heads-up display and coordinated control solutions will eliminate awkward postures of the upper extremity, which reduces the operator’s physical workload. It is anticipated such reduction in both mental and physical workload will translate into higher performance and job satisfaction.

- **Safety:** A safe HMI for the operator will be assured because of significant reductions in the operator’s cognitive and physical workloads. Improved operator mental health will be the outcome of reduced cognitive workload, which is needed for excellent job performance. Physical workload reduction results from information being directly projected, and appropriately positioned into the operator’s field of vision as he/she performs the job, providing better ergonomic placement as compared to the distraction of looking down at lower instruments which tends to induce awkward postures. The risk of injury will be reduced and the operator’s musculoskeletal health improved. This automatically translates into reduced healthcare and workers’ compensation costs.
- **Operational and energy cost savings:** HMIs developed using this strategy will allow operators to adopt efficient motion trajectories which will result in more efficient operation leading to significant savings in operational and energy costs. According to the Center for Compacting Efficient Power, a National Science Foundation Center focused in fluid power applications research, fluid power applications in the agricultural, mining and construction sector consumes $56 billion in energy annually. An improvement in the energy efficiency of

these sectors will save $9.8 billion annually. Improving the HMI of the hydraulic excavator will therefore be a significant contributor to such expected annual savings.

9.2.2 A mixed reality simulator for testing new hydraulic excavator HMI designs. This research has demonstrated the application of the augmented interaction strategy by developing a seating buck mixed reality simulator – the Hydraulic Excavator Augmented Reality Simulator (H.E.A.R.S) - for conducting usability evaluation of different HMI configurations for a hydraulic excavator. This simulator is the first of its kind for hydraulic excavator HMI research and its fidelity surpasses that of most academic simulators currently available. Essentially, such a mixed reality simulation platform is intended to provide designers with an efficient design tool for testing their design concepts and hypotheses. Traditionally, automotive designers make use virtual reality technology to test virtual prototypes of their designs. While this approach enables manufacturers to reduce the cost of expensive physical prototypes and reduce production lead times, there are some types of analyses that are unlikely to be performed by using only a virtual prototype of the design in question. When some important aspects such as visibility and ergonomics must be evaluated, interaction with the physical aspects of the design prototype is needed. This is where the strategy presented in this research can be useful. The use of a mixed reality simulator, as exemplified in this research, allows for the creation and development of designs that offer more realistic user experiences compared to those prototyped with virtual reality systems. With a mixed reality simulator, the relevant physical components can be integrated with the virtual components of the design to provide a mixed prototype which offers for a more realistic tool for testing and validating the design.

9.3 Research Limitations

Five key limitations were identified in this research. These have been classified as follows: (1) scope of augmented interaction, (2) realism of the simulation, (3) technological challenges, (4) task scenario, and (5) user selection.

9.3.1 Scope of augmented interaction. The first limitation stems from the scope of the proposed augmented interaction strategy for addressing the usability gaps in the HMI. The proposed strategy is limited to the scope of using a heads-up display and coordinated control concept for designing the HMI. While these two technical solutions are innovative and relevant, the usability of the HMI would be further enhanced were the scope to be expanded to include other intelligent interaction techniques such as touch interfaces for menu selection, and adaptive interfaces whose elements adapt to the needs of the operator and can in turn be altered by the operator.

9.3.2 Realism of simulation. This second limitation derives from the mixed reality simulation platform, H.E.A.R.S, specifically the use of mixed reality for prototyping the candidate HMI designs. Ideally, the best way to test the candidate HMI designs would have been to use a physical cab, and developing and integrating the heads-up display and the control elements within the cab to obtain a much more realistic HMI simulator. The standard approach in many design-related works, such as this one, has been the use of virtual prototypes to offset the cost of building physical prototypes. The development of the mixed simulator in this research sought to mediate between using a physical versus a virtual prototype of the HMI. Such a trade-off sacrifices some degree of realism because some elements of the HMI are still virtual, i.e. the visualization of the heads-up display. Realism is also lost in terms of the physical device used to simulate the heads-up display. An open see-through head-mounted display was used for this purpose. In reality, however, operators would not be wearing a head-mounted display to perform a task.

9.3.3 Technological challenges. There are some anticipated technical issues that can be identified with the proposed heads-up display and coordinated control scheme in terms of their actual implementation. With respect to the proposed heads-up display scheme, a problem with heads-up displays that is prevalent in aircraft cockpits, and that was overlooked in this research was the potential of information clutter and hence mental overload on the operator. The design concept proposed is simple and generic, and specifies job-critical information that needs to be provided, such as the bucket camera for enhancing work visibility. Clutter would only occur if designers who adopt the proposed strategy seek to include more information that was not captured in this research. In terms of the control, the problem lies in the technology maturity level of the coordinated control scheme. Currently available coordinated controls are haptic devices used as research tools and manufacturers are not focused on manufacturing coordinated control for use in hydraulic excavators. Thus, for such new technology to receive industry as well as user acceptance, it would require further usability and ergonomics studies, and must be proven to be an effective control option for hydraulic excavator HMI design.

9.3.4 Task scenario. The simulator developed in this research surpasses most academic simulators for hydraulic excavators in terms of its fidelity (i.e. the innovative combination of highly rendered virtual visualizations with physical components to represent the HMI); however, the simulation was limited by way of the task scenario that was simulated. A rock excavation task was used due to technical challenges with developing a soil excavation task (which is the most common task performed by a hydraulic excavator). The rock task was simulated because it was easier to implement and was also seen as one of the many different work scenarios that hydraulic excavator operators are likely to encounter on the job. Nevertheless, it is possible that the nature of the task can influence the results obtained in this research and one task scenario is not enough to validate the results obtained.

9.3.5 User selection. All the twenty participants selected for the usability evaluation of the candidate HMI designs were novices who had no relevant experience with operating hydraulic excavators; no expert operators were involved. It was realized that only novices could be used for the evaluation. This is a concern because using novices will not exactly represent the actual users of the HMI, i.e. trained excavator operators. Nevertheless, these novices were selected from among the university community since the simulation was offsite and there was a challenge with getting expert operators to participate in the evaluation. One problem that was probable with novice operators was learning how to use the joystick controls, since they had no prior experience with operating a hydraulic excavator. However, upon training them, they were able to learn how to use the joysticks in a relatively short amount of time. This did not apply to the phantom since it was intuitive.

9.4 Recommendations Future Work

Despite the valuable contributions made by this research, there remain some important issues that need to be addressed to improve upon the quality of this work, and to further validate the value and feasibility of the proposed strategy. A good starting point for doing this would be future studies geared toward overcoming the research limitations identified. Since these limitations constrain the ability to fully realize the proposed interaction strategy, such future investigations become expedient for the creation of a new, improved and innovative HMI for the hydraulic excavator. To this end, the following recommendations are made to serve as goal posts for future work:

1. Research focused on the enhancement of the heads-up display visualization to include functional virtual prototypes of the other visualization schemes proposed, in addition to the bucket display camera. Also, work concentrated on the design and development of a coordinated control device, specifically, for the hydraulic excavator is paramount, which includes form (size, weight, appearance etc.) and function (i.e. friction in the joints, degrees of freedom, match between system input and output etc.) design.
2. System design efforts focused on the technical implementation of the heads-up display and coordinated control through the development of actual working prototypes in the hydraulic excavator. These prototypes must be effectively tested and compared to the results of the mixed reality simulator presented herein before the results can be considered as valid. This would serve to provide verification for the proposed augmented interaction strategy as being suitable for bringing about improvements in the hydraulic excavator HMI.
3. The exploration of other interaction techniques and modalities such as touch interfaces for menu selection and adaptive user interfaces. These interaction techniques have the promise of delivering intelligent interfaces that are natural, adaptive and have some degree of autonomy.
4. Developing multiple, high fidelity task simulations to include the most performed tasks scenarios operators often encounter on the job such as excavation in dry and wet soils, climbs, demolition work, material handling work etc.
5. Extensive usability and ergonomic assessment of the proposed HMI designs using expert operators to better represent the users who actually interact with the HMI.

References

Akyeampong, J., Udoka, S.J., & Park, E.H. (2012). *A Hydraulic Excavator Augmented Reality Simulator for Operator Training.* Paper presented at the 2012 International Conference on Industrial Engineering and Operations Management, Istanbul, Turkey.

Annett, J., Cunningham, D., & Mathias-Jones, P. . (2000). A Method for Measuring Team Skills. *Ergonomics, 43*(8), 1076-1094.

Annett, J., & Duncan, K. D. (1967). Task Analysis and Training Design. *Occupational Psychology, 41*, 211-221.

Annett, J., Duncan, K. D., Stammers, R. B., & Gray, M. J. (1971). *Task Analysis* Department of Employment Training Information Paper 6. HMSO, London.

APCA. (2008). *Excavation and Trenching Best Practices for Operators* Retrieved from http://www.americanpipeline.org/BestPractices/English/ExcavAndTrenching_Operators.pdf

Arcane Technologies. (2012). *Beyond Reality: The Mirage HMD* Retrieved from http://www.arcane-technologies.com/en/

ARToolKit. (2012). *How Does ARToolKit Work?* Retrieved from www.hitl.washington.edu/artoolkit

Azuma, R. T. (1997). A Survey of Augmented Reality. *Presence: Teleoperators and Virtual Environments, 6*(4), 355-385.

Azuma, R. T., Baillot, Y., Behringer, R., Feiner, S., Julier, S., & MacIntyre, B. (2001). Recent Advances in Augmented Reality. *IEEEComputer Graphics and Applications, 21*(6), 34-47.

Barrientos, A., Luengo, O., & Mora, A. (1999). *Teleoperated Backhoe Excavator with Haptic Control*. Paper presented at the 16th International Symposium on Automation and Robotics in Construction, Madrid, Spain.

Bennink, C. (2010). *Control Options Influence Productivity* Retrieved from http://www.forconstructionpros.com/print/Equipment-Today/Extra/Control-Options-Influence-Productivity/5FCP228.

Berndtson, K. (2010). *Operators Benefit from Joystick Controls* Retrieved from http://www.forconstructionpros.com/print/Rental-Product-News/Construction-Equipment-Rental-Feature-Articles/Operators-benefit-from-joystick-controls/6FCP8934.

Bernold, L. E., Lloyd, J., & Vouk, M. (2005). *Equipment Operator Training in the Age of Internet2.* Paper presented at the 19th International Symposium on Automation and Robotics in Construction, Washington, D.C., USA.

Billinghurst, M., Grasset, R., & Looser, J. (2005). Designing Augmented Reality Interfaces. *Computer Graphics, The SIGGRAPH Quarterly Newsletter, 39,* 17-22.

Billinghurst, M., Kato, H., & Myojin, S. . (2009). Advanced Interaction Techniques for Augmented Reality Applications. *Virtual and Mixed Reality, 5622*(October), 13-22.

Billinghurst, M., Kato, H., & Poupyrev, I. . (2008). *Tangible Augmented Reality.* Paper presented at the ACM SIGGRAPH ASIA 2008 Courses.

Billinghurst, M., Poupyrev, I., Kato, H., & May, R. (2000). *Mixing Realities in Shared Space: An Augmented Realtiy Interface for Collaborative Computing.* Paper presented at the IEEE International Conference on Multimedia and Expo, New York, USA.

Boeriu, H. (2004). *Head-Up Display 2.0 – Augmented Reality* Retrieved from http://www.bmwblog.com/2011/10/07/head-up-display-2-0-augmented-reality/

Bordegoni, M. , & Caruso, G. (2012). Mixed Reality Distributed Platform for Collaborative Design Review of Automotive Interiors. *Virtual and Physical Prototyping, 7*(4), 243-259.

Boy, G.A. (2011). *The Handbook of Human-Machine Interaction: A Human-Centered Design Approach*. Surrey, England: Ashgate Publishing Limited.

Boyanovsky, H.. (2005). Imagining the Future for Hydraulic Excavators. *SAE OHE* 77.

Bureau of Labor Statistics. (2010). *Occupational Outlook Handbook 2010-11 Edition: Construction Equipment Operators* Retrieved from http://www.bls.gov/ooh/construction-and-extraction/construction-equipment-operators.htm

Calvert, K. (2009). *Machine Monitoring:Tools, Not Gadgets* Retrieved from http://www.constructionequipment.com/article/machine-monitoring-technology-tools-not-gadgets?page=show

Cameron, J. (2009). *Avatar* Retrieved from http://www.avatarmovie.com/?us=true

Caterpillar. (2004). *Performance Handbook* (35th ed.). Peoria, Illinois, USA: Caterpillar, Inc.

Caterpillar. (2006). *AccuGrade GPS* Retrieved from http://www.cat.com/cda/layout?m=355875&x=7

Caterpillar. (2009). *Hydraulic Excavators* Vol. 2011. Retrieved from http://xml.catmms.com/servlet/ImageServlet?imageId=C480966

Cemenska, R. A., Schneider, M. P., & Buege, T. J. . (1989). USA Patent No. 4800721. U. S. P. a. T. Office.

Center for Compact and Efficient Fluid Power. (2011). *5th Annual Report* Vol. 1. Retrieved from http://ccefp.org/about-us/annual-report

Christensen, C. . (1997). *The Innovator's Dilemma*. Cambridge, Massachussetts, USA.: Harvard Business School Press.

Cohrs, H. H. (1995). *The Classic Construction Series - 500 Years of Earthmoving*. KHL Group.: East Sussex, U.K.

Costlow, T. (2008, December 01, 2008). Electrohydraulic Engineers Embrace Integration *SAE Off-Highway Engineering (SAE OHE) 16*.

Dey, A. K., Abowd, G. D., & Wood, A. (1999). A Framework for Providing Self-integrating Context-aware Services. *Knowledge-Based Systems, 11*, 3-13.

Dhillon, S. (1986). *Human Reliability with Human Factors*. New York: Pergamon Press.

DiMaio, S. P., Salcudean, S. E., Reboulety, C., Tafazoli, S., & Hashtrudi-Zaad, K. (1998). *A Virtual Excavator for Controller Development and Evaluation.* Paper presented at the IEEE International Conference on Robotics and Automation, Leuven, Belgium.

Elton, M. (2009). *An Efficient Haptic Interface for a Variable Displacement Pump Controlled Excavator.* (Master's Thesis), Georgia Institute of Technology.

Engel, S., Alda, W., & Krzysztof, B. (2009). *Real-time Computer Simulator of Hydraulic Excavator.* Paper presented at the 7th Conference on Computer Methods and Systems, Krakow, Poland.

Erdfelder, E., Faul, F., & Buchner, A. (1996). GPOWER: A General Power Analysis Program *Behavior Research Methods, Instruments, & Computers, 28*, 1-11.

Esposito, F. (1997). *Fluid Power with Applications* (4th ed.): Prentice Hall.

Feiner, T. S., MacIntyre, B., & Webster, T. (1997). *A Touring Machine: Prototyping 3D Mobile Augmented Reality Systems for Exploring the Urban Environment*. Paper presented at the

IEEE International Symposium on Wearable Computers, Cambridge, Massachussetts, USA.

Ferrin, F. J. (1991). *Survey of Helmet Tracking Technologies.* Paper presented at the International Society for Optics and Photonics (SPIE) Conference.

Fisher, B. (2008). Digging Into Simulation. *Technology Today, 29,* 16-19.

Gabbard, J. L. (1997). *A Taxonomy of Usability Characteristics in Virtual Environments.* (Masters), Virginia Polytechnic Institute and State University. Retrieved from http://scholar.lib.vt.edu/theses/available/etd-111697-121737/unrestricted/etd.pdf

Global Spec - The Engineering Search Engine. (2010). *About Industrial Joysticks* Retrieved from http://www.globalspec.com/LearnMore/Industrial_Computers_Boards/Computer_Peripherals/Joystick_Controllers

Goodrum, P., & Haas, C. (2004). Long-term Impact of Equipment Technology on Labor Productivity in the U.S. Construction Industry at the Activity Level. *Journal of Construction Engineering and Management, 130*(1), 124-133.

Google Images. (2012). *What is Augmented Reality?* Retrieved from http://www.pocket-lint.com/news/38795/what-is-augmented-reality-ar

Green, A.E., & Bourne, A.J. (1972). *Reliability Technology*. London: John Wiley & Sons.

Haddock, K. (2002). *The Earthmover Encyclopedia*. Minnesota, USA: Motor Books International.

Haller, M., Billinghurst, M., & Thomas, B. . (2007). *Emerging Technologies of Augmented Reality: Interfaces and Design*. Hershey, Pennsylvannia, USA: Idea Group Publishing.

Hayashi, K., & Tamura, T. . (2009, August 9-12). *Teleoperation Performance using Excavator with Tactile Feedback.* Paper presented at the IEEE International Conference on Mechatronics and Automation, Changchun, China.

Hayn, H., & Schwarzmann, D. (2010). A Haptically Enhanced Operational Concept for a Hydraulic Excavator. In M. H. Zadeh (Ed.), *Advances in Haptics* (pp. 199-220). Vukovar, Croatia: In-Teh.

Heycraft, W. R. . (2000). *Yellow Steel* Urbana, Illinois, USA: University of Illinois Press

Hitachi Construction Machinery America. (2004). *Excavators* Retrieved from http://www.hitachiconstruction.com/en_US/cfd/construction/hitachi_const/pdf/brochures/excavator/d_series_construction_class.pdf

Holloway, R. , & Lastra, A.. (1995). *Virtual Environments: A Survey of the Technology.* Paper presented at the SIGGRAPH'95 Course.

Hull, P. (2009). *Telematics: From a Distance* Retrieved from http://www.gradingandexcavation.com/november-december-2009/telematics-equipment-monitoring-3.aspx

John Deere. (2010). *Excavators* Retrieved from http://www.deere.com/en_US/cfd/construction/deere_const/media/pdf/excavator/DKAX135D225D.pdf

Kikki's Workshop. (1997). *The Mechanism of a Hydraulic Excavator: Everything About Construction Equipment* Retrieved from http://www.kenkenkikki.jp/special/no01/e_index2.htm

Kiljander, H. (2004). *Evolution and Usability of Mobile Phone Interaction Styles.* (Doctoral Dissertation), Helsinki University of Technology.

Kim, D., Kim, J., Lee, K., Park, C., Song, J., & Kang, D. (2009). Excavator Teleoperation System Using a Human Arm. *Automation in Construction, 18*(2), 173-182.

Kim, D., Oh, K. W., Hong, D., Park, J.-H., & Hong, S.-K. (2008, October 14-17). *Remote Control of Excavator with Designed Haptic Device.* Paper presented at the International Conference on Control, Automation and Systems, Seoul, Korea.

Ko, A.-K , & Choi, J.-Y. (2007). *A Haptic Interface Using a Force-Feedback Joystick*. Paper presented at the SICE Annual Conference.

Komatsu. (2009). *Crawler Excavators* Retrieved from http://www.komatsu.com/ce/products/pdfs/PC130-8_.pdf

Komatsu. (2010). *The Heart of Komtrax* Retrieved from http://www.komatsuamerica.com/what-is-komtrax

Kontz, M. E. . (2007). *Haptic Control of Hydraulic Machinery Using Proportional Valves.* (Dissertation), Georgia Institute of Technology.

Kroemer, K. H. E., Kroemer, H. B. , & Kroemer-Elbert, K. E. . (2001). *Ergonomics: How to Design for Ease and Efficiency* (2nd ed.): Prentice Hall.

Kuijt-Evers, L.F.M. , Krausea, F., & Vinka, P. . (2003). Aspects to Improve Cabin Comfort of Wheel Loaders and Excavators According to Operators. *Applied Ergonomics, 34*(3), 265-271.

Lawrence, P. D., Salcudean, S. E., Sepehri, N., Chan, D., Bachmann, S., Parker, N., . . . Frenette, R. (1995). *Coordinated and Force-Feedback Control of Hydraulic Excavators*. Paper presented at the Fourth International Symposium on Experimental Robotics, Stanford, California, USA.

Logitech™. (2012). *Logitech™ Attack 3 Joystick* Retrieved from http://www.logitech.com/en-us/gaming/joysticks/attack-3-joystick

Mckinsey, J. R. , & Chiu, G. T.-C. . (2007). *Interfacing a Force-Feedback Joystick With a Hydraulic Robot Arm*. Paper presented at the IEEE International Symposium on Computational Intelligence in Robotics and Automation, Jacksonville, Florida, USA.

Meyer, K., Applewhite, H. L., & Biocca, F. A. . (1992). A Survey of Position-Trackers. *Presence: Teleoperators and Virtual Environments, 1*(2), 173-200.

Milgram, P., & Colquhoun, H. . (1999). A Taxonomy of Real and Virtual World Display Integration. In Y. Ohta & H. Tamura (Eds.), Environments (pp. 5-30): Citeseer. Retrieved from http://etclab.mie.utoronto.ca/publication/1999/Milgram_Colquhoun_ISMR1999.pdf.

Minitab Inc. (2013). Minitab 15. State College, Pennsylvania, USA. Retrieved from http://www.minitab.com/en-US/default.aspx

Montgomery, D. C. (2009). *Design and Analysis of Experiments* (7th ed.). Hoboken, New Jersey, USA: John Wiley & Sons Inc.

Moon, S.-M., Kim, B.-S., Hwang, J.-H., Kim, Y.-O. , Hong, D.-H., & Ryu, B.-G. (2009). *Development of Tele-operation Control Station for Intelligent Excavator*. Paper presented at the IEEE International Conference on Technologies for Practical Robot Applications, Woburn, Massachussetts, USA.

Moore, W. . (2004). *GPS Systems for the Earthmoving Contractor* Retrieved from http://www.constructionequipment.com/article/gps-systems-earthmoving-contractor

Ni, T., Zhao, D., & Ni, S. (2009). *Visual System Design for Excavator Simulator with Deformable Terrain*. Paper presented at the IEEE International Conference on Mechantronics and Automation, Changchun, China.

Nichols, H. L. (1976). *Moving the Earth: The Work Book of Excavation*. Greenwich, Connecticut, USA.: North Castle Books.

Norman, D. A. (2002). *The Design of Everyday Things*. New York, USA: Basic Books.

NVIS Technology. (2012). nVisor ST60. from http://nvisinc.com/technology.php?prod=nVisorSX

OptiTrak. (2012). *V100:R2 Optical Motion Capture System* Retrieved from http://www.naturalpoint.com/optitrack/products/v100-r2/

Oviatt, S. (2003). Multimodal Interfaces. In J. A. Jacko & A. Sears (Eds.), *The Human-Computer Interaction Handbook: Fundamentals, Evolving Technologies and Emerging Applications.* (pp. 286-304). Mahwah, New Jersey, USA: Lawrence Erlbaum Associates.

Panone, J. (2010). Design Considerations for Effective Human Machine Interface Systems.

Parker, N. R., Salcudean, S. E. , & Lawrence, P. D. (1993). *Application of Force Feedback to Heavy Duty Hydraulic Machines.* Paper presented at the IEEE International Conference on Robotics and Automation, Atlanta, USA.

Proctor, R. W. , Dunston, P. S., So, J. C. Y., & Wang, X. (2012). *Task Analysis for Improving Training of Construction Equipment Operators*. Paper presented at the Construction Research Congress.

Regenbrecht, H.T., M.T., Wagner, & G., Baratoff. (2002). Magic Meeting: A Collaborative Augmented Reality System. *6*(3), 151 - 166.

Rossow, J. A. . (1977). *The Role of Technology in the Productivity in Highway Construction in the United States.* (Dissertation), Cambridge, Massachussetts, USA.

Roth, M. . (2010). *Earthmoving's New Frontier*   Retrieved from http://rermag.com/trends_analysis/interviews/rer-interviews-earthmoving-equipment-manufacturers-20100401/index2.html

Rowe, S. (1999). *Adaptive Motion Planning for Autonomous Mass Excavation.* (Dissertation), Carnegie Mellon University.

Rubin, J., & Chisnell, D. (2008). *Handbook of Usability Testing, Second Edition: How to Plan, Design, and Conduct Effective Tests*. Indianapolis, Indiana, USA: Wiley Publishing, Inc.

Sarter, N. (2006). Multimodal Information Presentation: Design Guidance and Research Challenges. *International Journal of Industrial Ergonomics, 36*(5), 439-445.

Schreiber, F., & Rauch, P. (2008, June 24-26). *Use of a Machine Control & Guidance System, Determination of Excavator Performance, Cost Calculation and Protection Against Damaging of Pipes and Cables.* Paper presented at the International Conference on Machine Control and Guidance, Zurich, Switzerland.

Segura, A., Moreno, A., Brunetti, G., & Henn, T. . (2007). *Interaction and Ergonomics Issues in the Development of a Mixed Reality Construction Machinery Simulator for Safety Training* Paper presented at the 2007 International Conference on Ergonomics and Health Aspects of Work with Computers, Beijing, China.

Sensable™. (2011). *Haptic Devices*   Retrieved from http://sensable.com/products-haptic-devices.htm

Sharma, R., Pavlovic, V. I., & Huang, T. S. (1998). *Toward Multimodal Human-Computer Interface*. Paper presented at the Proceedings of the IEEE.

Spies, R., Ablaßmeier, M., Bubb, H., & Hamberger, W. (2009). *Augmented Interaction and Visualization in the Automotive Domain.* Paper presented at the 13th International Conference on Human-Computer Interaction. Part III: Ubiquitous and Intelligent Interaction.

Stanton, N. (2006). Hierarchical Task Analysis: Developments, Applications, and Extensions. *Applied Ergonomics, 37*(1), 55-79.

Sung, D. (2004). *What is Augmented Reality?* Retrieved from http://www.pocket-lint.com/news/38795/what-is-augmented-reality-ar

Tatum, C. B., Vorster, M., & Klingler, M. (2006). Innovations in Earthmoving Equipment: New Forms and Their Evolution. *Journal of Construction Engineering and Management, 132*(9), 987-997.

Torres-Rodriguez, H. I. , Parra-Vega, V. , & Ruiz-Sanchez, F. J. . (2005, July 18-20). *Integration of Force-Position Control and Haptic Interface facilities for a Virtual Excavator Simulator.* Paper presented at the IEEE 12th International Conference on Advanced Robotics, Seattle, Washington, USA.

Uden, L. (2007). Activity Theory for Designing Mobile Learning. *Journal of Mobile Learning and Organization, 1*(1), 81-102.

US Department of Transportation, National Highway Traffic Safety Administration. (1995). Human Factors Aspects of Using Head Up Displays in Automobiles: A Review of the Literature. Springfield, Virginia.

Usability Professionals' Association. (2012). *What is User-Centered Design?* Retrieved from http://www.usabilityprofessionals.org/usability_resources/about_usability/what_is_ucd.html

Virtual Realities. (2012). *Head-Mounted Displays* Retrieved from http://vrealities.com/addvisor150.html

Volvo Construction Equipment. (2010). *CareTrack* Retrieved from http://www.volvo.com/constructionequipment/na/enus/partsservice/caretrack/caretrack.htm?TAB=0

Wang, X. (2008). Improving Human-Machine Interfaces for Construction Equipment Operations with Mixed and Augmented Reality. In C. Balaguer & M. Abderrahim (Eds.), *Robotics and Automation in Construction* (pp. 211-224). Vukovar, Croatia: In-Teh.

Wang, X., & Dunston, P.S. (2007). Design, Strategies, and Issues Towards an Augmented Reality-based Construction Training Platform. *Information Technology in Construction, 12*(July), 363-380.

Yamada, H. , & Muto, T. . (2003). Development of a Hydraulic Tele-operated Construction Robot Using Virtual Reality (New Master-slave Control Method and an Evaluation of a Visual Feedback System). *International Journal of Fluid Power, 4*(2), 35-42.

Yamada, H., & Doi, T. (2008). *Teleoperation of Hydraulic Construction Robot Using Virtual Reality*. Paper presented at the 7th JFPS International Symposium on Fluid Power, Toyama, Japan.

Yamamoto, H., Moteki, M., Shao, H., & Ootuki, T. (2009). *Development of Autonomous Excavation Technology for Hydraulic Excavators.* Paper presented at the ICROS-SICE International Joint Conference (ICCAS-SICE 2009), Fukuoka, Japan.

Yoon, J. , & Manurung, A. . :. (2010). Development of an Intuitive User Interface for a Hydraulic Backhoe. *Automation in Construction 19*(6), 779 - 790.

Zimmermann, C. L., Cook, T. M., & Rosecrance, J. C. (1997). Work-related Musculoskeletal Symptoms and Injuries Among Operating Engineers: A Review and Guidelines for Improvement. *Applied Occupational and Environmental Hygiene, 12*(7), 480-484.

Zubko, N. (2007). Heavy Rotation - A New Generation of Hydraulic Excavators: Better, Stronger, Faster. *Utility Contractor,* 19-23.

Appendix A

NASA TLX Subscales Definitions

Title	End Points	Description
Mental Demand	Low/High	How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?
Physical Demand	Low/High	How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
Temporal Demand	Low/High	How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?
Own Performance	Good/Poor	How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?
Effort	Low/High	How hard did you have to work (mentally and physically) to accomplish your level of performance?
Frustration Level	Low/High	How insecure, discouraged, irritated, stressed, and annoyed or secure, gratified, content, relaxed, and complacent did you feel during the task?

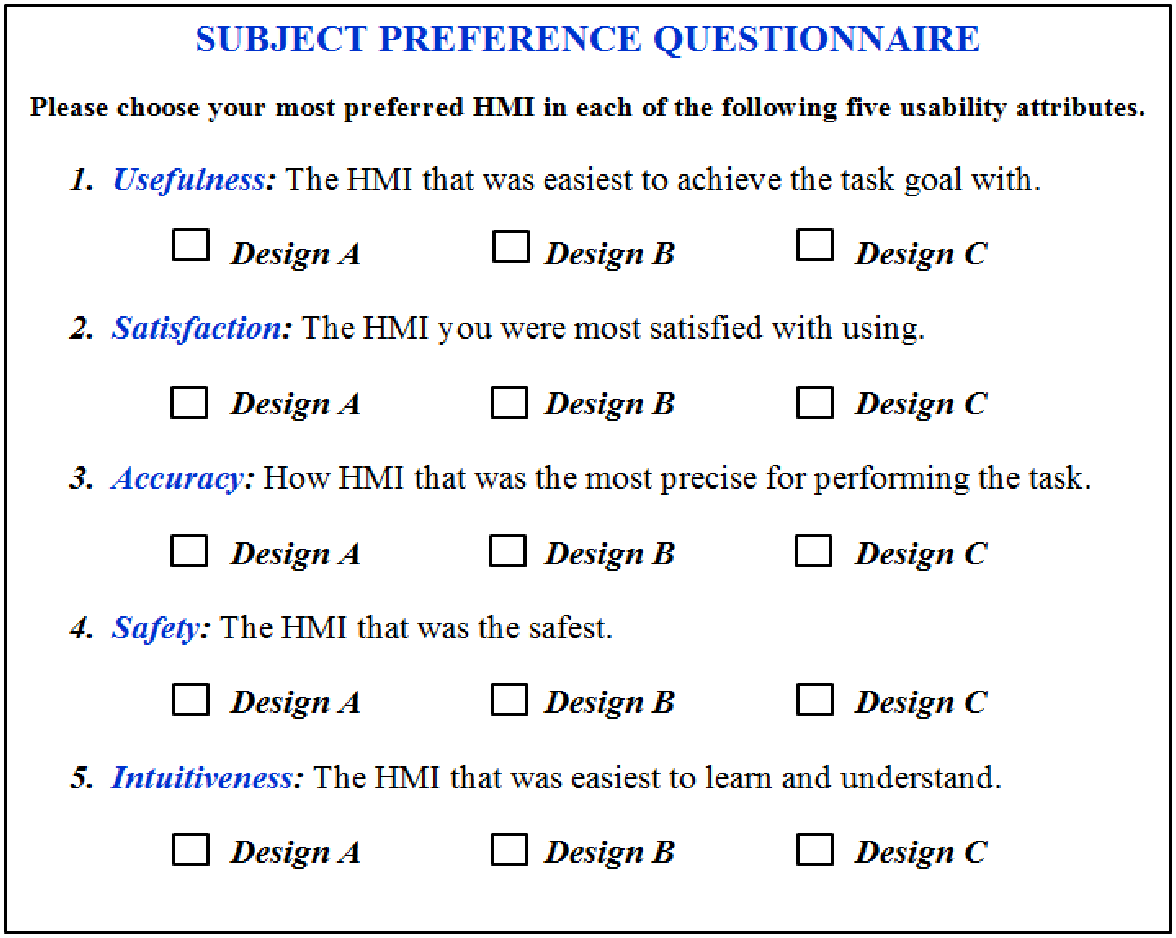
Appendix B

1. Qualitative Usability Metrics Definitions

Title	Description
Usefulness	Concerns the degree to which a product enables a user to achieve his or her goals, and is an assessment of the user's willingness to use the product at all." Usefulness is therefore an important usability requirement for hydraulic excavator HMIs in assuring that the specific goals of the operator can be achieved.
Satisfaction	Refers to the user's perceptions, feelings, and opinions of the product, usually captured through both written and oral questioning. Users are more likely to perform well on a product that meets their needs and provides satisfaction than one that does not. By asking users to rank the HMIs they are satisfied with helps to reveal the problems with a particular HMI.
Accuracy	This is a measure of effectiveness and has to do with the user's ability to operate the system correctly or precisely without making mistakes. A more accurate HMI is characterized by productivity, less frustration and increased user satisfaction.
Intuitiveness	This is a part of effectiveness and has to do with the user's ability to operate the system to some defined level of competence after some predetermined amount and period of training (which may be no time at all). It can also refer to the ability of infrequent users to relearn the system after periods of inactivity.
Safety	The quality of a system that prevents users from getting injured or endangered. Because hydraulic excavators operate in risky, injury-prone environments, the design of the HMI in terms of the layout of the interface elements becomes an important usability and ergonomic requirement in ensuring that operators can operate safely in such risky environments.

Appendix B (Continued)

2. Subjective Preference Questionnaire



SUBJECT PREFERENCE QUESTIONNAIRE

Please choose your most preferred HMI in each of the following five usability attributes.

1. ***Usefulness:*** The HMI that was easiest to achieve the task goal with.

   ☐ ***Design A*** ☐ ***Design B*** ☐ ***Design C***

2. ***Satisfaction:*** The HMI you were most satisfied with using.

   ☐ ***Design A*** ☐ ***Design B*** ☐ ***Design C***

3. ***Accuracy:*** How HMI that was the most precise for performing the task.

   ☐ ***Design A*** ☐ ***Design B*** ☐ ***Design C***

4. ***Safety:*** The HMI that was the safest.

   ☐ ***Design A*** ☐ ***Design B*** ☐ ***Design C***

5. ***Intuitiveness:*** The HMI that was easiest to learn and understand.

   ☐ ***Design A*** ☐ ***Design B*** ☐ ***Design C***

Appendix C

Randomization of Experimental Runs

Subject	**Test Run Order**		
1	B	A	C
2	B	C	A
3	B	C	A
4	A	C	B
5	B	C	A
6	C	B	A
7	A	C	B
8	A	C	B
9	C	A	B
10	B	A	C
11	B	C	A
12	C	A	B
13	C	A	B
14	A	C	B
15	B	A	C
16	C	B	A
17	B	C	A
18	A	C	B
19	A	C	B
20	C	B	A

Appendix D

Table of Task Completion Times for Designs A, B and C

Participant ID	**HMI Type**	**Task Completion Time *(in minutes)***
1	A	6.057
	C	7.411
	B	5.919
2	B	6.333
	C	9.526
	A	5.672
3	C	7.561
	B	7.744
	A	7.269
4	A	11.003
	C	12.262
	B	15.012
5	A	7.764
	C	6.390
	B	5.515
6	C	7.091
	A	6.042
	B	5.176
7	B	4.652
	A	8.330
	C	6.449
8	B	6.866
	C	6.164
	A	5.279

Appendix D (Continued)

Table of Task Completion Times for Designs A, B and C

Participant ID	**HMI Type**	**Task Completion Time *(in minutes)***
9	C	6.242
	A	7.102
	B	5.373
10	C	6.387
	A	10.243
	B	6.910
11	A	11.266
	C	12.559
	B	11.784
12	B	8.061
	A	9.502
	C	6.890
13	C	11.260
	B	10.058
	A	9.502
14	B	6.596
	C	10.086
	A	6.826
15	A	8.014
	C	6.497
	B	6.083
16	A	6.554
	C	7.666
	B	4.196

Appendix D (Continued)

Table of Task Completion Times for Designs A, B and C

Participant ID	**HMI Type**	**Task Completion Time** ***(in minutes)***
17	C	10.811
	B	6.802
	A	7.628
18	B	11.874
	A	11.837
	C	10.593
19	B	2.942
	C	4.985
	A	5.231
20	B	3.661
	C	7.566
	A	4.830

Appendix E

Table of Operating Errors Designs A, B and C

Participant ID	HMI Type	Operating Error			
		$Error\ 1\ (P_{ER1})$		$Error\ 1\ (P_{ER2})$	
		$No.of$ $Rocks\ Out$	$P_{ER1} = \frac{Rocks\ Out}{5}$	$No.of$ $Collisions$	$P_{ER2} = \frac{No.of\ Collisons}{25}$
1	A	0	0	8	0.2
	C	0	0	3	0.12
	B	2	0.4	5	0.32
2	B	2	0.4	3	0.12
	C	1	0.2	1	0.04
	A	0	0	1	0.04
3	C	1	0.2	6	0.24
	B	1	0.2	0	0
	A	0	0	11	0.44
4	A	2	0.4	25	1
	C	3	0.6	4	0.16
	B	0	0	3	0.12
5	A	1	0.2	0	0
	C	0	0	0	0
	B	1	0.2	2	0.08
6	C	0	0	1	0.04
	A	1	0.2	3	0.12
	B	1	0.2	1	0.04
7	B	0	0	0	0
	A	0	0	6	0.24
	C	1	0.2	0	0
8	B	2	0.4	0	0
	C	0	0	1	0.04
	A	0	0	8	0.32

Appendix E (Continued)

Table of Operating Errors for Designs A, B and C

Participant ID	**HMI Type**	**Operating Error**			
		$\boldsymbol{Error\ 1\ (P_{ER1})}$		$\boldsymbol{Error\ 2\ (P_{ER2})}$	
		$\boldsymbol{No.of\ Rocks\ Out}$	$\boldsymbol{P_{ER1} = \frac{Rocks\ Out}{5}}$	$\boldsymbol{No.of\ Collisions}$	$\boldsymbol{P_{ER2} = \frac{No.of\ Collisons}{25}}$
9	C	1	0.2	12	0.48
	A	1	0.2	13	0.52
	B	0	0	8	0.32
10	C	0	0	13	0.52
	A	0	0	3	0.12
	B	0	0	8	0.32
11	A	1	0.2	7	0.28
	C	3	0.6	0	0
	B	2	0.4	1	0.04
12	B	0	0	2	0.08
	A	1	0.2	14	0.56
	C	1	0.2	3	0.12
13	C	2	0.4	3	0.12
	B	0	0	2	0.08
	A	1	0.2	4	0.16
14	B	0	0	1	0.04
	C	1	0.2	1	0.04
	A	1	0.2	8	0.32
15	A	0	0	7	0.28
	C	1	0.2	2	0.08
	B	0	0	6	0.24
16	A	0	0	9	0.36
	C	0	0	6	0.24
	B	2	0.4	1	0.04

Appendix E (Continued)

Table of Operating Errors for Designs A, B and C

Participant ID	**HMI Type**	**Operating Error**			
		$Error\ 1\ (P_{ER1})$		$Error\ 2\ (P_{ER2})$	
		$No.of\ Rocks\ Out$	$P_{ER1} = \frac{Rocks\ Out}{5}$	$No.of\ Collisions$	$P_{ER2} = \frac{No.of\ Collisons}{25}$
	C	2	0.4	0	0
17	B	1	0.2	0	0
	A	1	0.2	4	0.16
	B	2	0.4	0	0
18	A	2	0.4	3	0.12
	C	1	0.2	0	0
	B	0	0	3	0.12
19	C	2	0.4	0	0
	A	2	0.4	2	0.08
	B	0	0	0	0
20	C	0	0	1	0.04
	A	0	0	0	0

Appendix F

Descriptive and Inferential Statistics for Task Completion Time

Descriptive Statistics: Task Completion Time

```
                      HMI
Variable              Type   Mean  SE Mean  StDev  Minimum  Maximum
Task Completion Time  A     5.980    0.447  2.001    2.942   10.008
                      B     7.798    0.477  2.132    4.830   11.837
                      C     8.220    0.508  2.274    4.985   12.559
```

General Linear Model: Task Completion Time versus HMI Type

```
Factor    Type   Levels  Values
HMI Type  fixed       3  A, B, C
```

Analysis of Variance for Task Completion Time, using Sequential SS for Tests

```
Source    DF   Seq SS   Adj SS  Seq MS     F      P
HMI Type   2   56.675   56.675  28.338  6.20  0.004
Error     57  260.684  260.684   4.573
Total     59  317.359


S = 2.13855   R-Sq = 17.86%   R-Sq(adj) = 14.98%
```

Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Task Completion Time

```
All Pairwise Comparisons among Levels of HMI Type
HMI Type = A  subtracted from:

HMI
Type   Lower  Center  Upper  --------+---------+---------+--------
B     0.1921   1.818  3.444           (----------*----------)
C     0.6143   2.240  3.866              (----------*----------)
                             --------+---------+---------+--------
                                   0.0       1.5       3.0


HMI Type = B  subtracted from:

HMI
Type   Lower  Center  Upper  --------+---------+---------+--------
C     -1.204  0.4222  2.048  (----------*----------)
                             --------+---------+---------+--------
                                   0.0       1.5       3.0


Tukey Simultaneous Tests
Response Variable Task Completion Time
All Pairwise Comparisons among Levels of HMI Type
HMI Type = A  subtracted from:

HMI   Difference       SE of           Adjusted
Type    of Means  Difference  T-Value   P-Value
B          1.818      0.6763    2.688    0.0251
C          2.240      0.6763    3.312    0.0045
```

Appendix F(Continued)

```
HMI Type = B  subtracted from:

HMI   Difference       SE of           Adjusted
Type    of Means  Difference  T-Value   P-Value
C         0.4222      0.6763   0.6243    0.8074
```

Appendix G

Descriptive and Inferential Statistics for Error 1 (Error Probability of Collisions)

Descriptive Statistics: Error 1

```
          HMI
Variable  Type    Mean  SE Mean   StDev  Minimum  Maximum
Error 1   A     0.2720   0.0526  0.2353   0.0000   1.0000
          B     0.0920   0.0231  0.1031   0.0000   0.3200
          C     0.1140   0.0340  0.1521   0.0000   0.5200
```

General Linear Model: Error 1 versus HMI Type

```
Factor    Type   Levels  Values
HMI Type  fixed       3  A, B, C
```

Analysis of Variance for Error 1, using Adjusted SS for Tests

```
Source    DF   Seq SS   Adj SS   Adj MS     F      P
HMI Type   2  0.38565  0.38565  0.19283  6.49  0.003
Error     57  1.69272  1.69272  0.02970
Total     59  2.07837


S = 0.172328   R-Sq = 18.56%   R-Sq(adj) = 15.70%
```

Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Error 1

```
All Pairwise Comparisons among Levels of HMI Type
HMI Type = A  subtracted from:

HMI
Type    Lower   Center     Upper    -+---------+---------+---------+-----
B     -0.3110  -0.1800  -0.04899    (--------*--------)
C     -0.2890  -0.1580  -0.02699       (-------*--------)
                                    -+---------+---------+---------+-----
                                  -0.30     -0.15      0.00      0.15


HMI Type = B  subtracted from:

HMI
Type    Lower   Center   Upper    -+---------+---------+---------+-----
C     -0.1090  0.02200  0.1530                  (-------*--------)
                                  -+---------+---------+---------+-----
                                -0.30     -0.15      0.00      0.15


Tukey Simultaneous Tests
Response Variable Error 1
All Pairwise Comparisons among Levels of HMI Type
HMI Type = A  subtracted from:

HMI   Difference       SE of           Adjusted
Type    of Means  Difference  T-Value   P-Value
B        -0.1800     0.05449   -3.303    0.0047
C        -0.1580     0.05449   -2.899    0.0145
```

Appendix G (Continued)

```
HMI Type = B  subtracted from:

HMI   Difference       SE of           Adjusted
Type    of Means  Difference  T-Value   P-Value
C        0.02200     0.05449   0.4037    0.9142
```

Appendix H

Descriptive and Inferential Statistics for Error 2 (Error Probability of Misses)

Descriptive Statistics: Error 2

```
          HMI
Variable  Type    Mean  SE Mean   StDev  Minimum  Maximum
Error 2   A     0.1200   0.0304  0.1361   0.0000   0.4000
          B     0.1800   0.0408  0.1824   0.0000   0.4000
          C     0.2000   0.0435  0.1947   0.0000   0.6000
```

General Linear Model: Error 2 versus HMI Type

```
Factor    Type   Levels  Values
HMI Type  fixed       3  A, B, C
```

Analysis of Variance for Error 2, using Sequential SS for Tests

```
Source    DF   Seq SS   Adj SS   Seq MS     F      P
HMI Type   2  0.06933  0.06933  0.03467  1.16  0.321
Error     57  1.70400  1.70400  0.02989
Total     59  1.77333


S = 0.172901   R-Sq = 3.91%   R-Sq(adj) = 0.54%
```

Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Error 2

```
All Pairwise Comparisons among Levels of HMI Type
HMI Type = A  subtracted from:

HMI
Type     Lower   Center   Upper    -+---------+---------+---------+-----
B     -0.07145  0.06000  0.1915        (------------*------------)
C     -0.05145  0.08000  0.2115          (------------*------------)
                                   -+---------+---------+---------+-----
                                 -0.10      0.00      0.10      0.20


HMI Type = B  subtracted from:

HMI
Type    Lower   Center   Upper    -+---------+---------+---------+-----
C     -0.1115  0.02000  0.1515    (------------*------------)
                                  -+---------+---------+---------+-----
                                -0.10      0.00      0.10      0.20


Tukey Simultaneous Tests
Response Variable Error 2
All Pairwise Comparisons among Levels of HMI Type
HMI Type = A  subtracted from:

HMI   Difference       SE of           Adjusted
Type    of Means  Difference  T-Value   P-Value
B        0.06000     0.05468    1.097    0.5196
C        0.08000     0.05468    1.463    0.3162
```

Appendix H (Continued)

```
HMI Type = B  subtracted from:

HMI   Difference       SE of           Adjusted
Type    of Means  Difference  T-Value   P-Value
C        0.02000     0.05468   0.3658    0.9290
```

Appendix I

NASA TLX Workload Ratings and Weights for Designs A, B and C

Participant ID	Factor	HMI Type					
		Deign A		**Design B**		**Design C**	
		Rating	*Weight*	*Rating*	*Weight*	*Rating*	*Weight*
1	Mental Demand	5	80	1	49	4	73
	Temporal Demand	1	12	3	37	1	41
	Physical Demand	0	14	2	26	0	15
	Own Performance	2	32	5	40	2	25
	Effort	4	52	3	51	3	63
	Frustration Level	3	70	1	29	5	72
2	Mental Demand	1	42	1	28	2	27
	Temporal Demand	0	27	0	19	0	15
	Physical Demand	2	63	3	51	4	60
	Own Performance	4	94	4	68	4	80
	Effort	3	40	2	11	1	53
	Frustration Level	5	87	5	61	4	72
3	Mental Demand	5	69	4	99	5	94
	Temporal Demand	4	54	5	100	3	70
	Physical Demand	0	6	0	3	0	9
	Own Performance	1	64	1	45	1	69
	Effort	2	72	2	100	4	86
	Frustration Level	3	80	3	100	2	95
4	Mental Demand	2	40	4	58	4	27
	Temporal Demand	2	20	2	30	0	37
	Physical Demand	0	30	1	42	1	40
	Own Performance	4	51	0	71	3	30
	Effort	3	48	3	74	2	52
	Frustration Level	4	50	5	72	5	47
5	Mental Demand	5	53	5	53	5	52
	Temporal Demand	0	0	0	4	0	0
	Physical Demand	3	4	1	0	2	5
	Own Performance	4	0	2	17	3	0
	Effort	2	10	3	30	4	18
	Frustration Level	1	0	4	42	1	0

Appendix I (Continued)

NASA TLX Workload Ratings and Weights for Designs A, B and C

Participant ID	**Factor**	**HMI Type**					
		Deign A		**Design B**		**Design C**	
		Rating	*Weight*	*Rating*	*Weight*	*Rating*	*Weight*
6	Mental Demand	4	44	2	36	5	64
	Temporal Demand	1	16	5	56	2	32
	Physical Demand	0	10	0	13	0	10
	Own Performance	4	28	3	54	2	39
	Effort	4	33	2	30	3	40
	Frustration Level	2	36	3	28	3	34
7	Mental Demand	0	81	0	65	4	85
	Temporal Demand	5	85	5	70	1	59
	Physical Demand	1	54	1	71	3	74
	Own Performance	3	20	3	52	1	33
	Effort	2	50	3	51	3	57
	Frustration Level	4	47	3	68	3	50
8	Mental Demand	4	65	2	60	4	69
	Temporal Demand	1	53	1	30	0	50
	Physical Demand	0	48	0	51	2	50
	Own Performance	5	39	5	50	5	69
	Effort	3	29	4	39	1	40
	Frustration Level	2	20	3	26	3	18
9	Mental Demand	5	68	5	60	5	79
	Temporal Demand	0	0	0	0	0	0
	Physical Demand	2	58	2	47	2	28
	Own Performance	4	77	4	78	4	71
	Effort	3	58	3	48	3	63
	Frustration Level	1	60	1	46	1	68
10	Mental Demand	4	61	3	59	4	63
	Temporal Demand	2	8	4	62	2	18
	Physical Demand	3	10	2	9	3	19
	Own Performance	5	0	5	0	5	0
	Effort	1	0	1	0	1	0
	Frustration Level	0	0	0	0	0	0

Appendix I (Continued)

NASA TLX Workload Ratings and Weights for Designs A, B and C

Participant ID	**Factor**	**HMI Type**					
		Deign A		**Design B**		**Design C**	
		Rating	*Weight*	*Rating*	*Weight*	*Rating*	*Weight*
11	Mental Demand	5	26	3	9	5	9
	Temporal Demand	1	1	0	19	1	0
	Physical Demand	2	30	1	0	0	11
	Own Performance	2	70	4	38	4	60
	Effort	2	50	3	10	2	17
	Frustration Level	3	39	4	62	3	40
12	Mental Demand	4	70	3	83	4	51
	Temporal Demand	0	17	1	35	0	50
	Physical Demand	2	80	1	49	2	76
	Own Performance	2	80	2	78	5	75
	Effort	4	64	3	79	3	41
	Frustration Level	3	64	5	81	1	13
13	Mental Demand	2	39	2	45	5	70
	Temporal Demand	0	4	0	33	1	13
	Physical Demand	4	57	2	48	3	49
	Own Performance	5	51	2	19	3	35
	Effort	3	42	5	60	3	57
	Frustration Level	1	13	4	70	0	19
14	Mental Demand	2	15	4	57	4	64
	Temporal Demand	0	12	2	12	1	10
	Physical Demand	3	15	3	26	2	36
	Own Performance	4	13	1	49	0	41
	Effort	5	34	5	34	5	27
	Frustration Level	1	15	0	50	3	48
15	Mental Demand	1	14	5	82	1	29
	Temporal Demand	4	60	1	16	5	9
	Physical Demand	5	67	1	53	4	77
	Own Performance	3	29	1	55	2	29
	Effort	2	16	3	83	3	19
	Frustration Level	0	2	4	24	0	4

Appendix I (Continued)

NASA TLX Workload Ratings and Weights for Designs A, B and C

Participant ID	Factor	**Deign A**		**HMI Type** **Design B**		**Design C**	
		Rating	*Weight*	*Rating*	*Weight*	*Rating*	*Weight*
16	Mental Demand	4	48	5	50	2	86
	Temporal Demand	2	9	0	10	0	30
	Physical Demand	0	70	2	59	4	78
	Own Performance	3	21	4	11	1	30
	Effort	3	52	3	25	3	67
	Frustration Level	3	25	1	33	5	91
17	Mental Demand	3	70	1	44	4	67
	Temporal Demand	0	41	0	25	0	21
	Physical Demand	1	57	3	40	2	50
	Own Performance	5	33	4	59	3	75
	Effort	3	53	2	31	3	32
	Frustration Level	3	41	5	39	3	71
18	Mental Demand	3	56	4	64	3	77
	Temporal Demand	0	51	0	40	0	80
	Physical Demand	1	16	3	10	1	55
	Own Performance	2	63	2	46	4	60
	Effort	4	75	5	74	3	81
	Frustration Level	5	80	1	53	4	72
19	Mental Demand	4	53	4	80	4	76
	Temporal Demand	0	36	0	47	0	38
	Physical Demand	4	33	4	83	4	69
	Own Performance	3	74	3	82	2	23
	Effort	3	46	3	81	3	46
	Frustration Level	1	12	1	100	2	51
20	Mental Demand	3	38	2	63	2	36
	Temporal Demand	0	23	0	11	0	18
	Physical Demand	3	55	3	38	3	59
	Own Performance	5	32	5	49	5	74
	Effort	3	29	3	39	4	54
	Frustration Level	1	53	2	28	1	50

Appendix I (Continued)

NASA TLX Data Summary for Design A

Subscale	***Rating***	***Weight***	***Adjusted Score***
Mental Demand	3	57.20	171.6
Temporal Demand	1	26.80	26.80
Physical Demand	2	35.95	71.9
Own Performance	3	48.05	144.15
Effort	3	47.50	142.5
Frustration Level	3	50.60	151.8

NASA TLX Data Summary for Design B

Subscale	***Rating***	***Weight***	***Adjusted Score***
Mental Demand	3	51.60	154.8
Temporal Demand	1	26.45	26.45
Physical Demand	2	38.35	77.7
Own Performance	4	43.55	174.2
Effort	3	42.65	127.95
Frustration Level	2	39.70	79.4

NASA TLX Data Summary for Design C

Subscale	***Rating***	***Weight***	***Adjusted Score***
Mental Demand	4	59.90	239.6
Temporal Demand	1	29.55	29.55
Physical Demand	2	43.50	87
Own Performance	3	45.90	137.7
Effort	3	45.65	136.95
Frustration Level	2	45.75	91.5

Appendix J

Subjective Preference Summary

Participant ID	**Metrics**				
	Usefulness	***Satisfaction***	***Accuracy***	***Safety***	***Intuitiveness***
1	A	B	A	B	A
2	A	B	A	A	A
3	B	C	B	B	B
4	B	B	B	B	B
5	B	B	B	B	B
6	B	B	B	C	C
7	B	B	C	B	B
8	C	C	C	C	A
9	C	B	C	B	C
10	B	A	B	B	A
11	B	C	B	B	C
12	B	B	A	B	B
13	B	B	B	B	A
14	B	B	B	B	B
15	B	B	B	B	B
16	B	B	A	B	A
17	B	B	A	B	A
18	A	B	A	B	B
19	B	B	A	B	A
20	B	B	B	B	A
Summary of Responses					
A	7 (35%)	3 (15%)	3 (15%)	1 (5%)	9 (45%)
B	10 (50%)	15 (75%)	15 (75%)	17 (85%)	8 (40%)
C	3 (15%)	2 (10%)	2 (10%)	2 (10%)	3 (15%)

Appendix K

Operator Interview Feedback

1. ***What are some of the problems with using the monitor display?***
    - *Beside the gauges and work modes that you can set with the monitor display, it does not provide any information about the job itself where most of the time and attention is concentrated.*
2. ***What are some of the problems with using the joystick controls?***
    - *There is not much difficulty with the use of the joysticks since dexterity is developed over many years of training. However, their repetitive use feels uncomfortable, and the cab is also less ergonomic. This leads to fatigue and discomfort.*
3. ***What information feedback is critical for performing the task?***
    - *On-the job information especially visibility of the ground during excavation.*
4. ***What improvements would you like to see in the design of the HMI?***
    - *Video display of ground*
    - *GPS technology for showing depth, slope or elevation of the ground*
    - *Force feedback via the controls may be beneficial*
    - *Improved ergonomics of the cab*