EVALUATING THE EFFECTIVENESS OF AUGMENTED REALITY AND WEARABLE COMPUTING FOR A MANUFACTURING ASSEMBLY TASK

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Abstract

The focus of this research was to examine how effectively augmented reality (AR) displays, generated with a wearable computer, could be used for aiding an operator performing a manufacturing assembly task. The research concentrated on comparing two technologies for generating augmented reality displays (opaque vs. see-through), with two current types of assembly instructions (a traditional assembly instruction manual vs. computer aided instruction). The study was used to evaluate the effectiveness of the wearable based augmented reality compared to traditional instruction methods, and was also used to compare two types of AR displays in the context of an assembly task.

For the experiment, 15 subjects were asked to assemble a computer motherboard using the four types of instruction: paper manual, computer aided, an opaque AR display, and a see-through AR display. The study was run as a within subjects design, where subjects were randomly assigned the order of instruction media. For the AR conditions, the augmented environments were generated with a wearable computer, and viewed through two types of monocular, head-mounted displays (HMD). The first type of HMD was a monocular opaque HMD, and the second was a monocular see-though HMD. Prior to the experiment, all subjects performed a brief training session teaching them how to insert the various components of the motherboard in their respective slots. The time of assembly and assembly errors were measured for each type of media, and a questionnaire was administered to each subject at the end of each condition, and at the end of the experiment to determine the usability of the four instructional media.

The results of the experiment indicated that both augmented reality conditions were more effective instructional aids for the assembly task than either the paper instruction manual or the computer aided instruction. The see-through HMD resulted in the fastest assembly times followed by the opaque HMD, the computer aided instruction, and the paper instructions

respectively. In addition, subjects made fewer errors using the AR conditions compared to the other two types of instructional media. However, while the two AR conditions were a more effective instructional media when time was the response measure, there were still some important usability issues associated with the AR technology that were not present in the non-AR conditions. Many of the subjects indicated that both types of HMDs were uncomfortable, and over half expressed concerns about poor image contrast with the see-through HMDs. Finally, this thesis discusses the results of this study as well as implications for the design and use of AR and wearable computers for manufacturing assembly tasks.

DEDICATION

I would like to dedicate this thesis to my family. Without their support and encouragement throughout my entire academic career, I would not be where I am today. I would particularly like to thank my mother and father. Only looking back now can I truly appreciate their efforts to instill the work ethic and appreciation of knowledge in me at a young age. They made my study when I didn't want to, work harder when I didn't need to, and fix my errors when I didn't think to. For this I thank you both.

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CHAPTER 1: INTRODUCTION

1.1. Motivation

Everything that individuals and societies use such as automobiles, airplanes, computers, clothing, food products, roads, etc., is the result of simple or complex manufacturing activities. *Manufacturing* is the transformation of raw materials into finished goods of greater value by application of one or more processes and delivering the final products to customers via an effective supply chain. In the United States, manufacturing accounts for approximately 30% of the gross national product (GNP); by contrast, primary industries such as agriculture, forestry, and mining, account for only 5-8% of the GNP (World Bank, 1982). Nevertheless, the road towards a vibrant and profitable level of manufacturing is continually changing and becoming more competitive.

Since the Industrial Revolution, manufacturing processes have continued to become more complex and more diverse (Askin and Standridge, 1993). With the rapidly increasing number and types of manufactured products on the market today has come the development of many novel and successful manufacturing trends such as agile manufacturing and just-in-time practices (Voss, 1994). However, the increased product diversity and consumer demand has led to many issues where current manufacturing practices are becoming more difficult to utilize. As this trend continues, new manufacturing technologies will be needed to meet the demands of the 21st century.

One of the most evident fields where augmented reality and wearable computing can be used to advance the state of the art and provide solutions to current and future problems is manufacturing. Through the integration of new technologies, the manufacturing community will be able to smooth the transition from current practices to effective production methods of the future. The constant transition and diversification that manufacturing undergoes as we reach the 21st century, illustrates the need for the exploration of new research avenues that would enable the utilization of novel methods and techniques, such as augmented reality and wearable computing, for supporting manufacturing activities (Siegel and Bauer, 1997).

Using augmented reality (AR), the ability to visualize and project three-dimensional data or textual information in the environment, provides the user an intuitive means to interact with information, explore structures, parts, or data, in a way that has not been previously available (Barfield, Baird, Shewchuk, and Ioannou, In Press). Providing the user with an egocentric or first person frame of reference to view data, will allow operators to use their natural spatial processing abilities to gain a sense of presence in the real world augmented with digital graphics. The ability to visualize and interact with an environment that has been augmented with virtual data could have a great impact on the way current manufacturing processes are accomplished, and provide solutions to the manufacturing problems of the future.

1.2. Scope, Goals, and Significance

The challenges associated with current and future manufacturing assembly practices are quickly changing the way that manufacturing systems engineering is being accomplished. The manufacturing processes of the future will be vastly different from that of today. Along with new advances in manufacturing technology, there will be a corresponding need to allow operators or shop-floor workers to interface with data and information associated with manufacturing processes. Some of this data may include information about the three-dimensional (3-D) structure of parts, assembly instructions, or information about the flow of material through a manufacturing facility. In each of these cases, the visualization of information or processes, and the need to manipulate the data, are the common theme (Ellis and Menges, 1997). The use of augmented reality and wearable computer technology for the visualization of information or processes and the direct manipulation of data associated with manufacturing processes, has tremendous potential for the manufacturing domain, particularly assembly tasks.

The purpose of this thesis was to evaluate the effectiveness of augmented reality for a manufacturing assembly task. Manual assembly tasks are some of the most common types of tasks done at manufacturing plants throughout the world. This type of task generally consists of one or more human workers following textual instruction manuals, drawings, or schematics, in order to assemble the pieces of a product into its final form. While these traditional methods of conveying instructions to an assembly worker have been in use for decades, new trends in manufacturing are rendering them inefficient at best and obsolete at worst. The need for extremely diversified product portfolios in today's market has lead to complex manufacturing systems and the need for dynamic and evolving assembly systems.

Computers have redefined the field of manufacturing systems and enabled the realization of integrated entities both at the shop floor and the enterprise-wide level. Agility and lean manufacturing, just-in-time response to market demands, design-to-cost, and concurrent engineering are inherently coupled with the need to handle and process a large amount of data in a short amount of time.

Complex, multi-step assembly and maintenance operations generally require the operators to alternate their attention between the assembly instructions and part being assembled. This constant change of attention consumes valuable time, especially when the instructions are not conveniently placed relative to the operation. An example of this would be an engine mechanic working on objects in tight quarters where there is no room for written instructions or to access a desktop computer. The constant change of attention may cause reduced productivity, errors, increased assembly times, and repetitive motion or strain injuries.

Augmented reality technologies that allow users to project knowledge in the real environment can provide annotated instructions in real time superimposed on the operator's field of view. The operator can then concentrate on the task at hand without having to change head or body position to receive the next set of instructions. Another advantage of using AR and wearable computers is the ability to network the user's computer with a local or remote server. This allows for the real time saving, retrieving, and sending of information vital to helping the user with the assembly task. A hypothesis tested in this research, is that using AR for an assembly task will provide a more efficient method for performing this type of manufacturing task.

Until now there has been little or no research investigating the effectiveness of different types of AR displays for a manufacturing assembly task. The research in this thesis is one of the first efforts to quantify and benchmark the utility of AR in the manufacturing domain. By taking this first step towards validating the use of AR for assembly tasks, hopefully more research will be implemented and this newly emerging technology will be recognized as a useful tool to aid future generations of assembly workers.

1.3. Organization

This thesis is organized into five chapters: Introduction, Review of Literature, Experimental Procedure, Results, and Conclusions. The first chapter, Introduction, describes the motivation for conducting the proposed research, as well as the scope, goals, and significance of the research.

Chapter 2, Review of Literature, examines current research in the fields of AR, wearable computing, current manufacturing practices, and the current use of AR and wearable computing in manufacturing. Through the literature review, an understanding of what makes an effective AR environment is examined as well as the hardware and software issues related to AR and wearable computers. Next a general overview of current manufacturing practices is given followed by future trends in manufacturing practices, and the reasoning why new techniques are required.

Experimental Procedure, described in chapter 3, outlines the experiment that was done to test the effectiveness of two types of AR displays compared to traditional paper instructions and computer aided instructions for a PC motherboard assembly task. In this experiment a wearable computer and head mounted displays are used to create the computer-generated images that are projected in the real world.

Chapter 4 discusses the results obtained from the experiment and presents the statistical analyses and data collected. Finally, chapter 5 presents the conclusions and describes future work that may be done to advance the field.

CHAPTER 2: LITERATURE REVIEW

2.1. Wearable Computing

Throughout the past decade, advances in computer processing power, graphics systems, power supplies, and miniaturization have been taking place at an increasingly rapid rate. In the 1970's computers were large mainframe machines that occupied entire rooms and had very limited processing power. Technology advances in the 1980's allowed computers to become small enough to put on desktops, and the processing power was rapidly increasing as new chip fabrication techniques were developed. In the 1990's came the mass popularization of mobile laptop computers. The development of power supplies such as lithium ion batteries, advances in active matrix LCD displays, and the miniaturization of computer components, allowed computers to become portable. Users can now carry around a self powered computer with a color screen and peripherals in a package no larger than a briefcase (Mann, 1997). The evolution of computers from mainframes to portables has been rapid and is continually occurring.

The next step in ubiquitous computing is represented by the development of wearable computers (Barfield and Baird, 1998 (a); Thorp, 1998). Wearable computers are fully functional, self powered, self contained computers that can be worn on the users body unobtrusively (See Figure 1). With the development of wearable computers has come the evolution of wearable displays, input devices, peripherals, networking tools, and in particular, augmented reality, which allows the user to project knowledge and information in their environment. The use of wearable computers for augmented reality is beginning to be seen in the areas of manufacturing, medicine, education and training, and as personal assistants (Barfield and Baird, 1998 (b)). As the technology develops, and the advantages of being able to wear a computer and project information in the environment are realized, the field will continue to grow at an increasing rate.

Figure 1. Picture of a Xybernaut wearable computer.
Picture from Xybernaut, www.xybernaut.com.

One of the main advantages of using a wearable computer in the manufacturing environment is that they allow the option of hands free use. Speech recognition or EEG and EMG input are a few ways for the user to interact with the computer in a completely hands free manner (Picard and Healey, 1997). Other unobtrusive input devices such as hand held keyboards or track pads allow the user to input data when complete hands free use is not necessary (Lewis, Havey, and Hanzal, 1998). For some applications, another effective tool in providing the user with a realistic experience is allowing the user to receive force feedback to provide a direct physical perception of 3-D objects. Haptic interfaces providing force feedback directly couple input and output between the computer and user. Force feedback acts as a beneficial addition to augmented reality simulations for problems that involve understanding of 3-D structure, shape, or fit, such as in assembly tasks.

In the past, virtual environments were only able to be generated using desktop computers, and required users to wear heavy and cumbersome head mounted displays. Very often in a manufacturing environment however, jobs are done on the shop floor, in confined spaces, or other areas where desktop computers are unable to be placed (Ockerman and Pritchett, 1998). Many manufacturing tasks also require the worker to move around the workspace or facility, which makes the use of desktop computers and heavy HMDs to aid in the task impractical. Laptop computers are small and mobile, but don't allow hands free use or have the ability to effectively project visual information in the environment through augmented reality. Often, manufacturing jobs require the worker to use one or both hands and traditional computer input devices would significantly slow down the job or be completely inappropriate for use (Sawhney and Schmandt, 1998). This is where the advent of wearable computers is able to provide the necessary functionality and mobility required to effectively use computers to create an augmented environment and aid in manufacturing tasks.

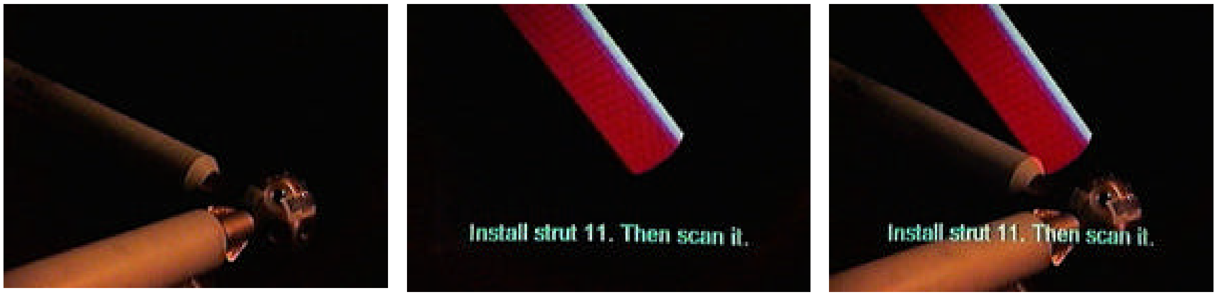
Advances in the miniaturization of computer components as well as in HMD technology, have allowed wearable computers to equal laptop computer processing power, and be small enough to wear unobtrusively (Post, Reynolds, Gray, Paradiso, and Gershenfeld, 1997). The technology of today's wearable computers is sufficient enough to store, generate, manipulate, and output virtual objects and information, in real time. Head mounted displays are able to clearly display readable text and virtual objects with sufficient resolution to provide the user with realistic virtual images. Technological advances in computer sound and force feedback technology are also being integrated into AR environments to enhance the AR experience.

2.2. Augmented Reality

Typical features of a virtual environment are a visual scene viewed using a head-mounted display (HMD), head tracking capabilities, and the ability to navigate and interact with virtual objects. In virtual reality, a stereoscopic scene is viewed using an opaque HMD providing the viewer a sense of "presence" within the virtual world (Barfield and Hendrix, 1995). With this type of display, the generated world consists entirely of computer graphics. However, for many applications it may be desirable to use as much of the real world in the scene as possible, rather than creating a new scene using entirely computer-generated imagery. Even the most sophisticated computers are unable to generate scenes with nearly the fidelity of the real world. The more real world scenery that can be used, the better the fidelity of the augmented environment (Barfield, Baird, and Bjorneseth, In Press). This area of virtual environments, where the designer is able to augment the real world with computer-generated information such as text or graphics, is termed augmented reality (Azuma, 1997) (See Figure 2). As in virtual reality, with augmented reality displays the user is typically yoked to a computer via a cable to a desktop computer. However, as an extension of the augmented reality metaphor, wearable computers allow mobile platforms to be used for augmenting the world with synthetic information.

In order to generate augmented environments with sufficient fidelity, and mobility, several issues need to be addressed. In terms of the presentation of visual information, displays need to be of high enough resolution to accurately and realistically render virtual objects as well as readable text in the real world. Current HMD technology that allows true VGA resolution and wide fields of view are able to do this, and as the display technology advances, even more realistic environments will be possible. Furthermore, appropriate input devices need to be utilized to allow the user to efficiently manipulate and interact with the data. In the manufacturing environment, the user is often using one or both hands to perform a task, therefore, the input devices need to be designed with this in mind (Ockerman, Najjar, and Thompson, 1997).

A major motivation for the use of augmented reality displays relates to the computational resources necessary to generate and update computer-generated scenes. In computer graphics, the more complex the scene (polygon count, texture mapping etc.), the more computational resources are necessary to render the scene, especially for real-time applications. However, the concept of augmented reality is to enhance the real world with virtual objects (Barfield and Baird, 1998). This approach does not require a scene that consists entirely of computer graphics, instead, the virtual objects are used as a supplement to the real-world scene. In addition, many applications of augmented reality do not require highly complex imagery. For example, some applications in augmented reality may require only wire frame graphics or text overlaid on top of the real world scene (Lion, Rosenberg, and Barfield, 1995). This was the case in the augmented reality system developed by Janin, Mizell, and Caudell (1993), where only 30-40 monochrome lines per frame were needed to augment a real world scene with wiring diagram information.



a b c

Figure 2. Example of an augmented environment., a = real object, b = virtual object, c= merged real and virtual object. Pictures from Computer Graphics and User Interfaces Laboratory at Columbia University. http://www.cs.columbia.edu/graphics/projects/arc/arc.html

Generally, to create an augmented reality scene, the following equipment is necessary: (1) hardware for generating visual images, (2) a position and orientation sensing system, (3) hardware for combining the computer graphics and real world into one image, and (4) the associated system software (Janin, Mizell, and Caudell, 1993). There are two types of displays that can be used to combine real world objects with computer-generated imagery to form an augmented scene, opaque HMDs and see-through HMDs. The research in this thesis evaluates the effectiveness of both (See Figures 3 and 4).

Figure 3: Opaque HMD.

Figure 4: See-through HMD.

Opaque HMDs are displays that are worn over one eye and create virtual images in the environment by fusing the images seen from the eye covered by the display with the eye that is not (Starner, Mann, Rhodes, Levine, Healey, Kirsch, Picard, and Pentland, 1997). See-through HMDs are worn over one or both eyes and create an augmented environment in one of two ways; video see-through, or optical see through (Azuma, 1997). Video based see-through displays are opaque displays that use cameras mounted near the users eyes to pass video of the environment to the display. The computer then fuses the video with the virtual image(s) to create a video based augmented reality environment. Optical see-through HMDs are worn like glasses with an optical mirror on the top (Spitzer, Rensing, McClelland, and Aquilino, 1997). The user can see the environment with their naked eyes and the computer sends images of the virtual objects through the optical mirror, which then reflects the images in the user's visual field. Both HMD types are commonly used for a variety of tasks and have different advantages and disadvantages associated with them (Holloway, 1997). For the purposes of this thesis, two types of optical see-though HMDs were examined. In summary, given a see-through HMD or an opaque HMD, the following two basic types of augmented realities can be created.

• *Video based augmented reality*: These systems can be used to view local or remote video views of real-world scenes, combined with overlaid computer graphics. The viewing of a remote scene is an integral component of telepresence applications.

• *Optical based augmented reality*: This system allows the observer to view the real world directly with one or both eyes with computer-graphics combined into the image. An advantage of this system is that the real world can be directly viewed and manipulated.

In conjunction with the output devices, effective input devices are necessary to allow the user to seamlessly interact with the virtual data being presented in the AR environment (Tan and Pentland, 1997). The input devices that have evolved for use with wearable computers are very diverse and continuously increasing. Growth in the popularity of wearable computers has sparked a increasing amount of research in the design and evaluation of input devices (Thomas, Tyermman, and Grimmer, 1997). For data entry or text input, body mounted keyboards, speech recognition software, or hand held keyboards are often used. Devices like IBM's Intellipoint, track balls, data gloves, and the Twiddler are used to take the place of a mouse to move a cursor and select options or manipulate visual data. When complete hands free operation is needed, speech recognition, gesture based, EMG based, and EEG based devices are options (Picard and

Healey, 1997). The common factors considered in the design of these input devices is that they all must be unobtrusive, if not hands free, accurate, and easy to use on the job.

2.3. General overview of manufacturing tasks

In general, manufacturing is comprised of a series of operations performed on raw materials of semi-finished goods (Williams, 1994). During each operation, a different manufacturing process is applied to the input items in order to change some of the items characteristics, increase their value, and generate one or more outputs. Each of these processes is undergoing rapid change in the way they are being performed with the advent of new technologies. The use of augmented reality and wearable computers is one of the emerging technologies that will change the way information is delivered for manufacturing processes.

Fabrication processes are those which change the input item's dimensions, geometry, physical, chemical, and/or mechanical properties by application of force or energy. Categories of fabrication processes include machining, bulk deformation (rolling, forging, extrusion, drawing), casting, sheet metal forming, nontraditional machining (water-jet cutting, electric-discharge machining, etc.), heat treatment, surface coating, and cleaning (Kalpakjian, 1995).

Assembly processes are those which change the input item by combining it with one or more other items. Categories of assembly processes include bonding, mechanical fastening, and welding (Boothroyd and Alting, 1992). Assembly is the manufacturing process that will be examined in the scope of this thesis. One of the crucial prerequisites for the successful production of complex products in discrete parts manufacturing facilities is the correct and efficient mating of components final assemblies. The relative placement and interaction between such components and subassemblies is determined both by the functionality of the design, cost, and spatial constraints. On the other hand, the strive for compact designs and increased functions of modern products restricts the feasible solution space, and causes inconsistencies and errors (Groover, 1996). Augmented reality technology offers the means for identifying such inefficiencies early in the design cycle by using virtual representations of complex products that can be manipulated. This would allow timely alterations and optimization of the design, and would proactively support the effective production at the shop floor (Christensen and Gulli, 1996). Assembly visualization and instruction (Adam, 1993) by viewing images or text in augmented reality can be used in several types of assembly applications to increase productivity and reduce errors.

In addition to fabrication and assembly, *inspection* and *testing* operations are often required to ensure that items are manufactured to the desired specifications and will function as intended (Groover, 1996). Though such operations do not add value to the item, they are still considered part of the manufacturing process. Industrial inspection is still widely used to assure proper levels of quality in manufacturing (Kleiner and Drury, 1993).

Finally, in order to accomplish the required operations, various *material handling* activities must be performed. Material handling refers to the physical transportation of raw materials, work-in-process, and finished goods between the manufacturing resources, as well as to the transfer of raw materials from storage to production areas, or of finished goods from the production shop to warehouses (Allegri, 1984).

To accomplish the manufacturing of complex products, elaborate manufacturing systems are required. A *manufacturing system* is a collection of machines, tools, equipment, people, and facilities arranged and controlled in a prescribed manner, in order to produce certain varieties of items, in certain quantities (Nagel and Dove, 1991). Manufacturing systems can be decomposed into three separate subsystems:

- the *physical processing system*, which performs the actual transformation of input materials into finished goods and delivers the end products to the customers. This system consists of all the machines, tools fixtures, material handling equipment, workers, facilities, transportation and distribution networks, etc. used to perform processing operations, material handling and storage activities, and transportation/distribution/delivery functions.

- the *planning and control system*, which determines how to utilize the physical processing system to perform the required transformations and operations. This system consists of all the decision-making resources (computers, planning personnel, scheduling personnel, transportation personnel, etc.), as well as the planning, scheduling, and control algorithms themselves.

- the *information system*, which supplies the necessary information to the planning and control system for decision-making, and transmits the resulting instructions to the physical processing system. This system consists of all the data-collection and communications equipment, as well as the coded data stored in various databases.

The environment faced by manufacturers today is undergoing considerable change. According to Browne, Sackett, and Wortmann (1992), discrete-part manufacturing in the next century will be characterized by the following:

- Extremely high product variety.
- Extremely low production volume.
- Extremely short time-to-market.
- Shortened product life-cycles.
- Product demand curves (introduction, maturity, decline) approaching square waves.
- Increased product life.
- Reduced customer lead time.

To cope with the such characteristics, new manufacturing techniques and technologies are being developed. One technique, called *agile manufacturing* is being employed and refers to manufacturing utilizing resources and people which can be changed quickly and efficiently, in unanticipated ways, to cope with variability and uncertainty (Noaker, 1994). The objective is for agile manufacturing systems to be able to perform in such environments as effectively as mass production systems do, in stable, repetitive environments (Daude and Weck, 1997). In traditional manufacturing systems, individual workers perform routine decision-making tasks, in pre-determined ways, based upon limited, localized data. A key tenant of agile manufacturing is the utilization of a highly knowledgeable, cross-trained workforce, which has instant access to information and works in teams, in order to increase the organizations flexibility and responsiveness (Sheridan, 1993; Thompson, Ockerman, Najjar, and Rogers, 1997). To enable the realization of such instantaneous decision-making, advanced information and communications technologies are required to provide the necessary information to workers at any time, anywhere.

To successfully compete in such environments, manufacturing systems must be capable of providing high levels of production capacity essentially ‘on-demand’, and producing at mass-production levels for relatively brief periods, for a large quantity of product variations (Pine, 1993). They must be able to simultaneously reduce time-to-market, increase quality, and decrease cost (Goldman, Nagel, and Preiss, 1995). Traditional product-based manufacturing facilities are unsuitable for such environments: there is insufficient lead time to bring capacity on-line and for learning and experience curves to come into play, and product life-cycles are too short to justify dedicated facilities. The use of augmented reality and wearable computers would provide an ideal solution to this type of need. Networked wearable computers and AR displays would allow individuals at the shop floor level to dynamically send and receive information and maintain an agile manufacturing environment.

Another emerging trend in the manufacturing industry is the concept of mass customization (Richards, 1996). Mass customization refers to the ability to produce customized products, in mass quantities, and at mass-production unit costs and production rates. These objectives are naturally conflicting and cannot be achieved with traditional manufacturing technology. Flexible manufacturing systems (FMS) can produce individual items rapidly and on short notice, but are extremely expensive and cannot approach mass-production per-unit costs. Additionally, though FMSs are flexible within a their pre-designed capability/capacity envelope, they are extremely difficult to modify once installed, further limiting their use in rapidly changing product environments.

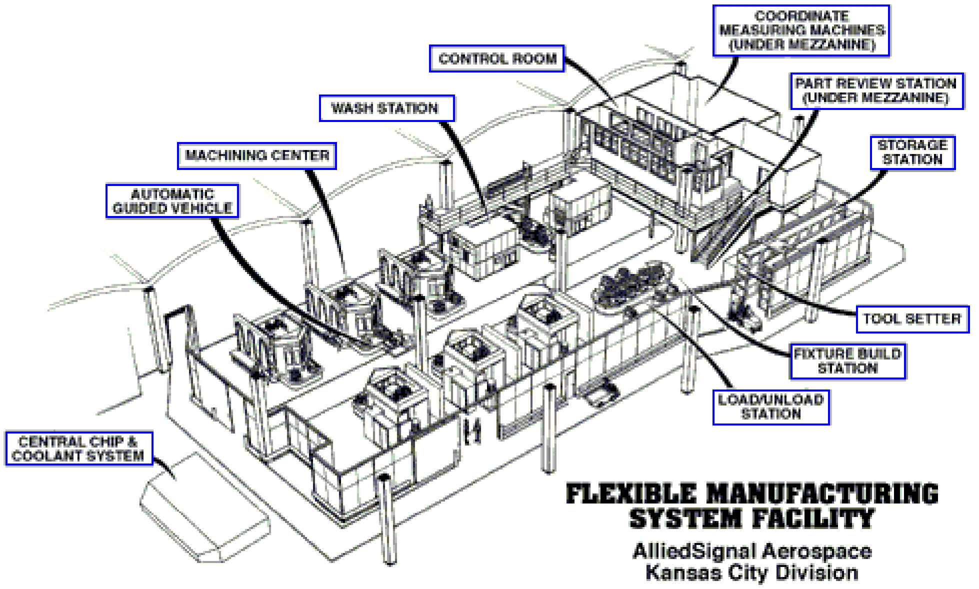


Figure 5: FMS Facility. Picture courtesy of www.os.kcp.com/home/map/fmsimage.html

Mass customization means that every end-item product is unique in some manner. Consequently, many of the manufacturing and related tasks required to produce each product will also be somewhat unique (Pisano and Hayes, 1995). As a result, the traditional approach of preparing detailed task instructions and training operators in advance of production is no longer viable, as the long production runs used to justify these activities no longer exist. The traditional approach would result in unacceptably long manufacturing lead times, and training would tie-up production facilities on a continual basis (Hormozi, 1994). The only way in which mass customization can be performed on a large scale is if workers are able to perform non-routine tasks in a routine manner (Barfield et. al., In Press). Unless workers are able to perform these complex, individual assemblies in a fast, efficient and reliable manner, mass customization on a large scale will not be viable.

To achieve the goal of mass customization, a new generation of manufacturing technologies is required, which are highly flexible at any given time, and can be rapidly and inexpensively reconfigured, in unanticipated ways, to obtain new capabilities and capacities (Bauer, Heiber, Kortuem, and Segall, 1998). AR through wearable computing also provides an ideal solution to the problems associated with developing an effective mass customization system. Using a database on the wearable computer, workers could get individual assembly instructions for each product as they come down the line (Stein, Ferrero, Hetfield, Quinn, and Krichever, 1998).

2.4. Current Applications of Augmented Reality in Manufacturing

The utility of wearable computers and augmented reality are beginning to be seen by the manufacturing industry. Companies are starting to implement these powerful tools on their shop floors, and more companies are beginning to look into the technology. There are several cases in industry where AR and wearables are being used to increase productivity and help workers perform manufacturing tasks. Some of these examples are as follows.

2.4.1. Aircraft assembly at Boeing

Engineers at Boeing have implemented wearable computers and augmented reality to aid workers in the assembly of airplanes. Their augmented reality project was designed to display pertinent instructions and diagrams in front of the manufacturing workers, who use the information to work on or assemble pieces of the aircraft. The wearable computer is used to render wire frame diagrams or text instructions arm's length in front of the user next to the work piece. The user looks at the piece and they see a diagram or text telling them what to do next and how. Since the computer is not required to render complex images, only wire frames or text, the wearable has no problem with the images. One of the main challenges associated with using AR and a wearable for this application is registering the user's position relative to the work piece so the diagram stay put when the user moves their head. In order to solve this problem, Boeing engineers are working on a real-time videometric tracker. A small, head-mounted video camera picks out markings on the work piece and sends the information to the processor which computes the users position and displays the diagram and text relative to the markings.

2.4.2. Quality assurance inspection in a food processing plant

Recently engineers at the Georgia Tech Research Institute were asked to improve the performance of quality assurance inspectors in a food processing plant (Najjar, Thompson, and Ockerman, 1997). They decided to use a wearable, voice operated computer with a wireless network. The QA workers at the plant were required to walk around very large plant and take food samples at various processing points. They would pick up a sample, measure it, wipe their hands, and then use a pen and a clipboard to record their results. At the end of their shift, the inspectors would hand in their reports which then needed to be typed into a networked computer so they could be read by other member of the management team. To improve the performance of this operation, the engineers used a wearable computer with voice recognition input and a monocular HMD connected to a wireless network. The wearable computer had a customized quality assurance application on it and data from the program was transmitted directly over the network after the user inputted it. The inspector would now go to a station, pick up a sample, and input their inspection data and comments into the computer by speech. The monocular display would show the inspector what they had entered and the measurements that were taken. Once the inspector was finished, the data was transmitted to a central computer over the wireless network and the inspector could go on to the next task.

2.4.3. Mobile Computing for Maintenance and Collaboration

Researchers at Carnegie Mellon University have developed a mobile wearable information and communication system for next generation train maintenance and diagnosis (Siewiorek, Smailagic, Bass, Siegel, Martin, Bennington, 1998). They combined wearable computers with the features of wireless networks to improve the efficiency and accuracy of maintenance work at a mass transit train company. In this case, the technology allowed train maintenance workers to go to the site of the breakdown or repair area, and communicate wirelessly with a remote helpdesk/expertise center through digital data, audio, and images. The local workers would go to the train site and get help diagnosing and repairing the problem with the collaboration of the remote experts.

2.4.4. Current Research Projects

The use of AR and wearable computer technology is still in its infancy in the manufacturing industry. Some companies have begun to implement the technology on their shop floors and are seeing improvements. However, while many companies are interested in the advantages and applications of AR and wearables, they have yet to fully implement them in their daily activities. Yet their interest has been strong enough to spark large amounts of research in the field. Universities and research companies have been doing research on the applications of wearable computers for years now and there has been an increasing number of people entering the field. In particular, the applications of wearable computers and AR to manufacturing tasks has become a field of increasing interest.

Researchers at Carnegie Mellon University are working on housing and cooling technologies for wearable computers designed for maintenance applications (Egan and Amon, 1996). One of the main considerations of designing wearable computers is the thermal regulation of the unit. With the all of the heat generating components of a computer being in such proximity to each other as in a wearable, the ability to dissipate this heat to avoid component malfunctions is an issue. A recently developed process called Shape Deposition Manufacturing allows designers to embed the components of a wearable computer to be embedded in a polymer composite substrate. This substrate serves as both a protective outer cover, and a very efficient heat dissipating medium. The VuMan3R is a wearable computer designed for aircraft maintenance that utilizes this technology. Researchers at CMU are using the VuMan3R to study the thermal properties of polymer and develop analytical models to predict heat flow paths within it.

The Computer Graphics and User Interfaces Lab at Columbia University is working on a project using augmented reality for construction tasks (Feiner, Webster, and MacIntyre, 1997). They used an optical see-through HMD system to display instructions and assembly information to the user performing a space frame construction task. The space frames were composed of cylindrical shapes and spherical nodes of similar sizes and shapes. Therefore, it is easy to assemble the components incorrectly which could lead to structural breakdown. The purpose of the augmented reality system was to guide workers through the assembly of the space frame and then inspect it to make sure the proper parts were assembled in the proper locations. First, the system directs the worker to a pile of parts and tells them which ones to pick up by displaying text instructions and playing a sound file with verbal instructions. Next, the user scans the piece with a bar code reader to ensure that the correct piece was selected. The system then directs the user to install the piece by showing a 3-D virtual image of where the piece should go on the structure, and then giving audio instructions how to install it. Finally, the user scans the component with the tracked barcode to ensure it was installed correctly and in the right place.

At Georgia Tech, researchers are investigating a wearable computer system to aid workers in the area of task guidance for aircraft inspection (Ockerman and Pritchett, 1998). Here studies are being performed to determine how the capabilities of wearable computers may be used to aid a user in an inspection task on a general aviation aircraft.

2.5. Literature Review Conclusion

It has been shown through the literature that manufacturing tasks have been and continue to be one of the most important functions that we as an industrialized society perform. In addition to this it is also evident that manufacturing practices are becoming more complex and varied. Therefore, the need for new and innovative technologies to deal with this changing trend is imminent. As a response to this, manufacturing companies and research universities are beginning to turn to wearable computers and augmented reality technologies to solve some of the complex problems associated with the changing manufacturing practices.

While there has been a growing amount of interest in wearable computing and AR technology as a solution to many of these problems, until now there has been little or no research investigating the effectiveness of different types of AR displays for many manufacturing tasks. By taking this first step towards validating the use of AR for assembly tasks, hopefully more research will be implemented and this newly emerging technology will be recognized as a useful tool to aid future generations of assembly workers.

2.6. Research Hypotheses

It is hypothesized that the AR conditions will yield the fastest assembly times and least amount of errors. This will be due to the smaller and less frequent head movements required to read the instructions and due to the virtual tags on cards eliminating the need to distinguish between similar looking cards. The instruction manual is expected to be the second fastest media since the user can move and manipulate the manual to reduce head movements and look at pictures of the cards. The computer-aided instructional media is expected to be the slowest since the user will have to turn nearly 90 degrees to read the screen and then turn back to perform the task. This may also lead to errors due to memory recall requirements associated with turning back and forth between the task and the instructional media.

For the subjective measures, it is hypothesized that users may prefer the familiarity with an instruction manual, and dislike some of the image registration issues associated with the AR equipment. Image registration can be somewhat disconcerting, particularly when users need to read small text, or image placement is crucial. For this experiment however, text will displayed in large font, with no graphical images being displayed.

As far as comparing the two types of HMDs, the results from this portion of the experiment are difficult to predict. There has been no previous research in this area and the issues arising from using these two types of HMDs have not previously been investigated.

CHAPTER 3: METHODS

3.1. Experimental Goals

The purpose of this experiment was to determine the effectiveness of AR in the for a manufacturing assembly task. Augmented Reality can be defined as the projection of "virtual" information in the real world. This is accomplished by using see-through or opaque head mounted display glasses that can combine virtual reality objects (text or graphics) with the real world visual scene as the participant views it with the unaided eye.

The reason for expanding AR to the manufacturing domain is that many manufacturing assembly tasks require the workers to read long and often confusing instruction manuals or assembly diagrams. The constant moving from assembly to instructions can cause longer assembly times and more errors. By projecting the assembly instructions on or near the actual work piece, it was hypothesized that assembly time and assembly errors will decrease. This will be both beneficial to the worker and the assembly operation.

The experimental task in this study consisted of human subjects performing a typical assembly task-inserting components onto a computer motherboard. Four types of media for accomplishing this task were compared: traditional paper instructions, computer-aided instruction, and two types of AR instruction. A motherboard assembly task was selected as the experimental task because it is an actual assembly task performed in the real world, and it is complex enough to meet the demands of the current experiment.

3.2. Methodology

3.2.1. Subjects

The subjects for this experiment were 15 students recruited from the graduate and undergraduate population of Virginia Tech. Subjects were recruited through personal contacts and were taken from both the undergraduate and graduate populations of a number of departments. Each subject attended one experimental session which lasted approximately 30-45 minutes each.

All 15 subjects were male and ranged in age from 20 to 37 years old with a mean age of 24.6.   In order to participate in the experiment, subjects were required have 20/20 vision corrected and were required to verify this using a Snell chart test prior to the experiment. On the initial survey, all 15 subjects reported using a computer frequently and 14 responded that they used a computer everyday. Fourteen of the 15 subjects had never built a computer motherboard, however all 15 had previously used a traditional paper instruction manual for some sort of assembly task. Eleven of the 15 subjects had previously used computer aided instruction and only one subject had previously experienced augmented reality.

3.2.2. Equipment

For the instruction manual condition a five page paper instruction manual printed on 8 ½ X 11 inch paper was used (See Appendix D). All motherboard and accessory images and instructions were printed in black and white on a HP 1000 laser printer. The motherboard and accessory images were taken with a Kodak DC110 digital camera and converted into the JPEG format.

The computer aided instructions were performed on a 300 Mhz Dell Dimension desktop computer using Microsoft Power Point. The condition consisted of seven slides with color images and black and white text. The images used in this condition were identical to the images used in the paper instructions. Subjects advanced the slides using either the keyboard or mouse.

For the augmented reality conditions, a Xybernaut P133 wearable computer (See Figures 6 and 7) was used in collaboration with either a Xybernaut monocular opaque HMD, or a Virtual I/O monocular see-through HMD. Both HMDs were able to display text and images in true 640x480, VGA resolution. Both the Xybernaut HMD and the Virtual I/O HMD had a field of view of approximately 35 degrees. The instructions were created using Microsoft Word Pad and were presented in black and white.

Figure 6: Wearable computer (back).

Figure 7: Wearable computer (front).

For the assembly task, a 486 PC motherboard was used as the test bed. The components installed on the motherboard included an ISA sound card, a VESA video card, four DIMM RAM cards, five ROM chips, an ISA modem card, and a ISA Ethernet card (See Figure 8). There were a total of eight slots for the four PC cards, eight slots for the four RAM cards, and ten slots for the five ROM chips. Therefore, there were enough configurations so that none of the four experimental conditions received the same configuration, and no user saw the same configuration twice. A digital stopwatch was used to time each of the subjects while performing the assembly task.

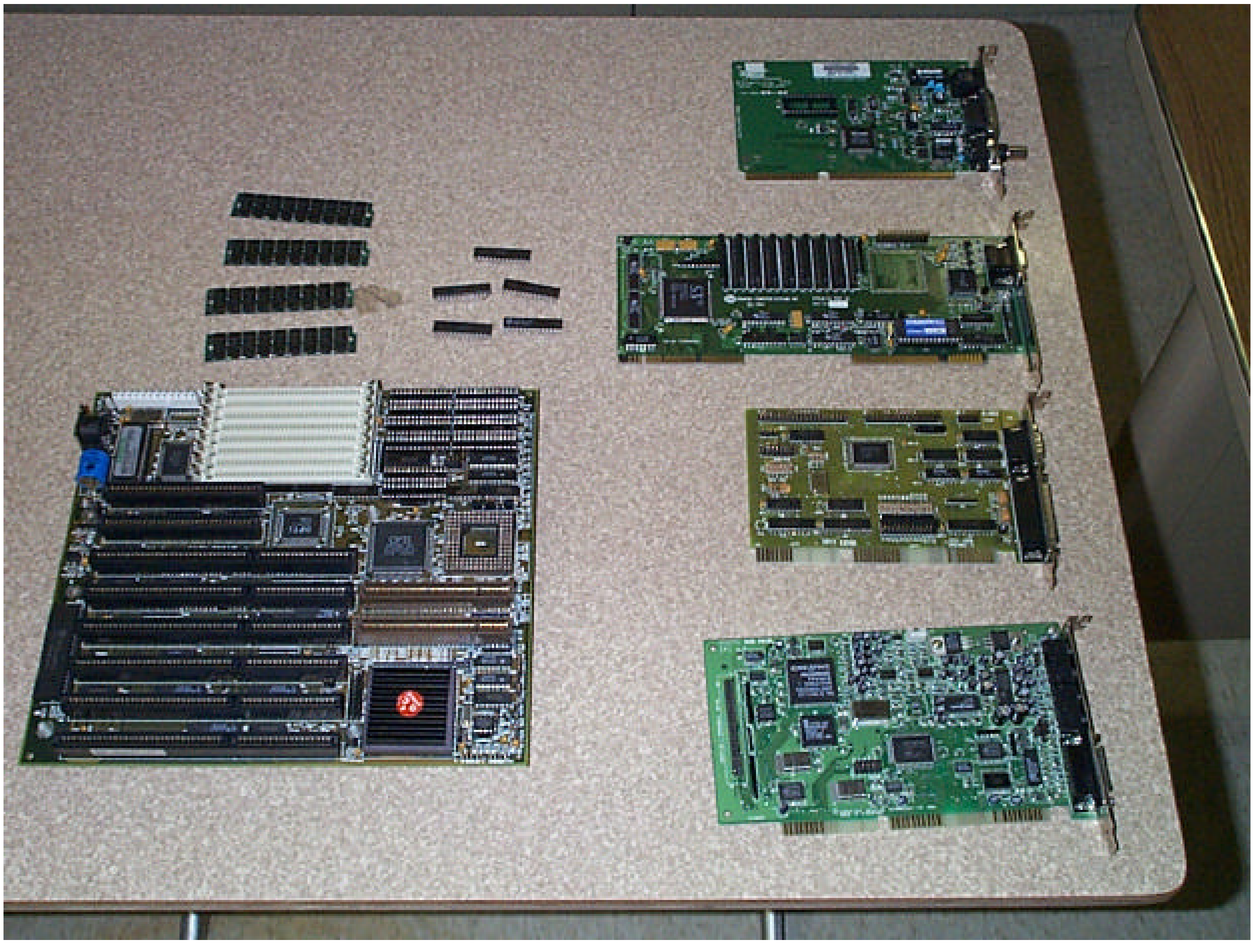


Figure 8: Computer Motherboard and Components.

3.2.3. Independent Variables

The experiment was run as a one-factor within-subjects design. The independent variable for the experiment was the type of assembly aid used, (traditional, computer aided, opaque and see-through AR display). The model for the experiment was as follows:

$$Y_{ijk} = \mu + IM_i + S_j + \varepsilon_{(ij)k}$$

where,

Y_{ijk} = dependent variable (time) measured under the i^{th} type of instructional media and j^{th} subject for the k^{th} response.

IM = i^{th} level of instructional media (i = 1,2,3,4).

S = j^{th} subject (j = 1,…,15).

ε = k^{th} response for the j^{th} subject and i^{th} instructional media.

3.2.4. Dependent Variables

The dependent variables for this experiment were the time to complete each condition, the number and types of errors made in the assembly, and responses to the questionnaire.

3.2.5. Procedure

Subjects were initially screened using a Snell chart to verify that they had at least 20/20 vision corrected. Upon successful completion of the vision test, subjects were allowed to participate in the experiment. Before the subjects began their first condition, each one filled out one page of general information about themselves including age, gender, and familiarity with computers and the four different types of instructional aids.

Next, each subject received a training session on how to assemble parts on a motherboard in order to minimize the effects of learning for the task. The experimenter explained each of the different components and where they fit on the motherboard and then showed them how to install each one in its correct slot. After watching the experimenter, the subject was then asked to install each type of component in its respective slot to gain practice on how the components fit and were installed. After subjects indicated they were comfortable putting each component in its slot, they moved on to the main part of the experiment.

One of the main experimental concerns of the study was controlling the effects of learning by the subjects. Since each subject performed the same assembly task over the four conditions, it was imperative to design the experiment to minimize the learning effect. The three measures taken to control the effects of learning were training each subject before the experiment, randomizing the treatment order, and randomizing the identity of the PC cards for each condition. The first control measure was to give each of the subjects the knowledge to put each of the components into the motherboard correctly. It also helped assure that all subjects started out with the same minimum level of initial knowledge. The second measure was to reduce the effects of learning in the data by randomizing the treatment order. Finally, the last measure was to assure that subjects would not learn the shape and contours of the PC cards and then not have to distinguish them during the latter conditions. By having the same PC card as the sound card in one condition and the Ethernet card in another, subjects had to continually identify the correct card across conditions.

After the initial questionnaire and training, each subject performed the assembly task under the four conditions in random order as assigned by a random number generator: 1) using traditional paper instructions, 2) using computer aided instruction, 3) using the opaque AR display, and 4) using the see-through AR display. The subjects were given as much time as they needed to assemble the motherboard under each condition and the time to complete each task was measured using a digital stopwatch to the nearest hundredth of a second. In addition to timing the subjects, the experimenter kept a log of any errors the subjects made during the experiment and documented the type of error and the condition under which it was made.

For the traditional paper instructions, subjects were given the instruction manual and asked to assemble the motherboard. This entailed flipping between the pages of the manual and reading black and white images and text instructions (See Appendix D). The computer-aided condition had subjects using a desktop computer running Microsoft Power Point complete the assembly task by following a series of directions given on Power Point slides. Each slide contained one step and displayed diagrams in color and instructions on screen for subjects to refer to. Finally, for the AR conditions, text instructions generated by a wearable computer, were virtually projected in the environment. Wearing each of the two HMDs, the subjects were able to read the instructions in the vicinity of the task and perform the assembly.

Upon completion of each condition, subjects were required to answer a questionnaire to determine their subjective preferences about the instruction media and about the usability of that media. Finally, upon completion of the assembly tasks for the four instructional media, another questionnaire was used to compare the four types of media as well to compare the two types of HMDs against each other.

CHAPTER 4: RESULTS

4.1. Quantitative Data

4.1.1. Descriptive Statistics

An examination of the data shows that the mean times for the paper instruction manual, computer aided instructions (CAI), opaque HMD, and see-through HMD conditions respectively were 197.10 seconds, 176.30 seconds, 107.66 seconds, and 95.24 seconds (Table 1). Furthermore, the standard deviations were smaller for the AR conditions compared to the non-AR conditions.

Table 1: Descriptive Statistics for the Experiment

Variable	Condition	N	Mean	Median	St. Dev.
Time (sec)	Paper	15	197.10	195.30	62.80
	CAI	15	176.30	168.90	49.60
	Opaque HMD	15	107.66	96.35	29.25
	See-through HMD	15	95.24	95.16	22.93

Variable	Condition	SE Mean	Minimum	Maximum
Time (sec)	Paper	16.20	105.70	333.00
	CAI	2.80	95.70	270.70
	Opaque HMD	7.55	65.57	179.48
	See-through HMD	5.92	69.73	166.51

4.1.2. Evaluating the Potential Learning Effect

The results of the ANOVA presented in Table 2 illustrate that there was no significant effect of order on time to complete the assembly task ($F_{3,56} = 0.33$, $p > .05$). This indicates that the measures taken to control learning were effective.

Table 2. One-way ANOVA on Time and Order.

Analysis of Variance for Time (sec)

Source	DF	SS	MS	F-value	P-value
Order	3	3883	1294	0.33	0.802
Error	56	218390	3900		
Total	59	222272			

Level	N	Mean	St. Dev.
Paper Manual	15	197.10	62.80
CAI	15	176.30	49.60
Opaque HMD	15	107.66	29.25
See-through HMD	15	95.25	22.93

4.1.3. Effects of Experimental Condition on Time

As shown from the results of the ANOVA (Table 3), there was a significant main effect for the time to complete the assembly task as a function of the instructional media used to perform the task ($F_{3,56} = 19.44$, $p < .001$). The results indicated that the paper instructions (level 1) not only had the highest mean time to complete the task, 197.10 seconds, but also resulted in the largest standard deviation of time, 62.76 seconds. Additionally, the see-through HMD condition (level 4) not only resulted in the lowest mean completion time, 95.24 seconds, but also resulted in the lowest standard deviation, 22.93 seconds. Additionally, there was a significant effect of subjects on time.

Table 3. Two-way ANOVA for Time (sec)

Source	DF	SS	MS	F-value	P-value
Condition	3	113383	37794	35.05	0.001
Subject	14	63604	4543	4.21	0.001
Error	42	45286	1078		
Total	59	222272			

4.2. Qualitative Data

4.2.1. Questionnaire Analysis

After each condition, subjects were asked the same four questions about the media used for that condition. They answered by circling a response on a 7-point Likert-type scale (See Appendix B). On this scale a response of 1 was the best, 7 was the worst. The four questions were as follows:

Question 1: How difficult was it to perform the task using the (previous media type)?

Question 2: How clear were the instructions in the (previous media type)?

Question 3: How difficult were the images/instructions to read?

Question 4: How effective do you feel the (media type) is for performing this task?

Table 4. Descriptive Statistics for the Questionnaire

Variable	Condition	N	Mean	Median	StDev
Question 1	1	15	3.600	4.000	1.242
	2	15	2.533	3.000	0.915
(Difficulty of task)	3	15	2.200	2.000	1.082
	4	15	2.600	2.000	1.595
Question 2	1	15	4.067	4.000	1.335
	2	15	2.467	2.000	1.246
(Clarity of Instructions)	3	15	2.600	2.000	1.682
	4	15	2.667	3.000	1.234
Question 3	1	15	4.867	5.000	1.598
	2	15	2.200	2.000	1.082
(Difficulty to read	3	15	2.200	2.000	1.265
images/instructions)	4	15	2.600	2.000	1.121
Question 4	1	15	4.133	4.000	0.834
	2	15	2.333	2.000	0.900
(Effectiveness of media)	3	15	2.067	2.000	1.223
	4	15	2.733	2.000	1.438

Note: 1 = best, 7 = worst

Conditions: 1 = Paper Instructions, 2 = CAI, 3 = Opaque HMD, 4 = See-through HMD

Table 4 (continued). Descriptive Statistics for the Questionnaire

Variable	Condition	SE Mean	Minimum	Maximum
Question 1	1	0.321	1.000	5.000
	2	0.236	1.000	4.000
(Difficulty of task)	3	0.279	1.000	4.000
	4	0.412	1.000	6.000
Question 2	1	0.345	1.000	6.000
	2	0.322	1.000	6.000
(Clarity of Instructions)	3	0.434	1.000	6.000
	4	0.319	1.000	5.000
Question 3	1	0.413	1.000	7.000
	2	0.279	1.000	4.000
(Difficulty to read	3	0.327	1.000	5.000
images/instructions)	4	0.289	1.000	5.000
Question 4	1	0.215	3.000	6.000
	2	0.232	1.000	4.000
(Effectiveness of media)	3	0.316	1.000	5.000
	4	0.371	1.000	5.000

Note: 1 = best, 7 = worst
Condtions: 1 = Paper Instructions, 2 = CAI, 3 = Opaque HMD, 4 = See-through HMD

Next, a Kruskal-Wallis test was performed on each question to determine if there were any significant differences among the responses to each question across the four different conditions. As shown in Table 5, there was a significant difference in the subjects' responses to Question 1 asking about the difficulty of the task ($H_{3df} = 9.11$, $p < 0.029$). Subjects indicated that the opaque HMD made the assembly task the easiest, followed by the see-through HMD, CAI, the paper instructions.

Table 5. Kruskal-Wallis Test on Question 1

Q1 Media	N	Median	Ave Rank	Z
CAI	15	3.000	28.8	-0.43
Opaque	15	2.000	23.9	-1.69
Paper	15	4.000	41.9	2.91
See-through	15	2.000	27.4	-0.79
Overall	60		30.5	

Question 2, asking about the clarity of the instructions, also resulted in a significant difference among conditions (Table 6). In this case, subjects preferred the CAI condition followed by the opaque HMD, see-through HMD, and paper instructions respectively.

Table 6. Kruskal-Wallis Test on Question 2

Q2 Media	N	Median	Ave Rank	Z
CAI	15	2.000	24.9	-1.43
Opaque	15	2.000	25.7	-1.23
Paper	15	4.000	43.4	3.30
See-through	15	3.000	28.0	-0.64
Overall	60		30.5	

H = 11.17 DF = 3 P = 0.011

For the third question, subjects indicated that the opaque HMD provided the easiest to read instructions (Table 7). The second most preferred media for this question was the CAI, followed by the see-through HMD and then the paper instructions respectively.

Table 7. Kruskal-Wallis Test on Question 3

Q3 Media	N	Median	Ave Rank	Z
CAI	15	2.000	23.3	-1.85
Opaque	15	2.000	22.6	-2.03
Paper	15	5.000	48.0	4.48
See-through	15	2.000	28.2	-0.60
Overall	60		30.5	

H = 21.00 DF = 3 P = 0.001

Finally, question 4 asked subjects which type of media was the most effective for performing the motherboard assembly task. Once again there was a significant difference among conditions (Table 8). Subject's responded that the opaque HMD was the most effective media for performing this task. The second most preferred media type was the computer aided instruction, followed by the see-through HMD, and the paper instructions were the least preferred.

Table 8. Kruskal-Wallis Test on Question 4

Q1 Media	N	Median	Ave Rank	Z
CAI	15	2.000	24.9	-1.43
Opaque	15	2.000	20.7	-2.50
Paper	15	4.000	47.0	4.23
See-through	15	2.000	29.3	-0.30
Overall	60		30.5	

H = 19.67 DF = 3 P = 0.001

The final statistical test performed on the data was a correlation analysis between the responses on the questionnaire and the time to complete the assembly task under each condition (Table 9). It is interesting to note that there were significant correlations between time and subjects' responses to questions 3 and 4, as well as significant correlations between questions 1 and 3, 2 and 4, and 3 and 4.

Table 9. Correlations between Time and Questions

	Time (sec)	Question 1	Question 2	Question 3
Question 1	0.103			
	0.432			
Question 2	0.236	0.200		
	0.070	0.126		
Question 3	**0.303**	**0.650**	0.168	
	0.019	**0.001**	0.200	
Question 4	**0.307**	0.238	**0.718**	**0.287**
	0.017	0.067	**0.001**	**0.026**

(Bold indicates a significant correlation)

4.2.2. Post Experiment Data

At the end of the main part of the experiment, subjects were required to rate the four types of instructional media on a scale from 1 to 4 where 1 is the best, 4 is the worst.

Table 10. Instructional Media Rankings

Subject	Paper	CAI	Opaque	See-through
1	4	2	1	3
2	4	1	2	3
3	2	1	4	3
4	4	2	1	3
5	4	3	1	2
6	4	3	1	2
7	4	1	2	3
8	4	3	2	1
9	4	2	1	3
10	4	2	1	3
11	3	2	1	4
12	4	3	2	1
13	4	2	3	1
14	4	2	1	3
15	4	1	3	2
Average	3.80	2.00	1.73	2.47

Note: 1 = best, 4 = worst

As indicated in Table 10, on average subjects preferred the opaque HMD, followed by the computer aided instruction, see-through HMD, and paper instructions. This corresponds with the subjects' preferences given on questions 2, 3, and 4, on the questionnaire.

4.2.3. HMD Comparisons

When subjects were asked which HMD did they prefer, the response was much more even (Table 11). Subject's responses were almost evenly split with eight preferring the opaque HMD, and seven preferring the see-through. Subjects were also asked the reasons they preferred a specific type of HMD as summarized in Table 12.

Table 11. Preferred HMD Type

	Preferred HMD	
HMD type	Opaque	See-through
# of subjects	8	7

Table 12. Reasons for Preferred HMD Type

Opaque HMD

More Comfortable	7
Better Contrast	6
Easier to read	6
Other	1

See-through HMD

More Comfortable	3
Better Contrast	0
Easier to read	4
Other	4

As shown in Table 12, of the eight subjects that preferred the opaque HMD, seven responded it was more comfortable, and six indicated it had both better contrast and was easier to read. One subject responded that he had better depth judgement while using the opaque HMD since it didn't look like the images were "just floating in space".

Of the seven subjects that preferred the see-through HMD, only three indicated it was more comfortable and four responded it was easier to read. Even despite the lower contrast of the see-through HMD, three subjects responded that they liked the lack of occlusion in their work space, and similarly one subject indicated that the see-through HMD "blended in" more with the task as opposed to switching viewpoint from HMD to motherboard for each step.

4.2.4. Errors in the Assembly Task

Another dependent variable collected in the experiment was the number and type of errors subjects made while performing the assembly task. As shown in Table 13, there were a total of 15 errors made throughout the 60 trials of the experiment. Of these errors, nearly half were made during the paper instruction condition. In addition, there were only two or less errors under the

AR conditions which is only half the errors of the CAI, and a quarter the errors of the paper instructions. This indicates that the non-AR conditions are more conducive to errors in the assembly task than either of the AR conditions.

Table 13. Error Descriptions

Media Type / Error Type	Paper Instructions	CAI	Opaque HMD	See-through HMD
Insert PC Card in wrong slot	1	0	0	0
Insert wrong PC card in slot	3	0	0	0
Insert RAM in wrong slots	1	2	1	0
Insert ROM in wrong slots	3	2	1	1
Total	**8**	**4**	**2**	**1**

CHAPTER 5: CONCLUSIONS

5.1. Discussion

Based on the results presented in this thesis, augmented reality was found to be a better instructional media for a motherboard assembly task than either computer aided instruction, or traditional paper instructions. It can be seen that regardless of the AR display type (opaque or see-through), the use of AR resulted in both lower assembly times and fewer assembly errors than the non-AR instructional media. This is an important finding because it serves as support for AR as a viable instructional media for a manufacturing task.

It is speculated that the reduction in assembly time and errors is in part the result of having the assembly instructions in the operator's direct visual work space as opposed to just being near it. This reduces the number of head, eye, and body movements required by the operator to read the instructions, and may also help reduce the amount of information the operator needs to store in memory. Since the instructions are in the operators field of view while they are performing the task, they don't need to look at the instruction, turn to the assembly, remember what they just read, and perform the task. There is no need for the operator to have to turn and recheck the instructions since at the slight move of the eye, the instructions are readily accessible using AR.

Another interesting result shown in the data is that not only was the assembly time better using the AR conditions, but the standard deviations for subject's times was also reduced. The opaque and see-through AR conditions had standard deviations of 29.25 and 22.93 seconds respectively, while the paper instructions and computer aided instructions had standard deviations of 62.80 and 49.60 seconds respectively. This may be attributed to the fact that the AR conditions provided a much more uniform instruction type than the non-AR examples. For example, when using the paper instructions, subjects varied how they flipped between pages, how quickly they were able to recognize the image, and how certain they were when they inserted a component. This sometimes resulted in some subjects flipping back and forth in the manual and double checking their work. For both the paper instructions and the CAI, subjects also performed the task very linearly. While not required to, all subjects performed the steps in the order they were presented in. Since this order was random, it may not always have been the most efficient or easy sequence to follow. However, for both the AR conditions, subjects had no flipping of pages and had all of the instructions right in their direct field of view to refer to at any time and in any order. If fact, with the AR conditions, there were a number of cases where subjects would begin the assembly by inserting the ROM and the RAM first even though they were not the first steps. Therefore, subjects seemed less constrained and more likely to perform better and more consistently.

One of the main experimental concerns of the study was controlling the effects of learning by the subjects. The results from the ANOVA performed on time and order (Table 2) indicated that the three measures taken to control the effects of learning were effective. There was no significant main effect of order on learning thus the results can be attributed to the effect of the conditions as opposed to the order in which they appeared. This finding was important in maintaining the validity of results.

The results obtained from the qualitative analysis also supported the hypothesis that AR is a better instructional media than non-AR methods given the current task. This was showed by the Kruskal-Wallis tests performed on the questionnaire responses. Question 1 asked subjects how difficult was the assembly task using each instructional media. The analysis yielded a significant findings with subjects highly ranking the opaque AR condition as easiest, followed by the closely ranked CAI and see-through conditions respectively, with the paper instructions a distant fourth (See Table 5). The relatively high ranking of the CAI could be attributed to the fact that this was the only condition that contained color images. This made the card recognition aspect of the assembly much easier.

The second question asked subjects how clear were the instructions for each media type. This question was not referring to the clarity of the text and images but the flow and layout of the instructional media. For the paper instructions this meant the manual style of instructions such as flipping through pages and being able to hold and manipulate the manual. For the CAI, this referred to the slide format and keyboard/mouse manipulation. And for both the AR conditions, this referred to the format of having all the instructions visible at once directly in the workspace field of view. In this case, the Kruskal-Wallis analysis was also significant and indicated that subjects preferred the CAI slightly over the two AR conditions (See Table 6). This may have been due to the fact that subjects preferred the structure of the slides as well as the fact that they didn’t have to deal with partial visual occlusion of the task by the AR. As expected, the two AR conditions were very closely ranked since they were basically the same format just different display types. For this question, once again the paper instruction manual was a very lowly ranked fourth.

Question 3 asked subjects how difficult were the images and text for each condition to read. The Kruskal-Wallis analysis was again significant with subjects ranking the opaque HMD slightly above the CAI (See Table 7). It is speculated that these two were closely ranked because they both presented the instructions clearly on a computer display. The fact that the opaque HMD had the instructions in front of the subject at all times and didn't require constant head movements to read, may have given it the slight advantage. The see-through HMD with its lower contrast than the other two computer displays was ranked third, and the paper instructions with its black and white images was ranked fourth.

The final question asked subjects which instructional media they felt was the most effective for performing the assembly task. The analysis of this data also yielded a significant result with subjects preferring the opaque HMD followed by the CAI, see-through HMD, and paper instructions respectively (See Table 8). The reasons for this raking are likely to be closely related to the reasons expressed in Question 3 as evidenced by the correlation analysis in Table 9.

A correlation analysis was performed between time and the responses to the four questions to determine if subject's qualitative responses were supported by the quantitative analysis (See Table 9). Based on the correlation analysis, five significant correlations emerged. Subject's assembly time was significantly correlated with responses to Questions 3 and 4, which asked how difficult were the instructions to read, and how effective they felt the instructional media were. The significant correlations were likely due to the fact that in both questions subjects highly rated the AR conditions, which corresponded with fast assembly times, and ranked the paper instructions last, which resulted in the slowest assembly times.

The correlation between responses to Questions 1 and 3 was also significant. Question 1 asked how difficult it was to perform the task, and Question 3 asked how difficult were the images to read. This significant correlation is not surprising because it is likely that the level of difficulty reading the instructions is related to the subject's perception of the difficulty of the task. That is, if the instructions are hard to read, the task is harder to perform accurately and correctly.

There was also a significant correlation between responses to Questions 2 and 4. These asked how clear was the instructional media and how effective was the instructional media. Once again this significant correlation is not surprising because if a subject feels that the instructional media is clear, they would likely also feel it is effective.

The final significant correlation from the correlation analysis was between Questions 3 and 4. These questions asked how difficult were this images and text to read, and how effective the media was. It is likely that if subjects felt the images and text were unclear, the instructional media was unlikely to be effective for the task.

Table 10 from the post experiment data reported the results of the subject's rank ordering of instructional media from best to worst. This ranking directly corresponds to the results from Question 4 of the questionnaire asking to evaluate the effectiveness of the media. In both cases subjects felt the opaque HMD was the best followed by the CAI, see-through HMD, and paper instructions respectively. The correspondence of this data helps validate the questionnaire since it yields similar findings for similar questions at different times in the experiment.

The post experiment data supported the hypothesis that the AR conditions would result in the fewest number of errors. As shown in Table 13, the number of errors for the AR conditions were at either half the number under the CAI condition, and one quarter the paper instructions. It is postulated that this is due to the memory recall requirements associated with turning back and forth between the task and the virtual tags on cards eliminating the need to recognize the images and distinguish between similar looking cards.

The post experiment data was also important in comparing the two HMDs. Table 11 showed that while AR was the most effective instructional media for the assembly task, HMD type was not very important. This finding in addition to Table 12 listing the reasons for HMD preference, has implications for the design and use of AR displays for manufacturing tasks. By combining the comfort and contrast of the opaque HMD with the less obstruction associated with the see-through HMD, a highly effective AR display would be created. Perhaps one of the future challenges for AR display makers should be to find a way to increase the image contrast of the computer-generated images of a see-through HMD and find a way to make it more comfortable to the user.

While the results of this thesis did not support the initial hypotheses that users would prefer the paper instruction manual and CAI over the AR due to familiarity, it did support the hypotheses that the AR instructional media would yield the fastest assembly times and fewest errors. The fact that users did not necessarily prefer the familiarity of the instruction manual or CAI instead further validates the importance and usefulness of AR for manufacturing assembly tasks.

5.2. Future Research

The research in this thesis supported the use of augmented reality for a particular manufacturing assembly task was beneficial. If the task was significantly more or less difficult, the results may have been different. Therefore, it would be useful to evaluate these instructional media for a variety of assembly tasks varying in difficulty. After being demonstrated as an effective media for assembly tasks, this research could also be applied to other manufacturing tasks such as inspection. Evaluating AR in conjunction with current inspection media may also prove to be a useful endeavor.

Additionally, further research into opaque vs. see-through HMDs may also be advantageous in determining just which are the best qualities of each display type and how to best combine them to make a more overall effective display for these types of manufacturing tasks.

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APPENDIX A: RAW DATA

Row	Subject	Condition	Time (sec)	Order
1	1	1	108.98	1
2	1	2	105.73	3
3	1	3	65.57	4
4	1	4	69.73	2
5	2	1	240.63	4
6	2	2	147.88	1
7	2	3	100.76	3
8	2	4	70.66	2
9	3	1	156.47	2
10	3	2	250.79	1
11	3	3	102.19	3
12	3	4	105.56	4
13	4	1	160.82	2
14	4	2	172.43	4
15	4	3	92.82	3
16	4	4	75.16	1
17	5	1	197.67	4
18	5	2	173.48	3
19	5	3	112.50	2
20	5	4	95.29	1
21	6	1	216.23	3
22	6	2	270.66	1
23	6	3	179.48	2
24	6	4	86.10	4
25	7	1	216.60	1
26	7	2	164.67	3
27	7	3	109.44	2
28	7	4	106.54	4
29	8	1	333.04	4
30	8	2	227.56	3
31	8	3	139.38	2
32	8	4	84.60	1
33	9	1	105.73	4
34	9	2	132.25	1
35	9	3	87.43	2
36	9	4	95.16	3
37	10	1	207.66	4
38	10	2	166.43	3
39	10	3	94.94	2
40	10	4	100.16	1
41	11	1	307.12	2
42	11	2	227.38	1
43	11	3	155.78	3
44	11	4	166.51	4
45	12	1	156.15	4
46	12	2	162.34	1
47	12	3	88.06	2

48	12	4	92.42	3
49	13	1	195.25	1
50	13	2	95.73	4
51	13	3	96.35	2
52	13	4	96.00	3
53	14	1	166.17	1
54	14	2	177.74	2
55	14	3	96.10	3
56	14	4	83.91	4
57	15	1	188.02	2
58	15	2	168.88	3
59	15	3	94.13	1
60	15	4	100.79	4

APPENDIX B: QUESTIONNAIRE

General Information

1. What is your age?

2. What is your gender? Male Female

3. How often do you use a computer? (circle 1)

1	2	3	4	5
Never	Rarely	Sometimes	Frequently	Everyday

4. Have you every built a computer motherboard? Yes No

5. Have you ever used an instruction manual? Yes No

6. Have you ever used computer aided instruction? Yes No

7. Have you ever used augmented reality? Yes No

Paper Instruction Manual

1. How difficult was it to perform the task using the instruction manual?

1	2	3	4	5	6	7
Very easy	Somewhat easy		Average	Difficult		Very difficult

2. How clear were the instructions in the instruction manual?

1	2	3	4	5	6	7
Very Clear	Somewhat Clear		Average	Unclear		Very Unclear

3. How difficult were the images to recognize?

1	2	3	4	5	6	7
Very easy	Somewhat easy		Average	Difficult		Very difficult

4. Would having the images in color help make the task easier?

Yes Maybe No

5. How effective do feel the instruction manual is for performing this task?

1	2	3	4	5	6	7
Very Effective	Somewhat Effective		Average	Ineffective		Very Ineffective

Comments:

Computer Aided Instruction

1. How difficult was it to perform the task using computer aided instruction?

1 2 3 4 5 6 7

Very easy   Somewhat easy   Average   Difficult   Very difficult

2. How clear was computer aided instruction slides?

1 2 3 4 5 6 7

Very Clear   Somewhat Clear   Average   Unclear   Very Unclear

3. How difficult were the images to recognize?

1 2 3 4 5 6 7

Very easy   Somewhat easy   Average   Difficult   Very difficult

4. How effective do feel computer aided instruction is for performing this task?

1 2 3 4 5 6 7

Very Effective   Somewhat Effective   Average   Ineffective   Very Ineffective

Comments:

Monocular Opaque HMD

1. How difficult was it to perform the task using this HMD?

1	2	3	4	5	6	7
Very easy	Somewhat easy		Average	Difficult		Very difficult

2. How clear were the instructions viewed in the HMD?

1	2	3	4	5	6	7
Very Clear	Somewhat Clear		Average	Unclear		Very Unclear

3. How difficult were the instructions to recognize?

1	2	3	4	5	6	7
Very easy	Somewhat easy		Average	Difficult		Very difficult

4. How effective do feel this type of HMD is for performing this task?

1	2	3	4	5	6	7
Very Effective	Somewhat Effective		Average	Ineffective		Very Ineffective

5. What were some problems, if any, with this HMD? Check all that apply.

- ☐ Instructions too small
- ☐ Poor contrast
- ☐ HMD was uncomfortable
- ☐ Other________________________________

Comments:

Monocular See-through HMD

1. How difficult was it to perform the task using this HMD?

1	2	3	4	5	6	7
Very easy		Somewhat easy	Average	Difficult		Very difficult

2. How clear were the instructions viewed in the HMD?

1	2	3	4	5	6	7
Very Clear		Somewhat Clear	Average	Unclear		Very Unclear

3. How difficult were the instructions to recognize?

1	2	3	4	5	6	7
Very easy		Somewhat easy	Average	Difficult		Very difficult

4. How effective do feel this type of HMD is for performing this task?

1	2	3	4	5	6	7
Very Effective		Somewhat Effective	Average	Ineffective		Very Ineffective

5. What were some problems, if any, with this HMD? Check all that apply.

☐ Instructions too small ☐ Poor contrast

☐ HMD was uncomfortable ☐ Other________________________________

Comments:

Post Experiment

1. Please rank order the instruction type from best to worst. 1=best, 4=worst

___ Instruction Manual

___ Computer Aided Instruction

___ Opaque HMD

___ See-Through HMD

2. Why did you feel the best type was the best instruction type?

☐ Easiest to read ☐ Most familiar

☐ Provided most effective instructions ☐ Other___________________________

3. For the AR conditions, which HMD did you prefer?

Opaque See-through

4. Why did you prefer this type of HMD? Check all that apply.

☐ Easier to read ☐ More comfortable

☐ Better contrast ☐ Other___________________________

Thank you for participating in the experiment.

APPENDIX C: INFORMED CONSENT FORM

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

Informed Consent for Participants
Of Investigative Projects

Title of Project: Evaluating the Effectiveness of Augmented Reality and Wearable Computing for a Manufacturing Assembly

Investigators: Kevin M. Baird and Woodrow Barfield, Ph.D

I. The Purpose of this Research/Project

The purpose of this project is to determine the effectiveness of Augmented Reality (AR) in the manufacturing domain. Particularly the use of AR for a manufacturing assembly task. Augmented Reality can be defined as the projection of "virtual" information in the real world. The reason for expanding AR to the manufacturing domain is that many manufacturing assembly tasks require the workers to read long and confusing instruction manuals or assembly diagrams. The constant moving from assembly to instructions can cause longer assembly times and more errors. By projecting the assembly instructions on or near the actual work piece, we hypothesize that assembly time and error rate will decrease. This will be both beneficial to the worker and the assembly operation. 15 participants will perform the experiment.

II. Procedures

Each subject will perform an assembly task of putting together a computer motherboard under 4 conditions: 1) using traditional paper instructions, 2) using computer aided instructions, 3) using an opaque HMD for AR, 4) using a see-through HMD for AR.

A brief training period showing subjects how to assemble parts and to get familiar with a motherboard will be first. Then subjects will be given as much time as they need (approx. 3-10 min. estimated) to assemble the motherboard under each condition. Only one session of about a half hour will be required. For the traditional paper instructions, subjects will be given an instruction manual and assemble the motherboard using them. The computer aided instructions will be delivered using a PC with Powerpoint slides. Finally, for the AR conditions, the instructions will be virtually projected in the environment next to the motherboard and by wearing the display glasses, subjects will be able to read them. The conditions will be presented in random order.

Upon completion of each task, subjects will answer a few questions on a questionnaire. The dependent variables for this experiment will be time to complete the tasks, any errors committed, and responses on the questionnaire. Independent variables will be assembly aid (traditional, computer aided, and AR) and order they are presented in.

III. Risks

There are minimal or no risks associated with this task.

IV. Benefits of this Project

The benefits to the subjects are exposure to new and useful technologies that may someday be used to help them work more productively. The use of augmented reality in the manufacturing domain is expected to increase productivity and reduce errors in the work place.

V. Extent of Anonymity and Confidentiality

Subject's identity or personal attributes are not an issue for this experiment. There will be no correlation between their name or other identifier to their experimental results assuring their confidentiality. Their times will be recorded on a sheet next to an arbitrary subject number, no correlation between subject number and subject name will be made.

VI. Freedom to Withdraw

Subjects are free to withdraw from this study at any time without penalty. Subjects are also free to not answer any questions or respond to experimental situations that they choose without penalty.

VII. Approval of Research

This research project has been approved, as required, by the Institutional Review Board for Research Involving Human Subjects at Virginia Polytechnic Institute and State University, and by the Department of Industrial and System Engineering.

VIII. Subject's Permission

I have read and understand the Informed Consent and conditions of this project. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent for participation in this project.

If I participate, I may withdraw at any time without penalty. I agree to abide by the rules of this project.

Signature Date

Should I have any questions about this research or its conduct, I may contact:

	1-9084
Kevin M. Baird	Phone
	1-2547
Woodrow Barfield	Phone
	1-5281
H.T. Hurd Chair, IRB Research Division	Phone

Biographical Sketch of investigators

Kevin M. Baird

-M.S. Graduate Student in ISE
-Has completed M.S. curriculum including Human Factors research design.
-Has conducted IRB approved research previously at the University of Buffalo.
-Has published in the AR and human factors field.
-Has served as a subject in Human Factors research and is familiar with procedures.

Woodrow Barfield, Ph.D.

-Professor in ISE
-Has conducted extensive human factors research at university level for over 12 years.
-Has published extensively in the areas of AR and human factors.

APPENDIX D: PAPER INSTRUCTION MANUAL

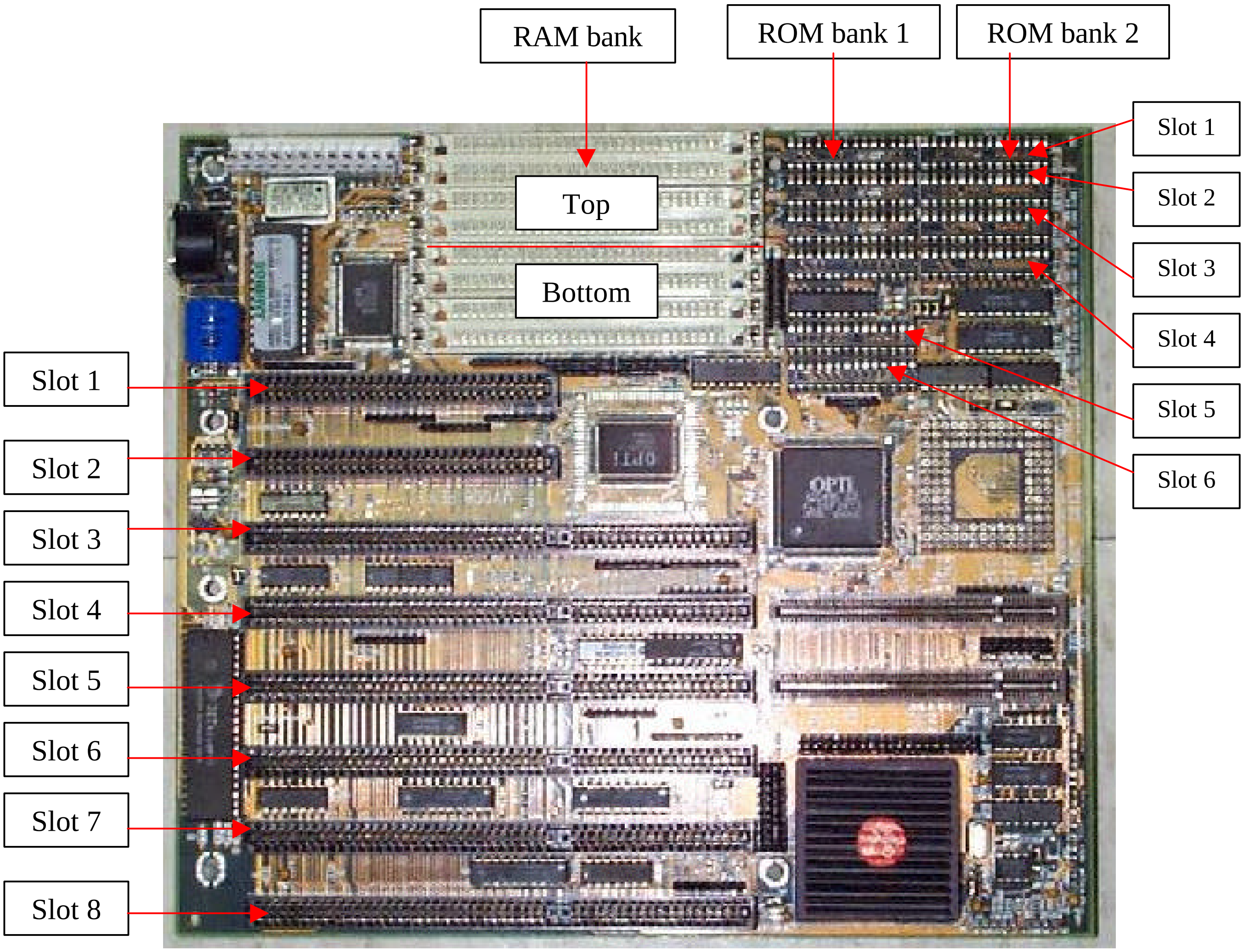
Instructions for Motherboard Assembly

Augmented Reality Study
Virtual Environment Lab

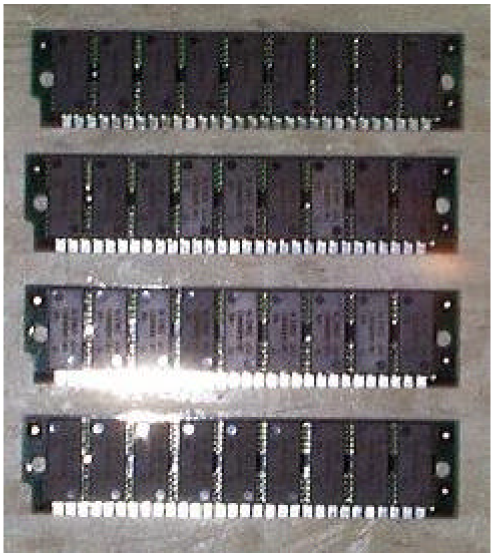
By

Kevin Baird

Motherboard and Components

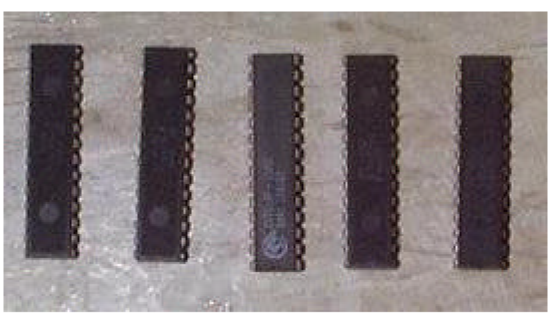


Step 1: Insert RAM Modules Into top RAM slot.



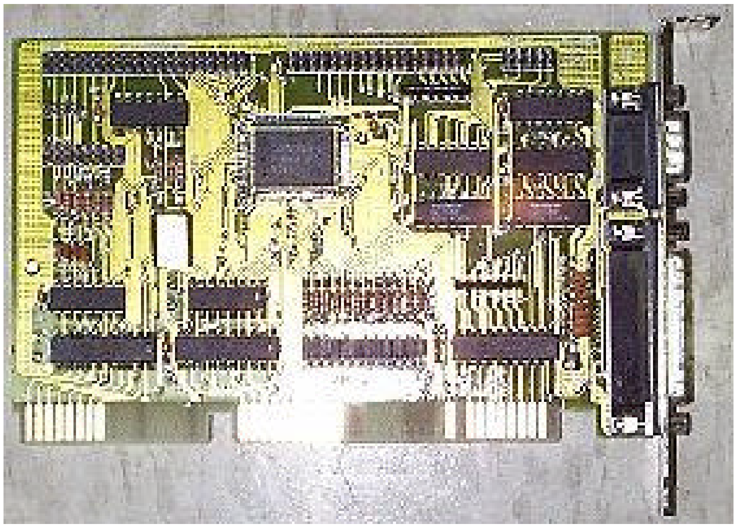
RAM Cards

Step 2: Insert ROM chips into bank 1(slots 1 ,3 , 5)
Insert ROM chips into bank 2 (slots 2, 4)



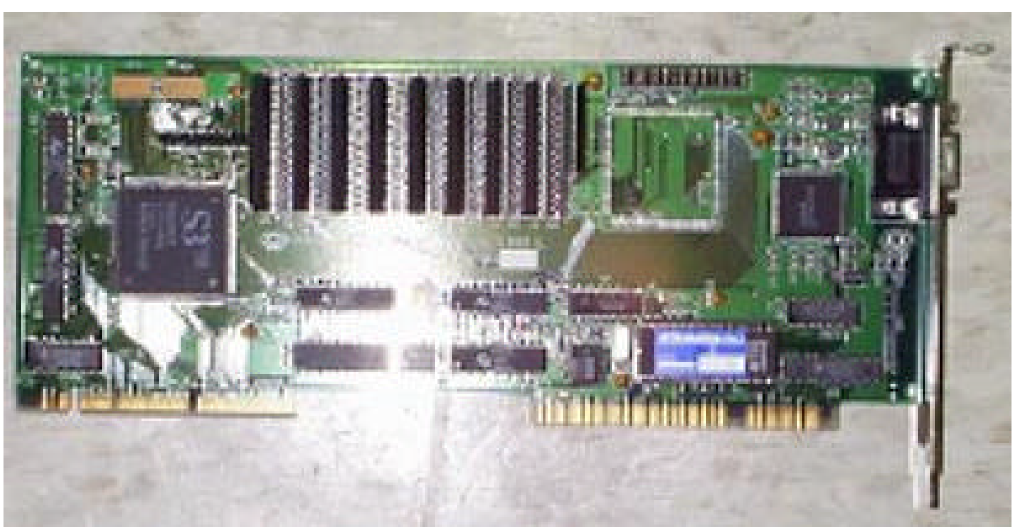
ROM chips

Step 3: Insert controller card into slot 1.



Controller card

Step 4: Insert Graphics card into slot 4.



Graphics Card

Step 5: Insert Ethernet card into slot 8.

Ethernet Card

Step 6: Insert Sound card into slot 6.

Sound Card

APPENDIX E: VITA

Kevin M. Baird
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(540) 552-0108
kbaird@vt.edu

Education

Virginia Polytechnic Institute and State University
Master of Science, Industrial and Systems Engineering
Graduation: June 1999 GPA: 3.72/4.0

State University of New York at Buffalo
Bachelor of Science, Industrial Engineering
Graduation: June 1997 Cum Laude

Experience

Research: Distributed Information Systems Corporation (DISC) at Virginia Tech
8/98-5/99
- -Conducted research in the area of 3D medical imaging techniques.
- -Developed software for viewing X-ray, MRI, and CAT scan data in 3D for training and diagnosis in the medical profession.
- -Supervised project teams on the research.

Research: Funded Research Assistant in the Industrial Engineering Department's Virtual Environment Laboratory
8/97-8/98
- -Conducted research in the areas of human computer interaction, interface design, usability, virtual/augmented reality, wearable computers, wireless networks, haptics, and computer graphics.

Teaching: Teaching Assistant for ISE 5694 *Fundamentals of Digital Technology*.
1/98-5/98
- -Taught C++ programming component of the course.
- -Wrote/graded programming assignments.

Internship: Steuben Foods Inc., Elma, NY
5/96-8/96
- -Designed and implemented a Computer Vision System for inspection and rejection of defects on production line.
- -Instituted a new Quality Control Program utilizing statistics.
- -Performed ergonomic job audits and recommended improvements at each workstation.

Study Abroad: University of Melbourne, Melbourne Australia
2/94-11/94
- -Spent 1 year living and studying philosophy and government at The University of Melbourne.

Honors and -Pratt Engineering Fellowship

Awards -Dean's List, Spring 1996-present
-Alpha Pi Mu Engineering Honor Society
-Selected to present at 1998 Human Factors and Ergonomics Conference
-Invited to speak at Xybernaut Corp.'s 1998 Conference on computing
-Served on the review committee for the International Symposium for Wearable Computers (ISWC '98) conference
-Served on the review committee for SIGGRAPH '98 conference

Membership/ Activities -Institute of Electrical and Electronic Engineers (IEEE)
-Institute of Industrial and Engineers (IIE)
-United States Golf Association (USGA)
-Sigma Pi National Fraternity, Epsilon Omicron Chapter
-Board of Directors, Animal Care NRV, Inc.

Publications

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