A Pilot Test for Identifying Tasks and Degrees of Visual Fidelity for Applications of Head Mounted Display Systems (HMD) for Construction

Cecilia Irene Soto

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Tanyel Bulbul, Chair
Farrokh Jazizadeh Karimi
Georg Reichard

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ACADEMIC ABSTRACT

The rise in technology and reduced costs has led to more research on use of Augmented Reality (AR). However, applications for AR Head Mounted Display (HMD) systems are still being defined and have not been fully implemented in the construction sector. A literature review shows that future applications for AR systems in the construction sector include *inspection*, *assembly*, *design*, *communication*, and *education*. More specifically, the AR HMD systems have potential to help users interact and experience information in a way that could improve their productivity and comprehension. Better understanding of AR HMD systems will allow for the development of ubiquitous systems such as Smart Safety Glasses that will allow construction workers to have higher productivity. This pilot study focused on identifying appropriate elements of visual fidelity for examining construction level of detail drawings for construction workers doing inspection and assembly tasks. This was done by conducting an experiment using Microsoft Hololens with three conditions for a roof deck model: *(1) 3D AR and 2D AR model*, *(2) 3D AR model,* and *(3) 2D drawing on paper*. Data was collected to measure participants' accuracy and comprehension of the roof deck model through a timed questionnaire about the model. The results from this study suggest that participants who used the 3D AR condition had better accuracy and comprehension than participants tested with the two other conditions.

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GENERAL AUDIENCE ABSTRACT

The rise in technology and reduced costs has led to more research on the use of Augmented Reality (AR). However, applications for AR Head Mounted Display (HMD) systems are still being defined. AR HMD systems have potential to help users interact and experience information in a way that could improve their performance. In the construction sector, workers use black and white construction level of detail drawings for assembly and inspection tasks. For this thesis, Microsoft HoloLens was used in an experiment to see the effects of AR models on user performance and comprehension. There were three conditions for this study, two of the conditions used AR model displays and the third condition used a traditional paper drawing of the model. This study measured participants' accuracy and comprehension of the model presented to them. The conclusion of this thesis is that using 3D AR models may improve participants' comprehension of construction drawings.

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CHAPTER 1: INTRODUCTION

Decreasing productivity is a challenge in the construction sector. It has steadily declined over past decades, meanwhile other industries have seen their productivity levels double. **Figure 1** shows the relationship between productivity for a period of forty years. In 1964, the productivity index of all industries started off at 100%. By 2004, other industries have surpassed the 200% productivity mark. Meanwhile, construction dropped its productivity to around 80%. This is partly because laborers' skills sets are dwindling over time, affecting the productivity and safety in construction environments (Johnston 2012). Another factor affecting productivity in construction is defect management. It can be costly in terms of man-hours, time, and money spent to correct errors (Park 2013). According to Teicholz (2004), one possible way to remediate the productivity problem in the construction industry is to adopt further use of new information technologies.

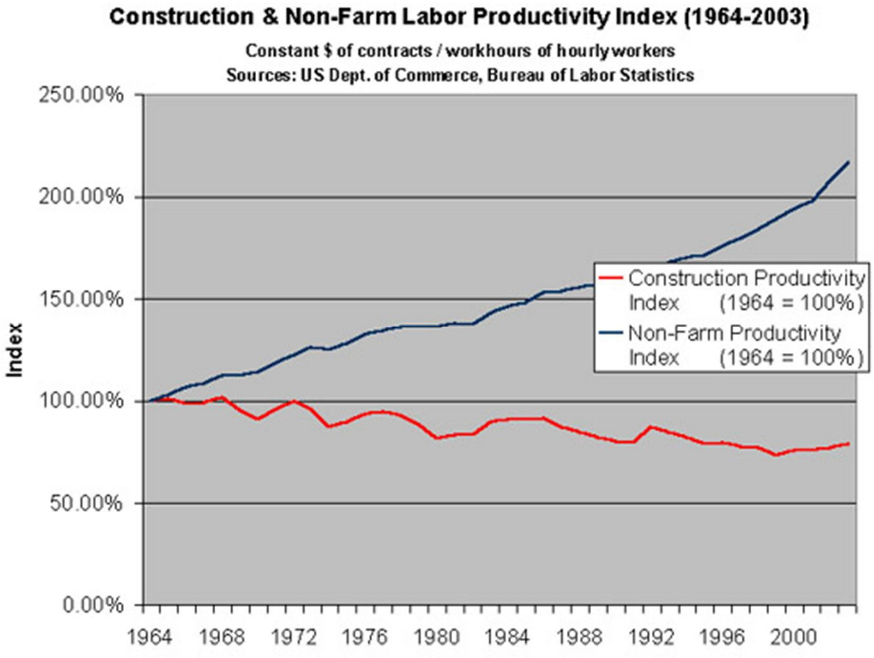


Figure 1. Labor Productivity Index from Teicholz 2004.

Another problem in the construction sector that needs to be addressed is safety. The construction industry is one of the most hazardous industries in the United States. Records from the Bureau of Labor Statistics show that the construction sector experienced almost 10 deaths for every 100,000 workers and it has the fourth highest fatality rate out of fifteen different industries (Coates 2011). According to many researchers, accidents happen because of unsafe behaviors such as inexperience and failure to follow safety procedures (Abdelhamid 2000; Chi et al. 2012). Accidents in the construction industry can occur due to human-machine interaction, worker overload, and inexperience (Everett 2000; Chi et al. 2012). Safety and inexperience in construction can be addressed with technologies in various ways. For example, researchers have developed virtual training simulations to successfully help workers, such as bricklayers, learn how to deal and identify hazards (Bosche 2015; Chen 2014). The use of technology such as *Augmented Reality* (AR) in the construction industry has potential to address some safety factors by providing workers with necessary safety information and training.

The rise of technology could help address productivity and safety in construction by using the Internet of Things (IoT). It is predicted that within the next decade, the Internet will be used to connect objects and information continuously (Miorandi 2012; Atzori 2010). Through IoT objects have potential to become “smarter” and able to *(1) interact with each other*, *(2) be identified*, and *(3) communicate*. For example, a smart object can have embedded information about its location, manufacturing, and current state, such as temperature (Kortuem 2010). The process of communicating and interacting with all of these smart objects could be done in various ways, such as by using *hand-held mobile devices* (HHMD) such as smartphones. It is possible that in the future, workers in the construction site will be able to interact with smart objects. Construction practitioners’ interactions with smart objects and augmented reality could enable streamlining of construction processes, help prevent data loss of storage, and help save workload space (Azuma 1997; Park 2013).

AR is an environment that contains both real world and virtual information (computer-generated information) that is superimposed on top of each other. This virtual information can be to enhance any of the five senses, however past research has focused mostly on visual displays. This allows users to have an enhanced understanding of the real world environment around them. AR systems should accomplish the following objectives (Van Krevelen and Poelman 2010):

- Combine real and virtual objects in a real environment
- Register real and virtual objects with each other
- Run interactively, in 3D, and in real time.

Most importantly, AR systems allow the user to remain engaged with the real world environment while receiving additional information from a computer (Wang and Love 2013). AR can deliver information to individuals in the context of their environment, allowing them to have an enhanced understanding of their surroundings, and allow for improved decision-making. Incorporating AR systems would supplement human skills instead of replace them. AR systems could also help workers with information intensive tasks by reducing the amount of time it takes to search and access information, reducing total task time by half, improving working memory, and improving the spatial cognition needed to complete tasks (Wang and Dunston 2006). Researchers project that productivity and safety will be improved by incorporating AR systems (Chi et al. 2013). AR systems that can connect to objects through the IoT and provide context-based information to construction workers could help improve both worker performance and safety in the construction field.

CHAPTER 2: LITERATURE REVIEW

During the past fifty years, AR has been researched across many disciplines, including the construction industry. However, due to technology shortcomings, such as being too cumbersome, low battery life, and lag; AR in the form of Head-Mounted Display (HMD) systems has not been implemented across the construction sector. Recently, AR and HMD system technology have improved to the point where it is feasible to incorporate augmented reality in construction sites. Prior construction-related research has focused mainly on the use of AR with HHMD, meaning that there is little research on HMD systems for construction-related applications. **Figure 2** shows categories with potential AR uses in the construction sector which were identified by this literature review. However, past studies have failed to explicitly identify compatible tasks or areas for AR HMD systems. Although many papers described potential for AR, none of the prototypes were developed enough to be used and tested in the industry. More research needs to be conducted to successfully incorporate this form of technology in the construction industry.

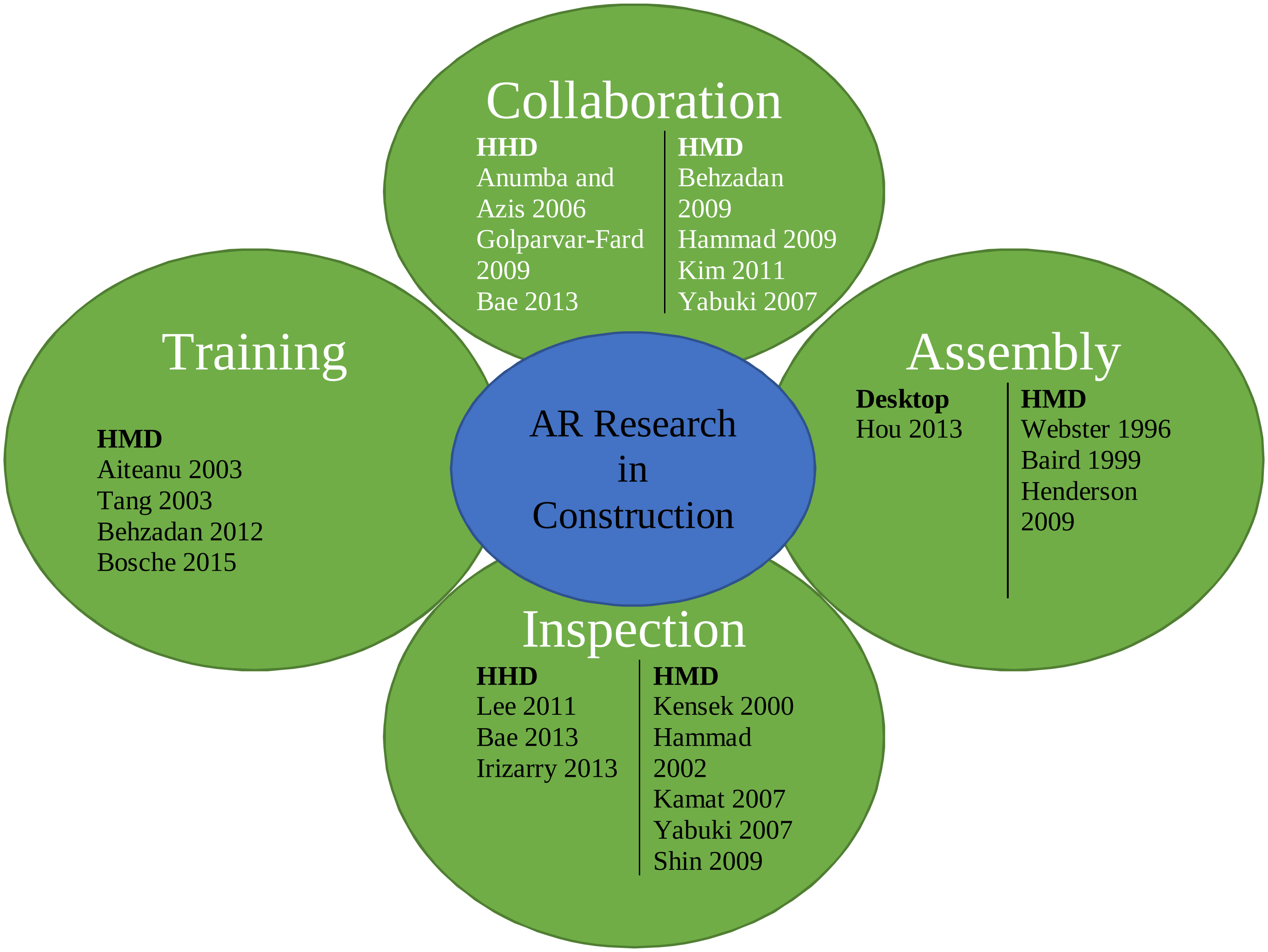


Figure 2. Classification of uses for AR in Construction

Collaboration and Communication: These papers included information about how augmented reality could be used in group settings. It could be in the form of working together as a group on a project or it could be by passing information to other groups by using AR.

Training: The papers included in this category were related to educating users such as construction students or practitioners.

Inspection: These papers were about inspecting field work and analyzing safety hazards.

Assembly: The papers in this category were about how AR could be used for assembling projects. Some of the uses of AR included giving animations, showing users what tools to use by matching, and providing the user with quality control.

2.1 Collaboration

Potential AR uses for collaboration include communication between users and remotely monitoring tasks. One case study using AR HHMD, in the form of cell phones, sent task lists to workers depending on their duties, location, and time of day (Anumba and Aziz 2006). This study demonstrated that by providing employees information about the tasks that need to be completed based on the users' context, workers spent less time accomplishing their tasks compared to subjects without context-based updates. An AR HHD prototype called 4-dimensional augmented reality (D^4AR) was developed to track construction progress by superimposing virtual images (Golparvar-Fard 2009). The D^4AR prototype had some problems with detection and matching objects, it was later replaced by Hybrid 4-Dimensional Augmented

Reality (HD^4AR). In 2013, Researcher Bae conducted a study using an AR HHD prototype called HD^4AR to help users identify their location by taking pictures of their surroundings and also allows users to input data into the system. The HD^4AR prototype was successful, but its localization technology needs to be improved so that it can provide users with localization information in real-time. Researchers Behzadan and Kamat (2009) developed an AR HMD prototype called Augmented Reality Visualization of Simulated Construction Operations (ARVISCOPE) which could also provide users with context-based information for excavation or material procuring tasks. The ARVISCOPE prototype was later discarded because it was bulky (users had to wear a backpack), the virtual images were too unrealistic, and had lag. In a different study, subjects assembling LEGO houses with 4D models were able to understand and communicate the sequence of construction to each other more effectively than groups only exposed to the 2D drawings of the LEGO house (Dawood and Sikka 2008). A see-through HMD system prototype called Distributed Augmented Reality visualizing Collaborative Construction Tasks (DARCC) was used for a case study simulation collaboration and crane activity, participants were able to adjust and communicate with each other successfully (Hammad 2009). However, this prototype had problems displaying an accurate 3D model in real-time. A case study using AR HMD and an interactive modeler allowed users to collaborate successfully and analyze where to put construction equipment based on context such as location of columns and girders (Kim et al 2011). This study was successful for users communicating with each other by using laptops, but further advancements are needed to make the proposed modeler more intuitive for users. In a similar case study, participants wearing AR HMD systems would talk to each other about position girders and rebar for IFC-Bridge. This case study was originally tested first indoor in a table-top setting and outdoor in a bigger setting (Yabuki 2007). Researchers conducted a case study using AR multiscreen (AR-MS) and found that this type of technology can enable participants find and discuss construction drawings and schedules more effectively (Lin 2014). The results of past studies using AR for collaboration and communication purposes in construction are promising. Future implementation of AR systems in the construction industry could allow users to receive context-based information in real-time based on the objects surrounding them and interact with other users.

2.2 Training

Use of AR for construction training would allow users to make visual connections with the information they are learning and improve memory (Tang et al 2003) and reduce the consequences of learning errors such as safety hazards (Behzadan 2012). Research about construction training has focused on the use of AR and virtual reality (VR). Researchers Lucas and Thabet (2008) conducted a study using VR to train workers on identifying safety hazards, they found that the use of virtual objects allowed workers to receive immediate feedback about their actions without negative consequences. Researcher Chen (2014) showed that workers were able to train and identify safety hazards quickly using augmented virtual reality in the form of a video game called SAVES. In another scenario, researchers used mixed-reality HMD systems to simulate heights to train bricklayers to perform on high scaffolds (Bosché et al. 2015), however there were some tracking problems with HMD system. Researchers developed a concept for an AR welding helmet to help welders improve the quality of their products without X-ray the welded products. This prototype was targeted to help novices know where to weld (Aiteanu 2003). A review of virtual reality applications in construction concluded that workers found virtual environments more intuitive and easier to retain information than real environments, however building realistic models using AR would be less cumbersome than using virtual reality (Bhoir and Esmaeili 2015). Researchers trying to teach students about construction process, developed a HMD prototype called AR Gen-1, they found that when participants were engaged with a scene, they were able to process more information (Behzadan 2012). Training labor forces with graphic instruction could improve communication and provide users with richer and more complete information about their tasks (Johnston 2012). The training investigations were successful but showed that systems using virtual reality (VR) or AR need to develop further before they are successfully incorporated in practice.

2.3 Inspection

These papers were about inspecting field work and analyzing safety hazards. The main drivers to implement AR for inspection are economic and safety considerations (Kamat and El-Tawil 2007) and increased access to information. An AR HHD prototype named InfoSPOT (Information Surveyed Point for Observation and Tracking) was designed to help facility managers identify objects and track object data. InfoSPOT users believed that using AR did not add to their cognitive load, however there were alignment problems with the virtual objects and the prototype was too bulky to hold in one hand (Irizarry 2013). A prototype using an AR HMD system was developed to allow facility managers to inspect HVAC and electrical systems and see important details about these systems such as the manufacturer's information, unfortunately this prototype's images were too jittery, faded colors, and lacked accuracy (Kensek 2000). A HMD AR prototype called Mobile Augmented Reality System for Infrastructure Field Tasks (MARSIFT) was developed to provide context-specific information and collect data for users inspecting bridges (Hammad 2002). Unfortunately, MARSIFT needed to have better accuracy before implementation in the construction industry. A prototype using a HMD system was developed to check reinforced bars in construction sites. This HMD prototype allowed users to be in the field or in the office and look at the alignment of reinforced bars (Yabuki 2007). An experiment which involved steel column inspection with an AR system compared to a TSI showed that augmented reality can simplify tasks, but there are still technical difficulties with AR technology (Shin and Dunston 2009). A different prototype using a HMD system was developed to check reinforced bars in construction sites. This prototype allowed users to be in the field or in the office and look at the alignment for the reinforced bars. When this experiment was tested outside four issues were identified: quality of combined view was unstable, the view was too narrow, and there were issues lining up the AR with the marker (Yabuki and Li 2007). Another group of researchers that AR could be used to provide accurate information to inspectors and check if buildings are safe after earthquakes (Kamat and El-Tawil 2007). The prototype HD4AR was developed to allow users such as field personnel to access 3D BIM without using any markers. This prototype would allow users to point their prototype in a location and take a photograph; this would in turn find the user's location. The goal of this is to help track future construction progress (Bae et al. 2013). Researchers developed a HHD AR system called AROMA-FF to give inspectors information about location of which parts need maintenance (Lee 2011). The conclusion from all these investigations show that augmented reality is a promising new technology, but drawbacks such as jittery images have prevented this technology from implementation in the construction industry. Further research will be needed before AR systems in any form including HMD can be incorporated in construction sites.

2.4 Assembly

The papers in this category were about how AR could be used for assembling tasks. Some of the uses of AR included giving animations, showing users what tools to use by matching, and providing the user with quality control. One of the first examples of HMD system using AR is an experiment where a worker assembles an aluminum structure. A prototype for HMD system (Webster 1996) was used to locate columns behind walls. A similar prototype was tested outside by Feiner and Webster in 1996, this prototype provided users with audio and visual cues for assembly. While users were able to complete the tasks, there were issues with low brightness, loss of tracking, and low resolution. An experiment using different types of HMD systems was completed and found that users were able to assemble motherboards more effectively and that see-through AR worked best for giving users information (Baird 1999). Over a decade later in 2009, Henderson et al. demonstrated the success of AR for assembling tasks for maintenance workers. Using virtual information displayedin the form of labels and arrows, the mechanics were able to find objects faster and spent less time turning their heads looking at the instructions. Other researchers tried approaching AR with video instruction for assembly tasks. In this case, researchers gave video instructions for assembly of LEGO models such as AR or 4D planning found that users performed better when they were able to visualize the 3D model (Dawood 2008; Hou and Wang 2013). In a study conducted by Researcher Hou (2013) testing pipe assembly using desktop AR, participants were able to complete the tasks faster, however there were calibration and tracking problems with the technology. While not specifically designed for AR, a prototype was developed using virtual prototypes to guide wall assembly successufully using pictographs to correctly position wall components (Jonhston 2016). For the maintenance tasks and for LEGO assembly, the results showed that users preferred the AR system- they found AR systems reduced user workload, task time, and number of errors. AR systems were more intuitive than paper instructions and the information needed to be referenced less often. The findings from these past studies was promising, however due to technology setbacks, users found the HMD systems used too cumbersome and with low resolution.

2.5 Timeline of HMD systems

HMD systems have been around since the 1960s. This section provides a small history and timeline of HMD prototypes relevant to the construction sector.

2.5.1 1960s

The first see-through HMD prototype was developed in the 1960s by Ivan Sutherland (1968). The objective of this prototype was to provide users with information in 3D. The HMD system could display images in 3D, but the prototype could not show opaque colors and the positioning system had to be above the person's head. Another problem with this prototype was wireframe display; some participants misinterpreted the images presented by HMD prototype. The tracking system is mounted to the ceiling meaning that this prototype could not be tested in outdoor settings. **Figure 3** below shows Sutherland's HMD system and tracking system which is mounted on the ceiling of the room.

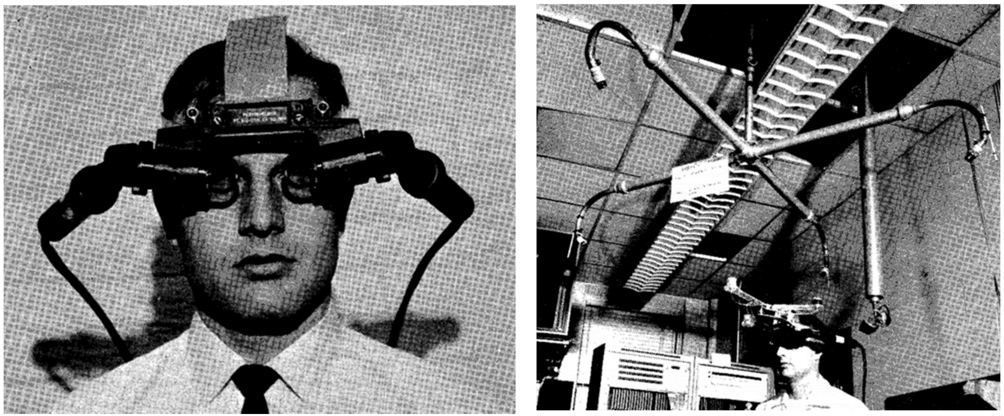


Figure 3. (a) Sutherland's HMD system and (b) HMD prototype and the tracking system

2.5.2 1980s

In the 1980s, Researcher Brooks (1987) developed an HMD system that allowed users to visit virtual spaces. This new prototype could show opaque colors in 3-D perspective and superimpose virtual images on top of real images. The goal of this HMD system was to allow designers to show their clients the designed spaces. However, this prototype faced technological problems such as a three second lag, low image quality, and low resolution. The prototype was bulky, participants wearing the HMD system had a headset and a fanny pack to carry electronic parts. Participants also experienced dizziness and disorientation wearing the HMD system. The HMD system was successfully finalized in 2001 for project walkthroughs using VR. **Figure 4** below shows a sketch of this prototype.

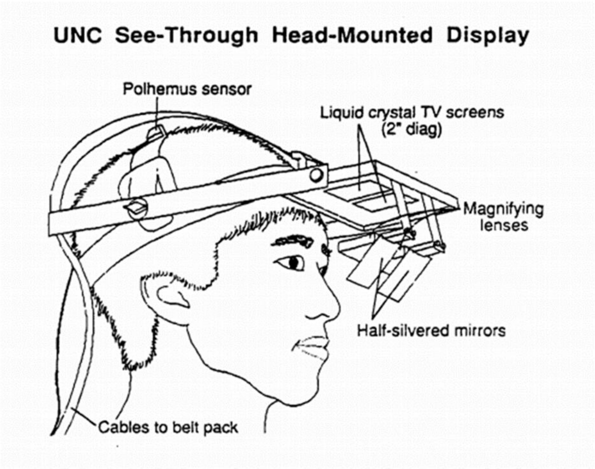


Figure 4. A sketch of Brooks' HMD prototype from Chung 1989

2.5.2 1990s

In 1992, Researcher Caudell coined the term "augmented reality" and developed a prototype called Heads-Up See-Through (HUDSET) HMD system. This prototype was developed to help users in airplane manufacturing because automation is not feasible due to high costs and high dexterity requirements for assembly tasks. The prototype was developed improve accuracy of projected images and increase the range of head positioning. Unfortunately, this prototype had poor positioning and low accuracy. Users expereinced problems with time lags, low range, and the virtual image was displayed in only one eye. **Figure 5** below shows a drawing of HUDset using Private Eye headset.

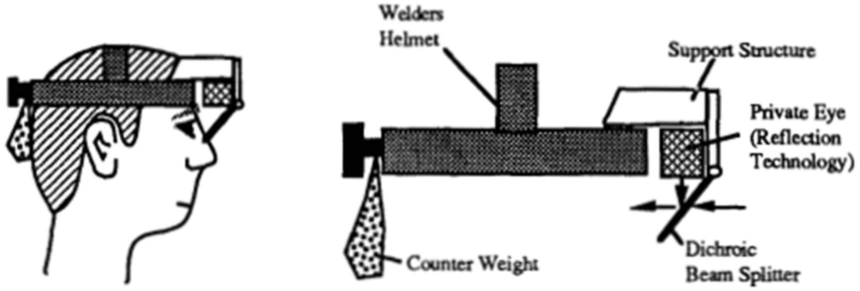


Figure 5. Drawing of HUDSET from Caudell 1992.

In 1993, a see-through HMD prototype was developed by Feiner (1993) with trackers worn on the users' torso, arms, and head. This system would overlay virtual images in 3D through a small display. The prototype was able to track objects and movements. Users were able to interact with objects and access hyperlinked media. This prototype also prevented jittery images by "smoothing" the vitual images. However, the tracker was inaccurate and the HMD system could only display information up to twelve feet away. **Figure 6** below shows a user wearing the prototype and what the overlayed text would look like using the HMD system.

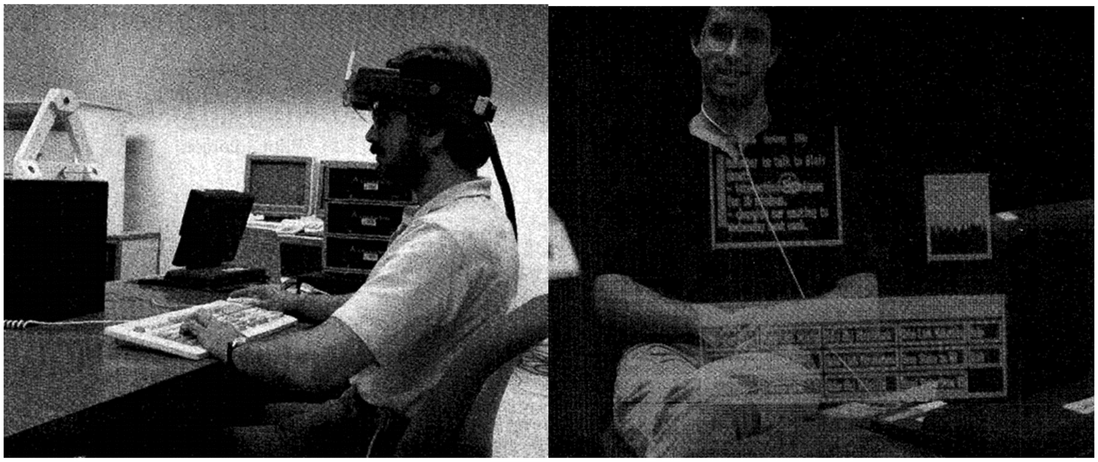


Figure 6. (a) Prototype developed by Feiner (1993) and (b) overlay of text as seen from the HMD prototype

In 1996, Researcher Webster published an article about preliminary work done developing an HMD system that would allow structural engineers to have “x-ray vision” when inspecting beams. This prototype was also tested for audio directions of assembly tasks. **Figure 7** shows the prototype and assembly task.

Figure 7. HMD Prototype from Webster 1996.

That same year, Columbia University’s Computer Graphics and User Interfaces Lab started a research project called Mobile Augmented

Reality Systems (MARS). This research group and went on to develop the Touring Machine.

In 1997, Researcher Feiner used commercial virtual I/O i-glasses for Touring Machine. This prototype had the ability to be tested in an outdoor setting. The prototype had an attached wearable computer in a backpack and a handheld device with a stylus. Some issues with this prototype included low brightness and problems with GPS tracking, because buildings blocked GPS line-of-sight. Figure 9 shows the Touring Machine.

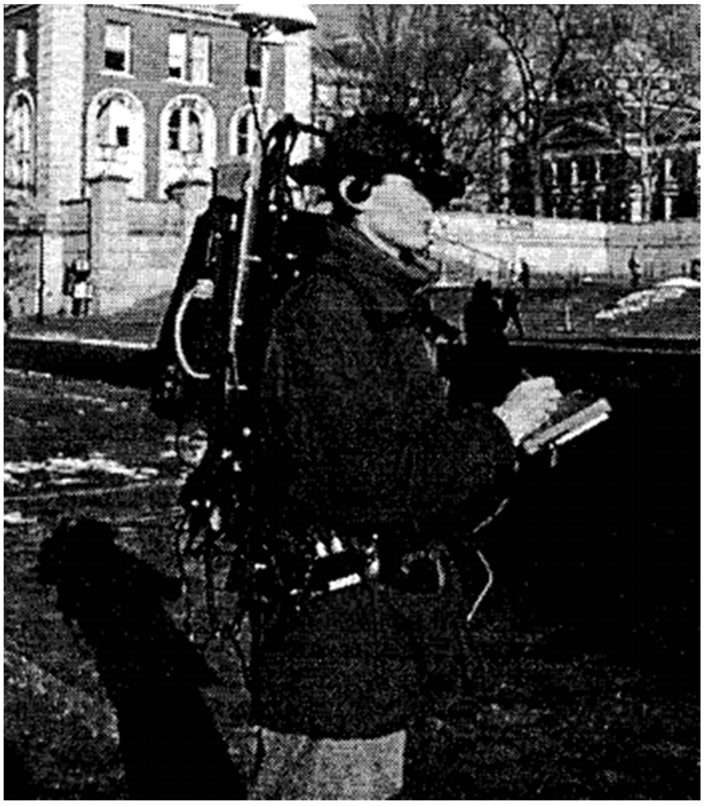


Figure 8. Touring Machine from Feiner 1997.

In 1998, Reiner did an experiment on door lock assembly using HMD systems with AR. The goal of this system was to guide assembly using virtual images. Users thought that the HMD system was too cumbersome and the virtual images could not keep up with fast head movement (Reiners et al. 1998). **Figure 9** shows the Reiner's HMD prototype.

Figure 9. HMD prototype from Reiner 1998

In 1999, Thomas developed Tinmith-2. It was designed for outdoor use and would overlay architectural designs. Tinmith-2 was developed to help users visualize revidsions to construction pland and provide hands-free use. Unfortunately, users found the Tinmith-2 prototype bulky since they needed to wear a backpack with the battery, and an antenna. The prototype also had alignment and registration problems. **Figure 10** shows the Tinmith-2 prototype.

Figure 10. Tinmith-2 Prototype.

2.5.3 2000s

In 2000, Researcher Kensek conducted a case study using HMD AR systems for facility managers to annotate and see object information such as the fixing schedule and manufacturer’s contact information (Kensek 2000). The goal was to provide users with an inexpensive tool that would allow users to receive context-based information. The prototype was successful, but the images were jittery, colors were not opaque, and there was lag. **Figure 12** shows the HMD prototype.

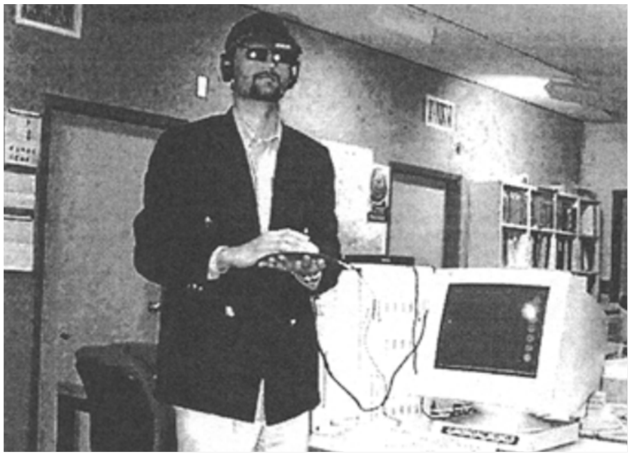


Figure 11. The HMD system used in Kensek's case study.

In 2002, Hammad developed a prototype called Mobile Augmented Reality System for Infrastructure Field Tasks (MARSIFT). This prototype was described as having applications for data collection and for future use bridge inspection. Overall, the goal of this study was to provide users with context-based information and allow users to communicate with each other and input data. There were some problems with MARSIFT including low accuracy and human factors since the system was so bulky. **Figure 13** shows a drawing of MARSIFT.

Figure 12. MARSIFT prototype drawing

In 2006, Wang and Dunston developed a prototype called AR-CAD, which was an AR HMD system and did a study on orienting objects. The aim of this research was to improve user perception through AR.

This study was conducted using a tabletop model and was continued in 2008.

In 2007, Kamat and el-Tawil developed a prototype to evaluate a building's structural damage after earthquakes with the use of markers (Kamat 2007) with the ultimate goal to reduce time spent marking buildings safe. This prototype experienced issues with jittery images, bulkiness, and using markers. The prototype could improve by relying on GPS locations to place the virtual objects. **Figure 13** shows the prototype for this study.

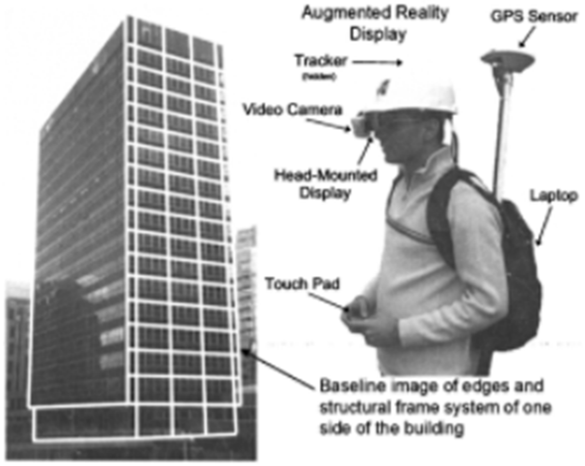


Figure 13. Prototype used in Kamat and el-Tawil's study

Also in 2007, Yabuki et al. developed a prototype to for inspection, **Figure 14**. The goal of this study was to develop a prototype that reduced time sequencing re-bar placement and allow users to communicate with each other. The prototype was tested inside and later outdoors. The prototype had some problems lining up the virtual images with the markers, lag, and a narrow field of view.

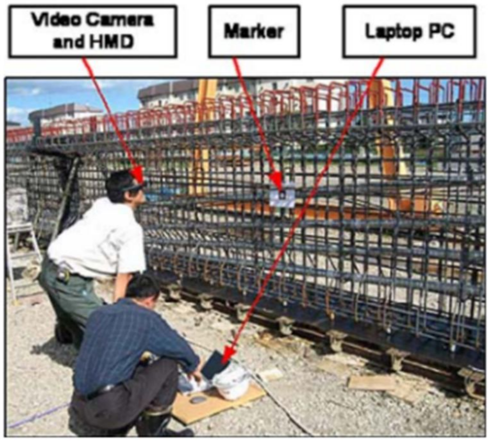


Figure 14. AR HMD prototype used in Yabuki 2007

In 2008, Wang and Dunston continued their studies using AR-CAD. However, participants said that AR-CAD had low resolution, caused fatigue, and was too cumbersome. Participants were able to complete tasks faster using this prototype but were more comfortable using the computer for this study. Figure 15 shows the AR-CAD prototype.

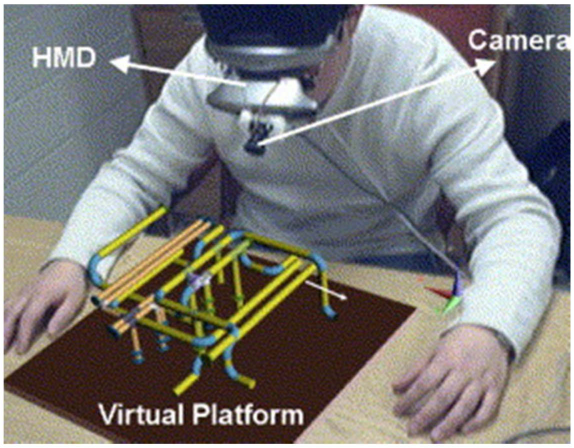


Figure 15. AR-CAD

In 2009, Researcher Hammad developed a prototype for visualizing collaborative construction tasks (DARCC) and used nVisor, see **Figure 16**. The prototype allowed users to communicate with each other. However, the prototype was not hands-free (users relied on joysticks), needed better tracking accuracy, and outdoor testing.

Figure 16. DARCC prototype.

In 2009, Behzadan and Kamat developed a prototype called Augmented Reality Visualization of Simulated Construction Operations (ARVISCOPE). This study's goal was to develop a framework of reusable software and hardware for future HMD studies. This prototype was able to track users' locations to give them realistic images. However, the images created by ARVISCOPE were not realistic, the prototype was bulky, and the prototype was still in the process of validation. This prototype was later replaced by a newer generation called ARMOR in 2010 (Dong 2010). Both prototypes are shown in **Figure 17**. However, ARMOR still experienced latency and needed to use a Wii remote as a controller.

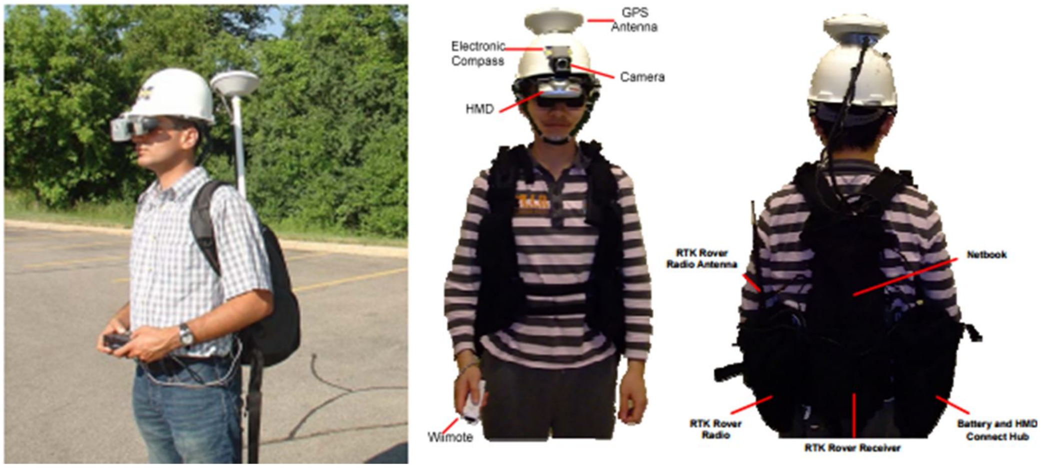


Figure 17. (a) ARVISCOPE from Behzadan 2009. (b) ARMOR from Dong 2010.

In 2009, Henderson and Feiner, see **Figure 18**, developed a prototype for maintenance tasks. This study was tested in a field setting and created a custom HMD system. Originally Feiner used nVisor for their study, (nVisor had a resolution of 1280x1024 and a field of view of 60 degrees), to allow users to freely move their head. The custom HMD display system used text, labels, and animations. The mechanics were able to complete their tasks faster using this HMD system. However, participants had problems moving their heads and using their peripheral vision while wearing the prototype.

Figure 18. HMD system in Henderson 2009

2.5.4 2010s

In 2012, Researcher Yeh developed an HMD prototyped called iHelmet, (see), and used an iPod Touch. The goal of this study was to provide users with a light-weight prototype and a system to navigate through 2D drawings, see **Figure 19.**The iPod served as a controller. Because the HMD system was projection-based, users had to find a wall to display information. There were problems with the projector brightness, controlling the iPad without looking at it, and the projected image was blurry at a distance.

Figure 19. IHelmet.

In 2012, Behzadan and Kamat developed a prototype called AR Gen-1, see **Figure 20**. This prototype allowed construction students to learn and participate with augmented reality through an interactive environment. The drawbacks of this prototype included relying on markers and larger experiments need to be conducted.

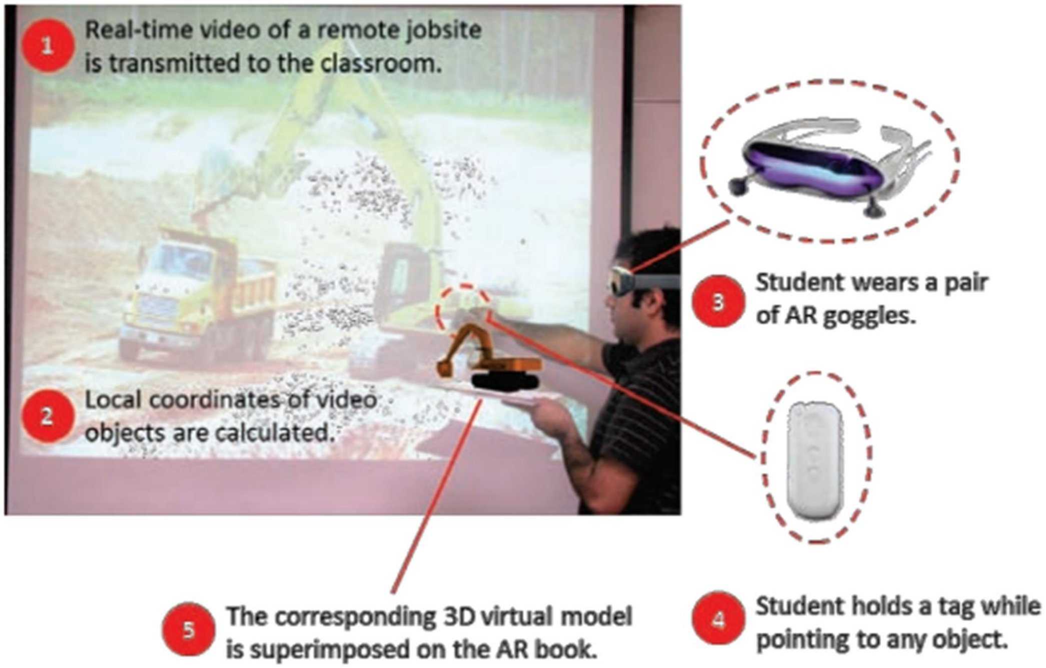


Figure 20. AR-Gen 1

In 2014, Willis conceptualized a HMD system called Voice-Activated Augmented Reality (VAAR) system, see **Figure 21**. This is the first prototype that is less cumbersome and based on commercialized AR HMD systems such as Google Glass. The prototype would be able to be voice-activated and record information just like Google Glass.

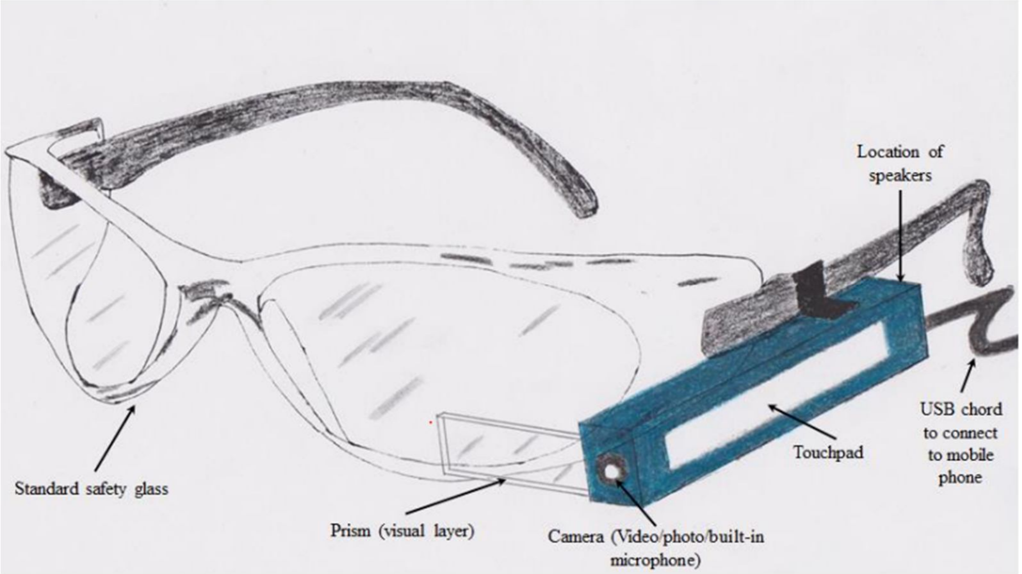
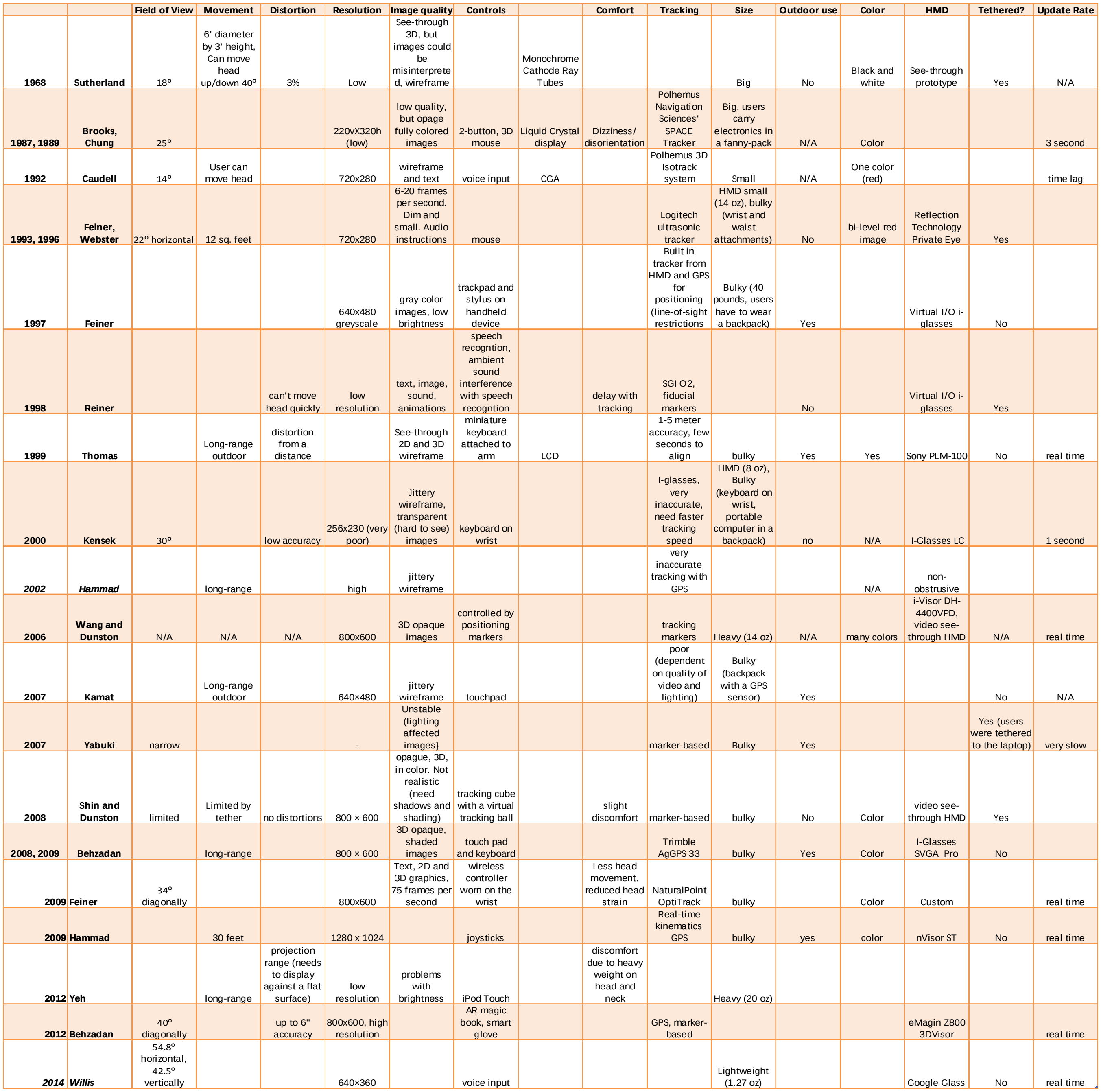


Figure 21. Drawing of VAAR from Willis 2014.

2.6 Future Uses and Point of Departure

The HMD system is not a new concept in the construction industry but has not been implemented because of technology drawbacks. For example, a study showed that test subjects wearing the monocular lens HMD had poor depth perception, poor situational awareness, and because of the translucent colors, participants were forced to wait until they were in the shade or use their hands to see virtual objects (Kerr et al. 2011). Another issue with AR in general, *not just for HMD*, is occlusion. *Occlusion* is the ability to line up virtual objects correctly in a 3D landscape, allowing objects to seem more realistic (Behzadan et al. 2015) between real-time and the virtual image (Behzadan and Kamat 2005). Another problem identified was that using a HMD system could cause fatigue, discomfort, or distraction (Wang and Dunston 2006). Technology pitfalls and human factor considerations have prevented AR in the form of HMD to be implemented by the construction sector.



		Field of View	Movement	Distortion	Resolution	Image quality	Controls		Comfort	Tracking	Size	Outdoor use	Color	HMD	Tethered?	Update Rate
1968	**Sutherland**	18°	6' diameter by 3' height, Can move head up/down 40°	3%	Low	See-through 3D, but images could be misinterpreted, wireframe		Monochrome Cathode Ray Tubes			Big	No	Black and white	See-through prototype	Yes	N/A
1987, 1989	**Brooks, Chung**	25°			220vX320h (low)	low quality, but opage fully colored images	2-button, 3D mouse	Liquid Crystal display	Dizziness/ disorientation	Polhemus Navigation Sciences' SPACE Tracker	Big, users carry electronics in a fanny-pack	N/A	Color			3 second
1992	**Caudell**	14°	User can move head		720x280	wireframe and text	voice input	CGA		Polhemus 3D Isotrack system	Small	N/A	One color (red)			time lag
1993, 1996	**Feiner, Webster**	22° horizontal	12 sq. feet		720x280	6-20 frames per second. Dim and small. Audio instructions	mouse			Logitech ultrasonic tracker	HMD small (14 oz), bulky (wrist and waist attachments)	No	bi-level red image	Reflection Technology Private Eye	Yes	
1997	**Feiner**				640x480 greyscale	gray color images, low brightness	trackpad and stylus on handheld device			Built in tracker from HMD and GPS for positioning (line-of-sight restrictions	Bulky (40 pounds, users have to wear a backpack)	Yes		Virtual I/O i-glasses	No	
1998	**Reiner**			can't move head quickly	low resolution	text, image, sound, animations	speech recogntion, ambient sound interference with speech recogntion		delay with tracking	SGI O2, fiducial markers		No		Virtual I/O i-glasses	Yes	
1999	**Thomas**		Long-range outdoor	distortion from a distance		See-through 2D and 3D wireframe	miniature keyboard attached to arm	LCD		1-5 meter accuracy, few seconds to align	bulky	Yes	Yes	Sony PLM-100	No	real time
2000	**Kensek**	30°		low accuracy	256x230 (very poor)	Jittery wireframe, transparent (hard to see) images	keyboard on wrist			I-glasses, very inaccurate, need faster tracking speed	HMD (8 oz), Bulky (keyboard on wrist, portable computer in a backpack)	no	N/A	I-Glasses LC		1 second
2002	***Hammad***		long-range		high	jittery wireframe				very inaccurate tracking with GPS			N/A	non-obstrusive		
2006	**Wang and Dunston**	N/A	N/A	N/A	800x600	3D opaque images	controlled by positioning markers			tracking markers	Heavy (14 oz)	N/A	many colors	i-Visor DH-4400VPD, video see-through HMD	N/A	real time
2007	**Kamat**		Long-range outdoor		640×480	jittery wireframe	touchpad			poor (dependent on quality of video and lighting)	Bulky (backpack with a GPS sensor)	Yes			No	N/A
2007	**Yabuki**	narrow			-	Unstable (lighting affected images}				marker-based	Bulky	Yes			Yes (users were tethered to the laptop)	very slow
2008	**Shin and Dunston**	limited	Limited by tether	no distortions	800 × 600	opague, 3D, in color. Not realistic (need shadows and shading)	tracking cube with a virtual tracking ball		slight discomfort	marker-based	bulky	No	Color	video see-through HMD	Yes	
2008, 2009	**Behzadan**		long-range		800 × 600	3D opaque, shaded images	touch pad and keyboard			Trimble AgGPS 33	bulky	Yes	Color	I-Glasses SVGA Pro	No	
2009	**Feiner**	34° diagonally			800x600	Text, 2D and 3D graphics, 75 frames per second	wireless controller worn on the wrist		Less head movement, reduced head strain	NaturalPoint OptiTrack	bulky		Color	Custom		real time
2009	**Hammad**		30 feet		1280 x 1024		joysticks			Real-time kinematics GPS	bulky	yes	color	nVisor ST	No	real time
2012	**Yeh**		long-range	projection range (needs to display against a flat surface)	low resolution	problems with brightness	iPod Touch		discomfort due to heavy weight on head and neck		Heavy (20 oz)					
2012	**Behzadan**	40° diagonally		up to 6" accuracy	800x600, high resolution		AR magic book, smart glove			GPS, marker-based				eMagin Z800 3DVisor		real time
2014	***Willis***	54.8° horizontal, 42.5° vertically			640×360		voice input				Lightweight (1.27 oz)			Google Glass	No	real time

Figure 22. Matrix of Past HMD Prototypes.

Figure 23

The matrix in **Figure 22** shows past prototypes related to construction. There were two prototypes included in the matrix (Hammad 2002 and Willis 2014) were in development and were not tested. The trend with development of HMD systems was improved resolution, field-of-view, light-weight, and real-time update rate. This improvement in technology will allow users to have an enhanced understanding of information based on their context. AR HMD prototypes will allow users to see information such as a black and white 2D drawing in 3D with colors and in a larger scale. This could allow users to see more details and understand the drawing better. In turn, improved comprehension could lead to reduced times during different types of tasks. The prototypes displayed in the matrix show how technology for HMD systems has improved over time to a point that it is possible to include AR HMD systems in construction sites in the near future.

Now that technology has reached a point where images can be displayed in real-time, with a more realistic view, it is feasible to incorporate this technology in the construction field in the near future.

Recent improvements in AR HMD technology alleviate majority of these issues, allowing this technology to be implemented in the construction industry. A prototype called Head Marker Tracking Augmenting Reality (HMTAR) after giving great results as “extensive tracking capability, event memory mechanism, and scenario sharing mechanism” (Kuo 2013) would allow in the future for instant 3D display of future construction progress, flaws positioning for construction management, making real time additional or alternative design on site, and recording of AR images for worker instruction or education purposes (Kuo 2013). The problems identified with HMD systems are disappearing as technology improved, making other drivers to implement AR in HMD in construction more pronounced, such as economic and safety considerations of keeping workers' hands free (Kamat and El-Tawil 2007; Jang 2009). The use of HMD systems could improve users' understanding of documents through AR displays. By visualizing information based on context (such as its dimensions or based on its surroundings), users could have improved comprehension of their tasks.

Construction tasks compatible with augmented reality based on cognitive load have been identified, but not specifically for HMDs (Dunston 2011; Willis 2014). These include: *layout, supervision, excavating, inspecting, jointing, covering, building, attaching, and positioning,* as well as, *accessing* and *receiving information*. However, the tasks identified based on physical, working environment as well as the mental load do not differentiate between tasks that would benefit from HHMD or HMD systems. Very little research has been conducted on specific HMD AR tasks. Research shows that in the construction industry, AR in the form of HMD would be most beneficial when there are safety risks such as workers' hands are occupied (Jang 2009) during assembly tasks. Henderson et al. (2009) and Baird (1999) conducted research that show the benefits of using HMD AR specifically for assembly tasks. While some researchers have explored the use of different levels of visual fidelity for either AR HMD (Nash 2000) and visual fidelity for AR desktop devices (Radkowski et al 2015), there is a research gap for the levels of visual fidelity that could be compatible for use with AR and HMD systems for construction tasks.

This review showed that there are many benefits and possible drawbacks to using HMD systems with AR in construction sites. One article defined the Ferrell Theory which states that human errors (accidents) happen in the construction industry when a worker is overloaded or when a worker takes a risk purposely or not (Everett 2000). HMD systems with AR could remediate the issues of overloading and risk-taking by providing the user with more knowledge about the task at hand. HMD systems will not prevent injuries and deaths in the construction industry from happening directly, but there is a possibility that by displaying additional information to users, injuries will decrease in the construction sector. Also, the use of AR HMD systems could bring many benefits including less time to do work, less cognitive workload, better quality control, and instant access to information. The use of HMD and AR in construction could remediate the downward productivity trend by reducing the amount of time to search, access information and total task time. The current literature showed the benefits and shortcomings of AR, however it failed to identify specific tasks that could be facilitated through AR HMDs and level of visual fidelity most appropriate for that could be used for these tasks.

CHAPTER 3: METHODOLOGY

The purpose of this research is to build on previous research and use AR HMD systems to improve construction workers' comprehension and identify levels of visual fidelity that provide the right amount of information to users. More specifically, this study will answer the following questions:

- ***RQ1**: What levels of visual fidelity improve users' comprehension?*
- ***RQ2**: What factors influence user performance while wearing HMD AR systems?*

Past studies such as Henderson et al. (2009) suggest that user performance is improved by wearing HMD systems due to less head-movement to access information. Along with these questions the following hypothesis have been formulated to for the surveys:

- ***H1: The 3D AR model will allow users to better understand the level of detail drawing because it requires less mental load in the form of spatial visulization.***

  Hypothesis 1 addresses of user comprehension and accuracy while using AR conditions. Since the two AR conditions will allow users to see the roof deck model in color and in 3D, users will be able to understand the model and information presented to them.

- ***H2: Subjects using the 3D AR and 2D AR model will be able to answer the interview questions faster than the subjects only using the 2D drawing on paper***

  Hypothesis 2 addresses how quickly users will find the information they need for the study. It is predicted since users in the group with 3D AR and 2D model will be able to complete the timed portion faster since they will have access to two forms of information display.

3.1 Participants

Fifteen participants (five for each condition) were recruited from a pool of undergraduate students from the Myers-Lawson School of Construction at Virginia Tech. Subjects were recruited through an email sent out through a list-serve. Each participant was involved in fifteen-twenty minute survey session. All participants were over eighteen and had varying degrees of experience through classes and internships. They were classified into two groups: participants with higher levels of experience in construction (2+ years of internships) and participants with less than two years of internships. There were four participants who were classified as users with two + years of internships, they were split into the three treatment options evenly in **Table 1**. Six of the fifteen participants were familiar with augmented reality, three participants had used augmented reality before, and four subjects had used HMD systems.

Table 1: Distribution of Participants with two or more years of construction experience

2D Drawing on Paper	3D AR + 2D AR model	3D AR model only
1	1	2

3.2 Device Specifications

Hololens, shown below in **Figure 23**, by Microsoft will be used for this study. Currently, the Hololens is the only AR HMD commercial system available with potential applications for the construction sector (Agarwal 2016). The Hololens has a see-through holographic display. It weighs about 1.2 pounds and has a battery life of 2-3 hours. It has a Windows 10 operating system and can interact with users through hand gestures and voice input. The resolution for Hololens is 1268x720 and the field of vision is 120 degrees horizontally and vertically.

Figure 24. Hololens image from Google

The Hololens is mostly a video game system and has the ability to hold many applications including SketchUp Viewer. SketchUp Make and its extensions library was used to access a roof deck model. The roof deck model had level of detail information added by the student.

3.3 Research Design

The two hypothesis were tested by an experiment that involved survey questions as well as a timed portion. While this research does use virtual objects in a real-world space, it is not a true AR environment since participants were not able to interact with AR models presented to them in this study. Fifteen subjects were be assigned to one of three levels of visual fidelity (five for each):

- *Real world- 2D drawing on paper*

- *3D AR model through the Hololens*
- *2D AR drawing + 3D AR model through the Hololens*

The surveys were broken into three parts. **Table 2** shows a summary of the three survey sections and the information gathered by each section. The timed portion section overall was linked to both hypotheses, while the questions in the exit survey were used to test different parts of each hypothesis (**Table 3**).

Table 2. Summary of Pilot Study Survey Sections

Section	*Section Name*	*Information gathered*
1	Background	Background information such as experience with level of detail drawings and familiarity with AR.
2	Timed Portion	The amount of time it took participants to finish the timed portion, number of times referencing the model, and information the participants found in the model.
3	Exit Questions and Additional Comments.	Participant feedback on the timed portion and free response about AR and the roof deck model.

Table 3. Relationship between Questions and Hypothesis

Hypothesis	*Survey Section*	*Questions*	*Metric*
H1	Timed Portion	All	Accuracy and Comprehension
	Exit Questions	4	Accuracy
	Exit Questions	1,2, and 5	Comprehension
H2	Timed Portion	All	Speed

	Exit Questions	3	Speed

The questions in the survey were tested on Building Construction and Civil Engineering Graduate students to ensure question clarity and that the information presented in the roof deck model was accurate before the study commenced. This was done to ensure that information presented for this study would be easy to understand for the participants and to remove any discrepancies.

Each participant first answered the background questions in Section 1. Then each participant was given a few minutes to familiarize themselves with the roof deck model. In the case of the two AR conditions, participants were encouraged to walk around the entire model. When the participants were ready, they would either remove the Hololens or turn over the paper and answer questions by recalling information about the roof deck model. The participants were allowed reference the model as needed to complete the rest of the timed portion. Whenever participants would reference the model, they would flip over the piece of paper to reference the drawing and then flip it back over to continue. Participants who were in the AR treatment options would have to put Hololens on and then take it back off to continue answering the questions in the timed portion. For the third section of the survey, participants gave feedback about the clarity of the information presented by the roof deck model. This was done to discern which condition was the most helpful in understanding the roof deck model. Additionally, participants gave feedback on the clarity of questions during the timed portion. Some participants also wrote comments about the AR condition or the roof deck model.

CHAPTER 4: PROCEDURE

Each subject was randomly assigned to one of the three levels of visual display *(1) 2D drawing on paper*, *(2) 3D model*, or *(3) 3D AR + 2D AR model*. **Figures 25-29** show what these models looked like.

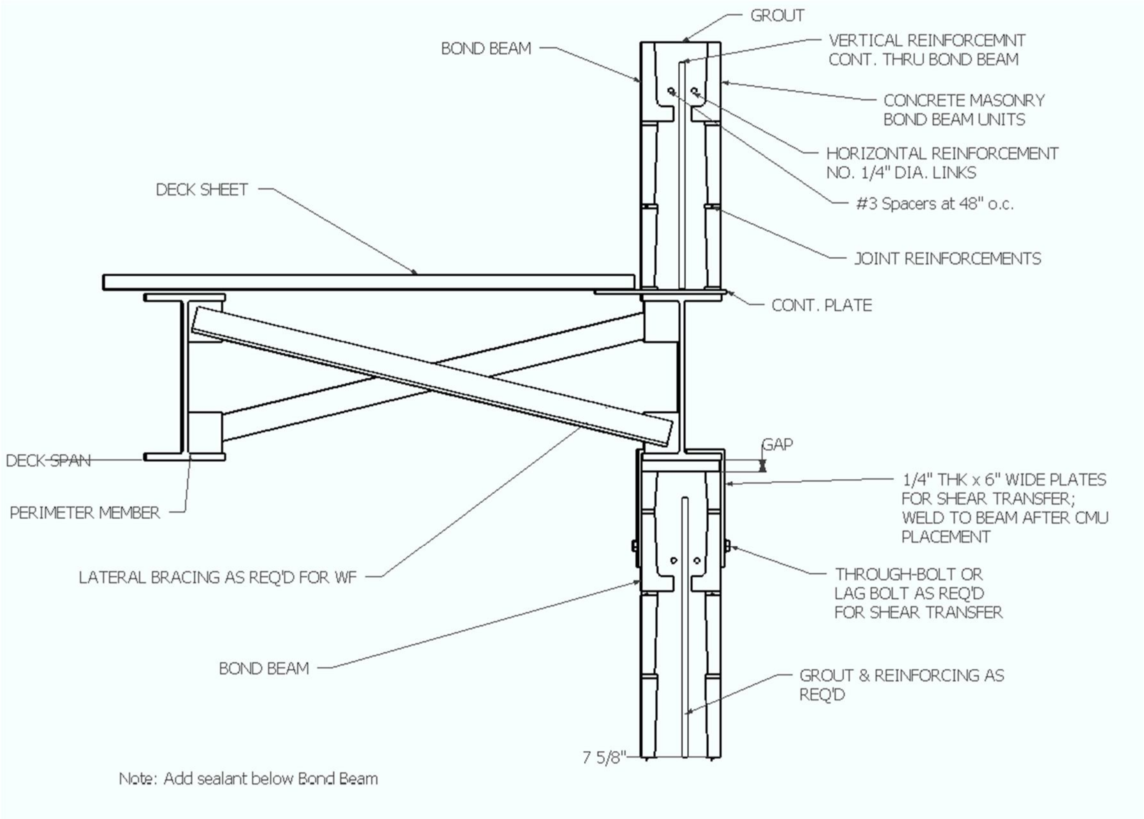


Figure 25. Mono-chromatic level of detail construction drawing display of the roof deck model paper condition.

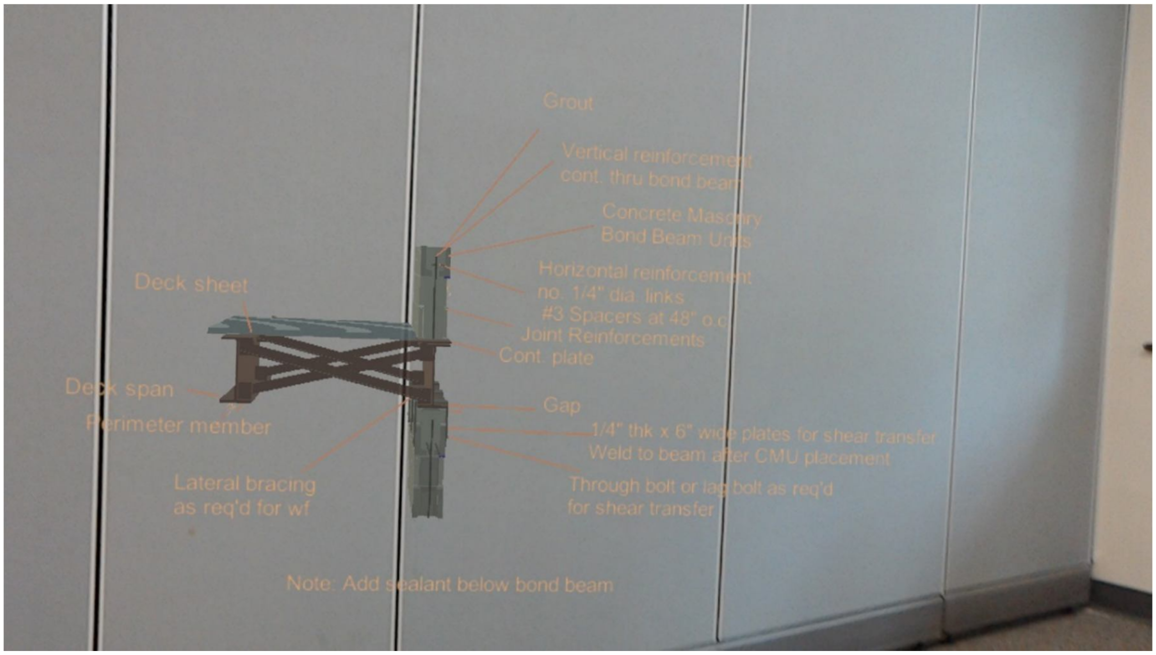


Figure 26. 3D Roof Deck model display.

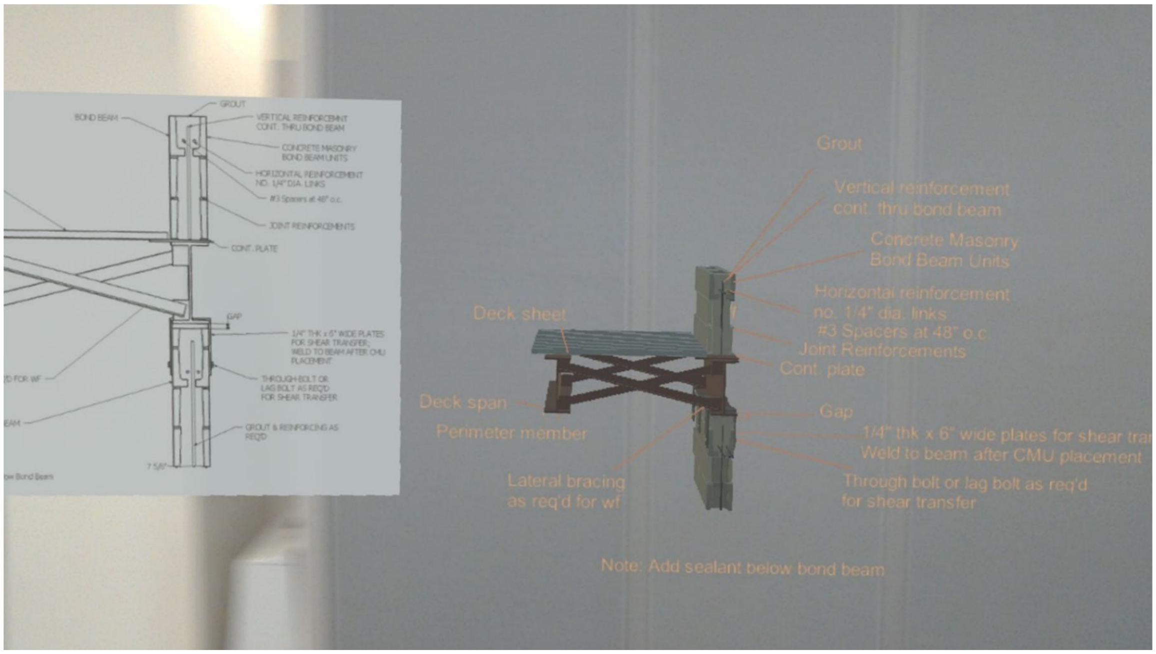


Figure 27. Partial view of 3D AR and 2D AR Roof Deck condition.

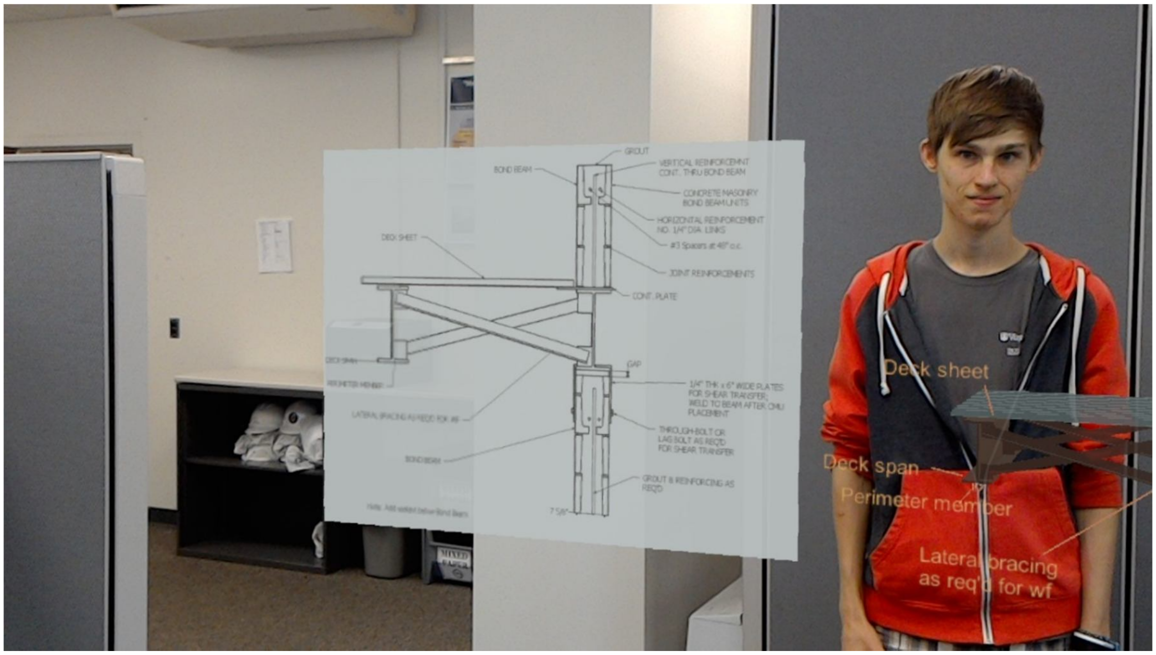


Figure 28. Another view of the 3D AR and 2D AR model with a student for reference.

Figure 29. Side view with a student for reference.

The participants completed the study with only one of the three treatment options. All participants were given a set of background questions before the timed portion. Once the participants completed the background survey, each participant was given a few minutes to familiarize themselves with the level of visual fidelity and roof deck model presented to them. The participants with the AR condition were allowed to walk around all sides to study the AR model. Once the participants were familiar with the roof deck model, the timed portion of the study would begin with specific questions about the roof deck model.

The data was collected through participants' responses to the survey questions, the time it took to complete the portion about the roof deck model, and the number of times participants referenced the roof deck model. During the timed portion of the experiment, participants were given a questionnaire that asked them to identify specific information included in the roof deck model. If participants answered one of these questions incorrectly, it would count as an error. However, most participants were able to answer most of these questions correctly.

CHAPTER 5: RESULTS

5.1 Timed Portion of Study

Data from the timed portion of the study was collected in the form of (1) *number of incorrect answers*, (2) *times referencing model* and (3) *the time taken to complete the task*. **Table 4** summarizes the results from the study. **Table 4** shows the average number of mistakes across the five participants as well as the average number of times participants in each group referenced the model. Although the results are not statistically significant, they demonstrate that users presented with the AR 3D model condition outperformed participants in the other two groups in terms of accuracy and comprehension to complete the task.

Table 4. Timed Section Results Summary

	Paper (n=5)	**3D AR and 2D AR model (n=5)**	**3D model only (n=5)**	**P-value**
Average amount of time (seconds)	501.2	515.8	447.4	0.286
# Average Number of Incorrect Numbers	1.6	1.6	0.8	0.563
# Average Number of Times Referencing the Model	6.60	9.00	4.200	0.174

5.2 Accuracy

Accuracy was measured by the number of wrong answers given by the participants during the timed portion of the study as well as their perception of accuracy in the exit survey. The results were analyzed using ANOVA one-way statistics. **Table 5** summarizes the results relating to accuracy in the study.

Table 5. Summary of Accuracy Results

	Paper	**3D AR + 2D AR model**	**3D model only**	**p-value**
# of Incorrect Answers	1.6	1.6	0.8	0.563
Exit Question #4	4.2	3.7	2.2	0.032

5.2.1 Participants' Accuracy during Timed Portion

During the timed portion of the study, the participants answered questions about the model. The mean number of incorrect answers are summarized in **Table 4** and included in **Table 6** in more detail. For paper condition (M= 1.6, SD= 2.08) and 3D AR and 2D AR model condition (M= 1.6, SD= 0.55), participants answered incorrectly twice the amount of questions than users presented with the 3D model only (M= 0.8, SD= 0.84). These results are not statistically significant F=0.60, p=0.56, this is shown in **Table 7**.

Table 6. Average Number of Mistakes per condition

Condition	**N**	**Mean**	**StDev**	**95% CI**
Paper	5	1.600	2.074	(0.305, 2.895)
3D AR + 2D AR model	5	1.600	0.548	(0.305, 2.895)
3D model only	5	0.800	0.837	(-0.495, 2.095)

Table 7. Analysis of Variance for Number of Mistakes

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Condition	2	2.133	1.067	0.60	0.563
Error	12	21.200	1.767		
Total	14	23.333			

5.2.2 Exit Survey Question 4- Participant Perception of Accuracy

Exit Question 4 accounted for the participants' perception of how many wrong answers they believed that they gave during the timed portion of the survey questions. This was measured by using a seven point Likert scale (1=no wrong answers, 7= a lot of wrong answers). The analysis of variance (**Table 9**) showed that the effect of using AR for perception of accuracy was significant F= 4.68, p= 0.032. Participants in the 3D model only condition (M= 4.2, SD= 0.84) believed that they gave few wrong answers, this can be seen in **Table 8**. Meanwhile, participants in the 2D and3D model (M=3.7, SD=1.57) and paper conditions (M=2.2, SD =0.57) believed that they gave more incorrect answers during the timed portion of the study.

Table 8. One-Way ANOVA for Participant Perception of Accuracy

Condition	N	Mean	StDev	95% CI
Paper	5	4.200	0.837	(3.151, 5.249)
3D AR + 2D AR model	5	3.700	1.565	(2.651, 4.749)
3D AR model only	5	2.200	0.570	(1.151, 3.249)

Table 9. Analysis of Variance for Participant Perception of Accuracy

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Condition	2	10.83	5.417	4.68	0.032
Error	12	13.90	1.158		
Total	14	24.73			

5.3 Comprehension

Participant comprehension was measured by how many times the users referenced the roof deck detail model as well as by end survey questions. The end survey questions included questions such as if the model was difficult to understand, if the questions were asked clearly, and difficulty finding necessary information from the model. **Table 10** summarizes the results of the comprehension section. In general, the users that were in the 3D model group understood the model and the information presented to them more clearly than participants in the paper or the 3D AR and 2D AR model groups.

Table 10. Summary table of Comprehension Results.

	Paper	**3D AR and 2D AR model**	**3D model only**	**p-value**
# of Times Referencing the Model	6.6	9	4.2	0.174
Exit Question #1	*4*	2	2	0.026
Exit Question #2	4.2	3.7	2.2	0.032
Exit Question #5	3.6	*2.8*	1.7	0.173

5.3.1 Participants' Comprehension during Timed Portion

Comprehension was measured by participants' ability to find the information they needed by the number of times that the user referenced the model. This was done with the assumption that there is an inverse relationship with comprehension and times referencing the model. The participant would reference the model more often if they had problems understanding the roof deck model and the information presented to them. The participants referenced the model for the paper condition (M=6.6, SD=3.78), 3D AR and 2D AR model (M=9, SD=5.15), and the 3D model only (M=4.20, SD=1.30), this can be seen in **Table 11.** The results in **Table 12** show that they were not statistically significant (F=2.03, p=0.174), but participants 3D model condition referenced the model the least amount of times, while users with the 3D AR and 2D AR model condition referenced the model the most amount of times.

Table 11. One-Way ANOVA for Number of Times Referencing the Model

Condition	**N**	**Mean**	**StDev**	**95% CI**
Paper	5	6.60	3.78	(2.93, 10.27)
3D AR + 2D AR	5	9.00	5.15	(5.33, 12.67)

model				
3D AR model only	5	4.20	1.304	(0.533, 7.867)

Table 12. Analysis of Variance for Number of Times Referencing the Model.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Condition	2	57.60	28.80	2.03	0.174
Error	12	170.00	14.17		
Total	14	227.60			

5.3.2 Exit Survey Question 1- Comprehending the Roof Deck Model

Question 1 from the Exit Survey measured the degree of difficulty users had understanding the image presented to them (1= easy to understand, 7= difficult to understand). The results from the Question 1 (**Table 13**) show that participants with the paper condition (M=4, SD=1.41) believed that the roof deck model was more difficult to understand than participants with the 3D AR and 2D AR model (M=4, SD=1.23) and 3D model only (M=2, SD=0.71). The results from the analysis of variance in **Table 14** were statistically significant (F=5, p=0.026) and demonstrate that both conditions featuring AR with the Hololens allowed users to understand the images presented to them more clearly than the image presented in the 2D paper condition.

Table 13. One Way ANOVA for End Survey Question 1

Condition	N	Mean	StDev	95% CI
Paper	5	4.000	1.414	(2.875, 5.125)
3D AR + 2D AR model	5	2.000	1.225	(0.875, 3.125)
3D AR model only	5	2.000	0.707	(0.875, 3.125)

Table 14. Analysis of Varience for End Survey Question 1

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Condition	2	13.33	6.667	5.00	0.026
Error	12	16.00	1.333		
Total	14	29.33			

5.3.3 Exit Survey Question 2- Clarity of Questions

Question 2 focused on degree of how clear the questions were asked during the timed portion of the study (1= clear, 7=unclear). It can be seen in **Table 15**, that participants given the paper condition (M=4.2, SD=1.92) thought that the questions were not asked as clearly as participants given the 3D AR and 2D AR model (M=3, SD=1.41) or 3D model only (M=1.7, SD=0.84). The results for section were not statistically significant with F=3.66 and p=0.057 (see **Table 16**), but participants with the AR conditions thought that the questions were more clear than the participants with only the paper condition.

Table 15. One Way Anova for End Survey Question 2

Condition	N	Mean	StDev	95% CI
3D AR + 2D AR model	5	3.000	1.414	(1.577,4.423)
3D AR model only	5	1.700	0.837	(0.277,3.123)
Paper	5	4.200	1.924	(2.777,5.623)

Table 16. Analysis of Varience for End Survey Question 2

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Condition	2	15.63	7.817	3.66	0.057
Error	12	25.60	2.133		
Total	14	41.23			

5.3.4 Exit Survey Question 5- Ease of Finding Information

Question five measured the level of difficulty to find important information with roof deck model (n=1 easy, n=7 difficult). The results of the analysis of variance are shown on **Table 17** are non-significant F=2.04, p=0.173. However, the mean score this question (shown in

Table 18) show that participants with the 3D AR model only score (M=1.7, SD=0.45) was lower than the scores given by participants with 3D AR and 2D AR model (M=2.8, SD=1.79) and paper only (M=3.6, SD=1.82). This means that participants with the 3D model only believed that it was relatively easier for them to find the information they needed compared to the other two test groups.

Table 17. One Way ANOVA for End Survey Question 5

Condition	**N**	**Mean**	**StDev**	**95% CI**
3D AR + 2D AR model	5	2.800	1.789	(1.344, 4.256)
3D AR model only	5	1.700	0.447	(0.244, 3.156)
Paper	5	3.600	1.817	(2.144, 5.056)

Table 18. Analysis of Varience for End Survey Question 5

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Condition	2	9.100	4.550	2.04	0.173
Error	12	26.800	2.233		
Total	14	35.900			

5.4 Speed

Table 19 shows that on average the time it took to complete the three conditions were: the 2D paper drawing (M= *501 s, SD=111 s)*, 2D display and the 3D model (M=*516 s, SD= 105 s)*, and 3D model display (M= *447* s, SD= 100 s). While the results demonstrate that the participants in the groups using the AR conditions performed the timed portion faster than the users with the paper condition, the results were not statistically significant (F= 0.58, p= 0.29), this can be seen in **Table 20** below.

Table 19. One-Way ANOVA for Amount of Time

Condition	N	Mean	StDev	95% CI
Paper	5	501.2	111.4	(398.4,604.0)
3D AR + 2D AR model	5	515.8	104.8	(413.0,618.6)
3D model only	5	447.4	99.8	(344.6,550.2)

Table 20. Analysis of Variance for Amount of Time

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	2	25954	12977	1.31	0.286
Error	27	266962	9887		
Total	29	292915			

5.4.1 Exit Survey Question 3- Participant Perception of Time

Question 3 asked participants how quickly they believed that they completed the timed portion (n=1 quick, n=7 slow). On average, participants believed that they completed the timed portion faster when they used the AR conditions. As can be seen in **Table 21**, the participants using the 3D model only condition (M=3.9, SD=1.03), believed that they completed the timed portion faster compared to participants wearing the 3D AR and 2D AR model (M=5.4, SD1.41) and the 2D drawing on paper (M=5.7, SD=1.64) conditions. These results, match closely with the results of the timed portion, but the results were in **Table 22**, were not statistically significant (F=2.31, p=0.14).

Table 21. One Way Anova for End Survey Question 4

Condition	N	Mean	StDev	95% CI
3D AR + 2D AR model	5	5.400	1.517	(4.016, 6.784)
3D AR model only	5	3.900	1.025	(2.516, 5.284)

Paper	5	5.700	1.643	(4.316, 7.084)

Table 22. Analysis of Variance for Question 3

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Condition	2	9.300	4.650	2.31	0.142
Error	12	24.200 2.017			
Total	14	33.500			

5.5 User Preference of 2D model vs 3D model in AR

Participants in the 3D AR and 2D AR model display had an additional question asking whether or not they relied more on the 2D display or the 3D display (n=1 3D model, n=7 2D model). The users in this group rated the question M=1.8, SD=0.84, showing their preference for the 3D model display over the 2D model display. Additional qualitative feedback from participants included that it was easier to see details such as materials in the 3D model and that 2D drawing was confusing for participants.

CHAPTER 6: DISCUSSION

6.1 Accuracy and Comprehension

The goal of this thesis was to build on past studies and determine which levels of visual fidelity improve user performance for assembly and inspection tasks while wearing AR HMD systems. The results from this study were consistent with Hypothesis 1, which was about which media display would improve the accuracy and comprehension of the users looking at a roof deck model. Participants with the 3D AR model condition had better accuracy and comprehension than participants with other media display. Both AR conditions in this study either had the same level of accuracy (less errors) or better accuracy than the control paper condition. This is consistent with findings in past studies. Baird (1999) found that when participants had improved accuracy (less errors) when using AR conditions for assembly tasks. Researchers Hou and Wang (2013), also found that participants had less errors while performing Lego assemblies when using AR conditions over traditional paper displays. Researcher Tang (2003) tested HMD and AR conditions and found that users using the AR condition had fewer errors than toy block assemblies. The results that the participants had a better accuracy and comprehension by using the 3D AR model only (less errors and less referencing of the model) contradicts some findings from a past study (Radkowski 2015) where users had higher errors (less accuracy) while using 3D AR models, because it can take longer for participants to adjust and comprehend 3D models. It is possible that for this study, participants were given enough time to understand the roof deck AR model and did not make as many errors during the timed portion.

The results from this study validate findings from other studies such as Wang and Dunston 2008, which found that using a 3D AR model can reduce the cognitive load and aid spatial cognition of the user. Researcher Dawood (2008) found that by presenting participants with richer information, 4D model vs 2D model, participants had improved understanding of their assembly task. While participants in this study were presented with a 2D and/or 3D representation of a roof deck model, Dawood's findings are consistent with the results from this thesis, participants gave these comments:

- "The 3D model was definitely easier to look at and see individual components and details…"
- "Much easier to see components in 3D model, especially when colored"
- "3D model is more clear and easy to see background and surrounding, but I feel the 2D drawing is confusing"
- "I think it is more worthwhile to use the 3D model when it can show you more than just 1 detail at the same time. For example, it will be more time efficient to look at one 3D model having multiple detail from different angles rather than having to look at multiple pages of details."

The feedback given by the participants for this thesis, compliments findings from Tang (2003) that AR conditions add context to information provided to users. According to researchers Ellis and Whitehill (1996), qualitative information- such as pictures, in the case of this thesis 3D and colored model, can improve comprehension of information presented to users. This is also validated by Shabbari et al

(2016), a study that students were able to identify with greater accuracy parts in a roof and masonry case study by using AR video conditions.

6.2 Time

The results based on time for this study are not statistically significant, but suggest that participants in the 3D AR model display had the fastest completion time compared to the other two conditions. Participants in the other AR condition with the 2D AR and 3D AR display performed the slowest. Past studies, such as Baird (1999) suggested that AR conditions would lower completion time for assembly tasks due to less movement required to find information and complete tasks due to information being displayed in front of the user. For this study, participants did not have assembly tasks, instead they had to recall specific information from the roof deck model that users would need to assemble and inspect the roof deck. Also, participants using either of the two AR conditions for this study had to get up and move around the AR model to see certain parts of information, while participants with the 2D paper condition were able to remain seated and find the information directly in front of them. These findings suggest that the 3D AR model only display had lower completion time due to the model having more details available for the users, despite having to walk around the model to find specific information.

The results of this study partly contradict the results from other studies since participants in the 2D AR and 3D AR group took 3% (14 seconds) longer to complete the timed portion than the paper condition. In past studies, such as Henderson and Feiner (2011), participants were able to complete tasks faster using AR displays compared to other traditional media display of maintenance and assembly instructions. Baird (1999) tested five conditions for the assembly of a motherboard with fifteen participants for each condition and found that participants had faster times with the two AR conditions over conditions with Computer-Aided Instructions (CAI) and paper. In 2006, Wang and Dunston conducted an experiment comparing monitor and HMD display AR conditions, in this case, the HMD AR condition resulted in less time to complete the tasks. Graduate students involved in steel column inspection performed their tasks faster using an ARCam compared to a regular TSI (Shin and Dunston 2009). While Dawood's study (2008) did not test any AR conditions, the study tested for 2D vs 4D conditions, and found that participants with the 4D condition were able to complete a higher percentage of the assembly since it took participants in the 2D condition more time to analyze and understand the model presented to them. While part of the results from the study conducted in this research contradict past studies, the results suggested by the 3D AR condition only are consistent with similar past studies.

The results for H2 suggest that participants who used the combination of 2D AR display and the 3D AR model had the slowest completion time, which is the opposite of H2. It is speculated that participants in the 2D AR and 3D AR model display condition had the slowest completion time due to information overload. According to the split-attention principle, instruction guides should avoid using instructions that require users to split their attention between different sources of information (Ayers 2014). In case of this study, it means that participants had to spend more time trying to understand and match corresponding information in the 2D AR display to the 3D AR model. This is consistent with the idea of ‘selective looking’, that participants are unable to process two sources of information at the same time (Neisser 1975). Participants that only had 2D AR and 3D AR model stated that they mostly relied on the 3D AR model and one participant stated that they found the 3D model easy to understand due to the more detail, but found the 2D AR display confusing.

6.3 Limitations and Future Research

Due to the nature of this pilot study, further research needs to be conducted before making solid conclusions about the results in this study. There were fifteen participants in this study with varying degrees of construction-related knowledge and expertise with level of detail drawings. Most of the participants were between their second and fourth year of college, which means they are not practitioners and are not construction laborers. Also, although not all participants in this study were familiar with AR and HMD systems, it is possible that testing a population with different age groups may produce different results based on participants’ experience with technology. For future studies, participants with higher levels of construction knowledge should be included. A larger pool of participants with more experience might show different results than the results in this thesis’s study.

Another limiting factor in this study was the use of the Hololens as an AR HMD system. The Hololens is a device designed for video games not for assembly or inspection tasks for construction workers. There are prototypes for AR HMD systems being developed for construction workers such as DAQRI. In the future, a study could be conducted to compare the performance of DAQRI (or other prototypes developed for construction tasks) versus Hololens using accuracy, comprehension, and time metrics.

The software Unity was used to add the AR model application to the Hololens is also mainly used to develop video games for the Hololens. Currently, there is an application on the Hololens available that is compatible with SketchUp, however the SketchUp app did not have all the components necessary for this study. For this study, the researcher had to use three different software (SketchUp, Blender, and Unity) and export information between them to finally upload a 3D AR model on the Hololens for display (please see Appendix B). In the future, SketchUp or other software such as Revit may develop applications with more features available in the Hololens or other AR HMD systems.

Applications available on the Hololens allow users to interact with 3D AR objects and rotate and scale them accordingly. For this study, the AR models displayed to the participants were static and users could not interact with the objects once the objects were displayed. According to the definition of AR, this study was not truly augmented reality since participants were not able to interact with the AR models. One participant wrote, “I thought all the text was on the two sides- missed the "apply sealant" because of this,” even though all participants in the two AR conditions walked around all sides of the AR model and the sealant was displayed in a bright color for easy identification, see Figure 29. In the future, text used in the model could also be programmed to rotate so that users can always read the text no matter the angle of the model. In future studies, the objects can be coded to enable rotating and scaling features.

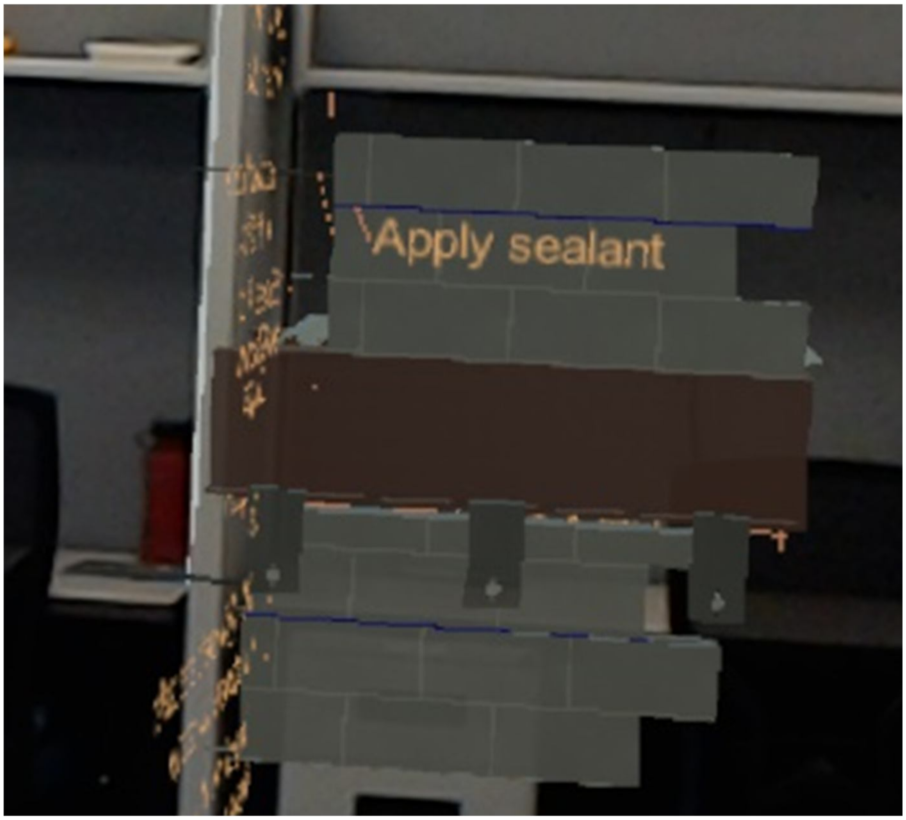


Figure 30. Side view of 3D display showing where to apply sealant.

In past studies, participants experienced overheating and low battery lives with AR HMD systems. Participants did not experience low battery life or overheating with the Hololens since these issues have been reduced with technology advances. This has been done by having a smaller viewport for augmented reality. Participants commented that the quality and detail from the AR displays was greater than the; however participants had to move around or turn their heads to see the entire AR model. However, in some cases this made viewing the entire roof deck model hard for participants. In the case of participants who had two displays- the 2D AR and 3D AR model displays, these users had to move around and pivot their heads to be able to see the displays. They were unable to see the both displays at the same time. This is a possible explanation for slower completion times for those participants. In the future, studies could expand the viewing window or make the AR components smaller and determine whether participants using 3D AR and 2D AR model display have improved performances and comprehension of the information.

One limitation of this study was caused by timing. Participants using the 2D drawing on paper had a timing advantage over participants in the other two treatment options. For example, participants in the two AR conditions had to put the Hololens on and then take it back off to answer the questions during the timed portion, meanwhile participants in the 2D drawing on paper only had to flip over the drawing. In addition, participants in the paper treatment condition were exposed to analog media only, while participants in the two other conditions had to switch from digital to analog media. In a future study, participants using analog conditions could simulate putting on the HMD system and taking it back to remove some of the time bias or require participants in AR treatment options to fill out questionnaires electronically instead of answering the questions on paper.

For this study, participants did not assemble the roof deck model. Instead participants inspected the model and answered specific questions about materials that make up the roof deck component. The size of the 3D AR model was about 4ftx3ftx5ft. (LxWxH), making the model scale of this study larger than past studies which featured Lego assemblies and tabletop models. This study’s 2D roof deck drawing and the 3D roof deck model were a more accurate representation of level of detail drawings used by construction laborers for assembly and inspection tasks.

In future studies, participants could procure materials and assemble the entire roof deck model with the information presented in the AR models to resemble laborer assembly. Future studies could also test participants' situational awareness, depth perception, and measure head movements. Surveys could include questions about comfort, fatigue, and distractions while wearing the AR HMD. These considerations would permit a Smart Safety Glasses prototype to be developed so that an AR HMD system can be successfully implemented for use by construction workers doing assembly and inspection tasks.

CHAPTER 7: Conclusion

Levels of visual fidelity could impact the comprehension and performance of construction workers. The use of AR HMD systems should be studied further to improve worker comprehension. The outcomes of this study suggest that users have improved accuracy and comprehension while looking at 3D AR roof connection model. The results also suggest that users prefer to use a 3D AR model over 3D AR and 2D AR model due to possible information overload. While this study did not feature true AR models since participants were not able to interact with the virtual models presented to them, these results show promising potential for AR HMD systems to improve user comprehension for inspection and assembly tasks in construction. Further studies with more participants should be conducted before implementing AR HMD systems in the construction sector.

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APPENDIX A

Background Questions

Are you familiar with augmented reality?

Have you used augmented reality before?

Have you used a Head Mounted Display system before?

Years of experience working in the construction industry (including internships):

Level of familiarity reading construction documents:

1 – 2 – 3 – 4 – 5 – 6 – 7

None Very familiar

What is your experience and familiarity reading construction documents and detail drawings?

How long does it usually take you to go through construction documents and find level of detail drawings?

What goes through your mind when looking at detail drawings? Construction drawings?

How much of your knowledge about construction detail drawings did you learn from work experience?

1 – 2 – 3 – 4 – 5 – 6 – 7

None All

Please explain: ________________

Questions about the Model

1. How many rows of CMUs are in the model?
2. What is the size of horizontal reinforced diameter links?
3. What are the specifications for vertical reinforcement?
4. The “gap” is located under the _____? (Where is the gap located?)
5. What size are the wide plates in the model?
6. How far apart should #3 spacers be placed?
7. How many lateral bracing bars can be seen in the model?
8. What are the bolt options for shear transfer?
9. The cont. plate sits on top of what component?
10. How many pairs of horizontal joint reinforcement are shown in the model?
11. The deck sheet sits on top of the perimeter member and the _____?
12. What kind of materials (construction components) are used for the roof deck detail?
13. Where does the sealant need to be applied? (use numbered diagram as reference)

Exit Questions

Using a scale from 1 through 7 please rate the questions below

1. How difficult were the images presented to you to understand?

   1 – 2 – 3 – 4 – 5 – 6 – 7

   Easy Difficult

2. Were the questions asked to you clearly?

   1 – 2 – 3 – 4 – 5 – 6 – 7

   Clear Unclear

3. How quickly do you think you finished the questionnaire?

   1 – 2 – 3 – 4 – 5 – 6 – 7

   Quick Slow

4. How many wrong answers do you think you gave?

   1 – 2 – 3 – 4 – 5 – 6 – 7

   None A lot

5. How difficult was it for you to find the information you needed?

   1 – 2 – 3 – 4 – 5 – 6 – 7

   Easy Difficult

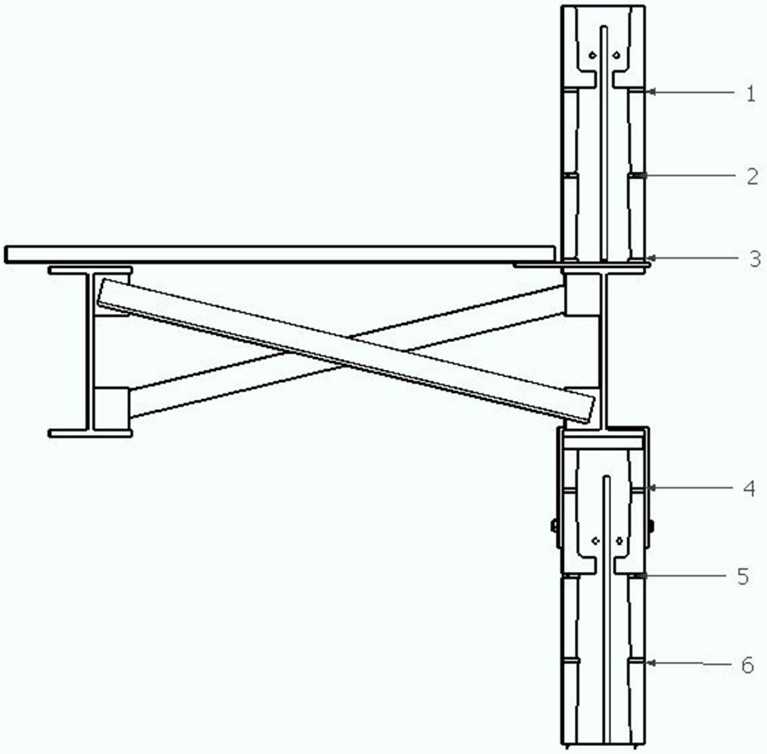
If you used, the 3D model and 2D view at the same time:

Which model did you use the most?

1 – 2 – 3 – 4 – 5 – 6 – 7

3D model 2D view

Numbered Diagram



Appendix B

Step 1: Google SketchUp was used to create the level of detail drawing using a model found in the SketchUp 3D Warehouse library.

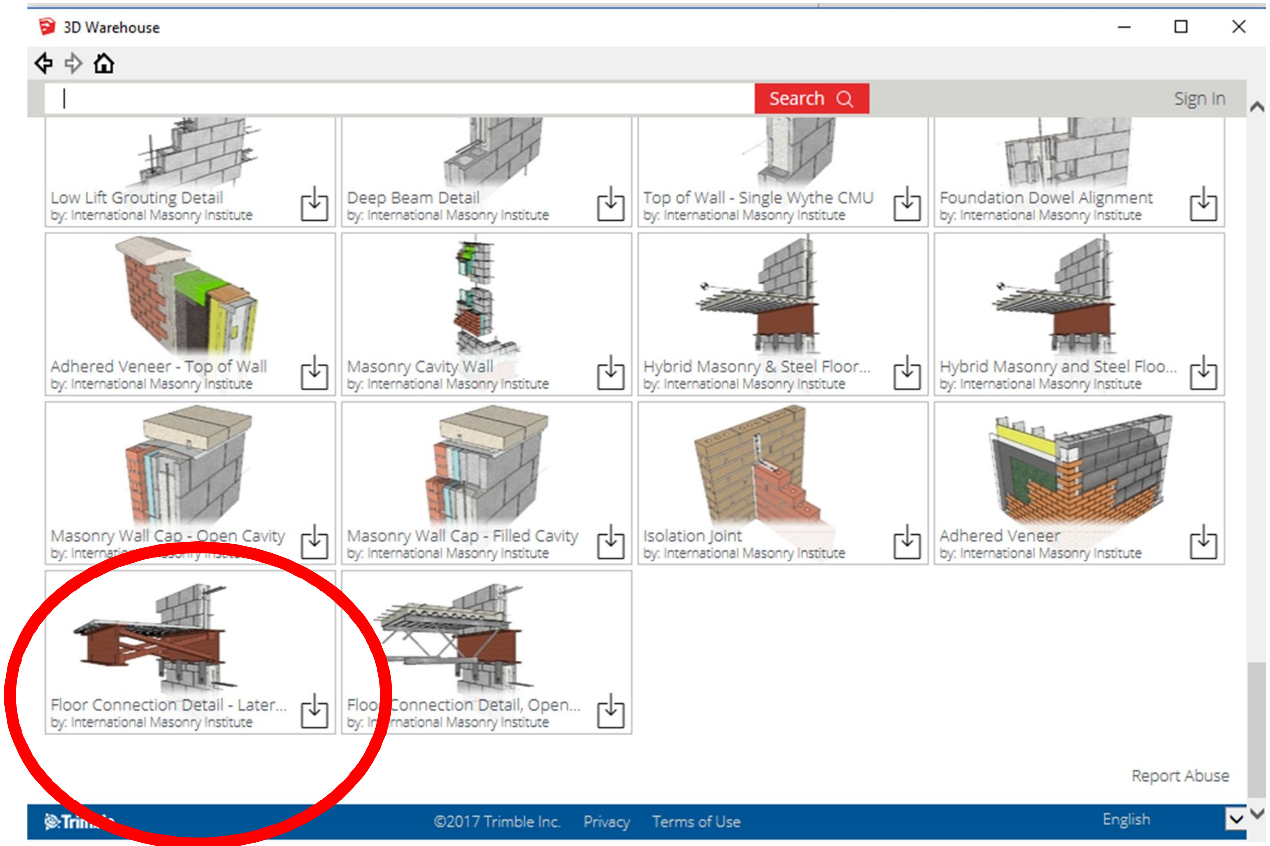


Figure 31. Image from Google SketchUp 3D Warehouse library.

Step 2: The SketchUp model .dae file was exported to Blender. This was done so that AR model could be displayed in color.

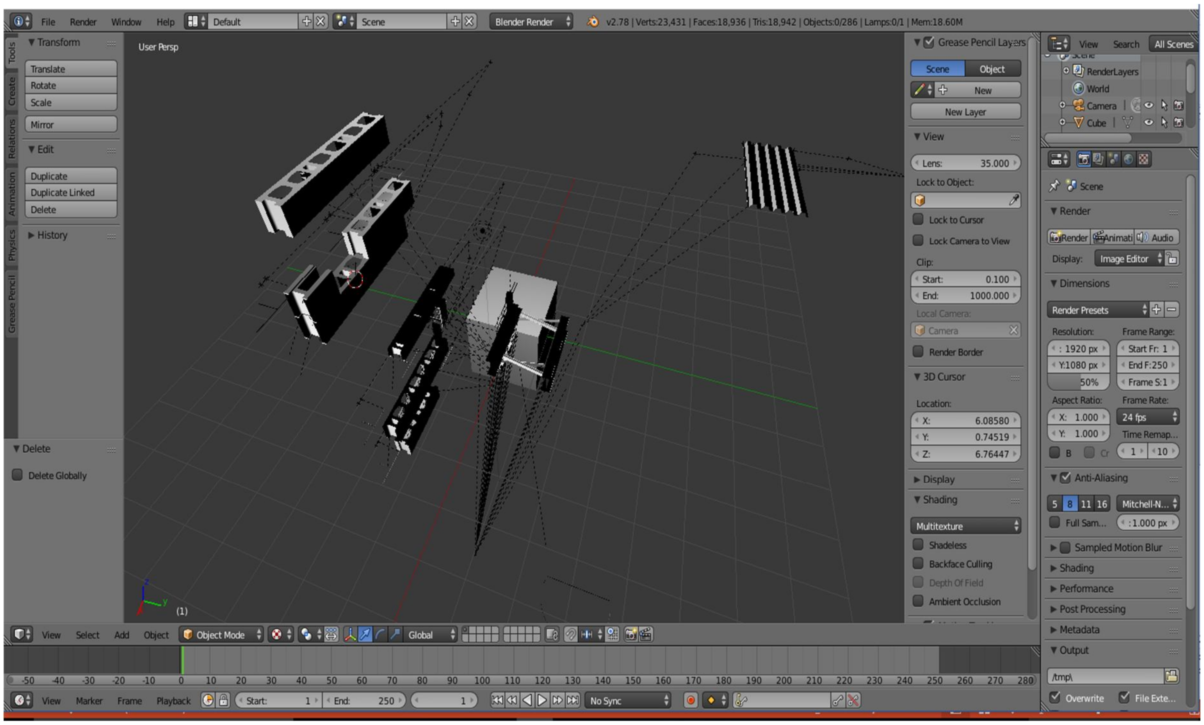


Figure 32. Image of imported Roof Deck Model in Blender

Step 3: The SketchUp model was imported as a .skp file to Unity. The textures folder created from Blender were imported into the Unity model as an .fbx file.

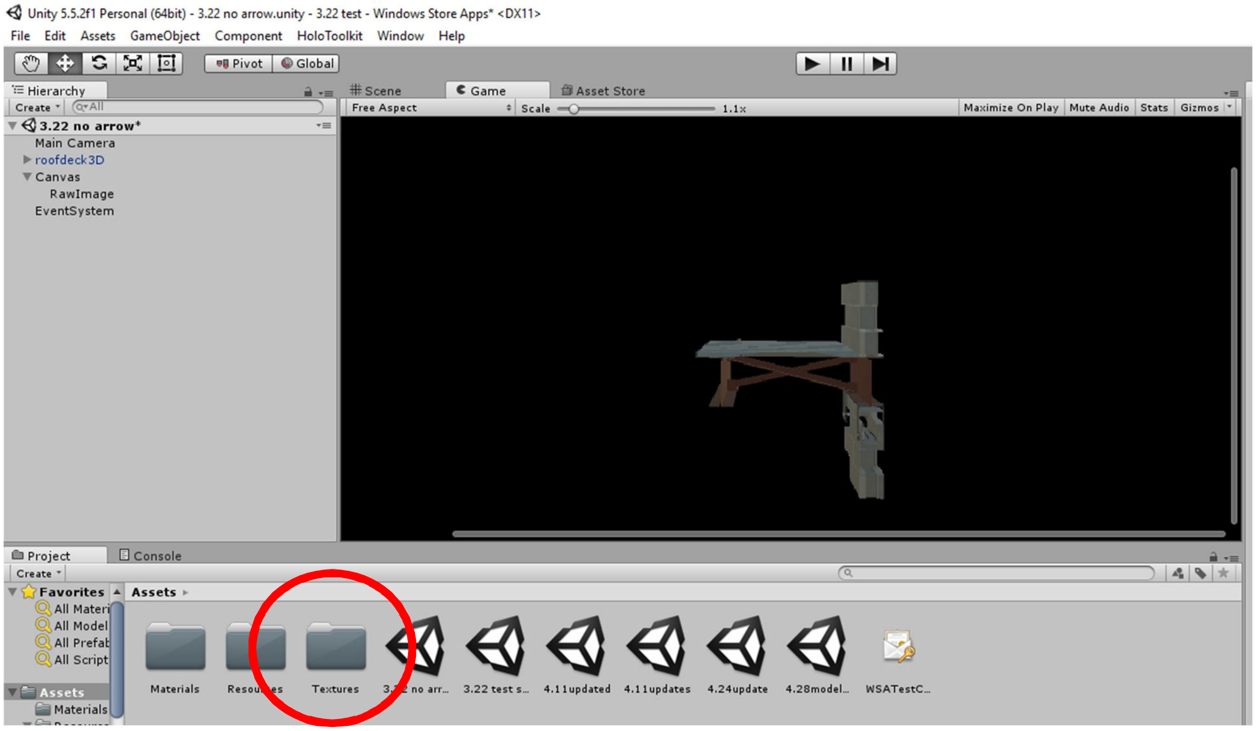


Figure 33. Image from Unity of the Roof Deck model.

Step 4: The model was annotated like a level of detail drawing construction drawing.

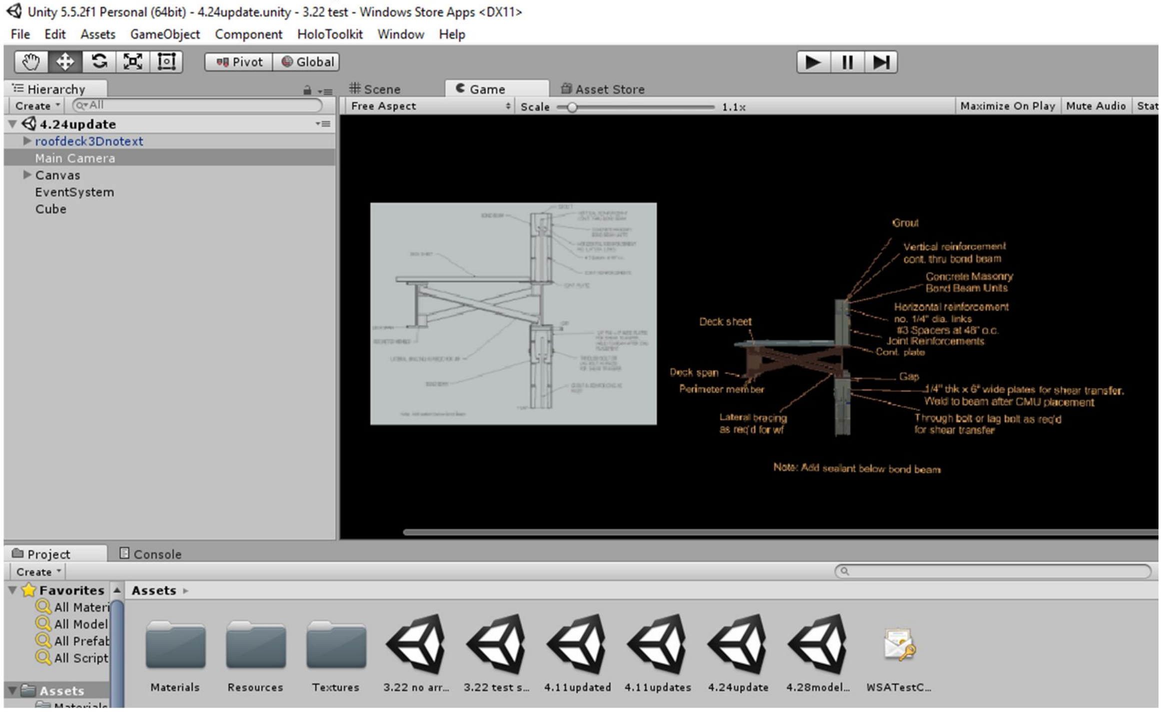
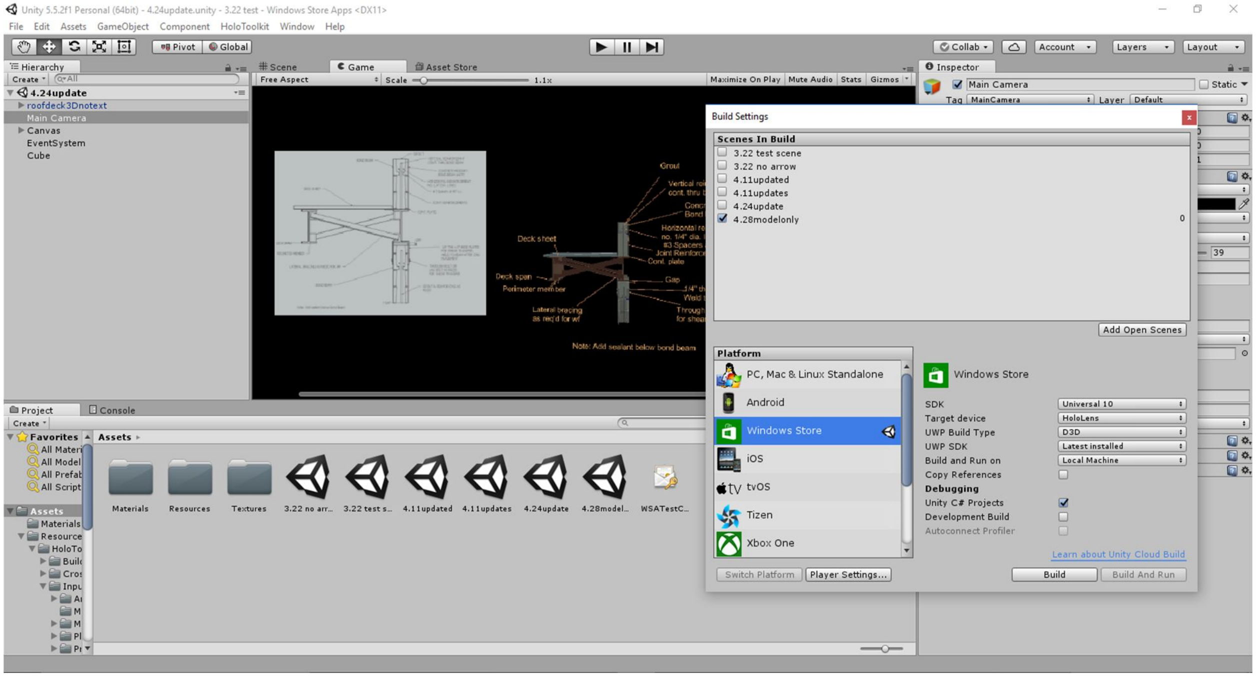


Figure 34. Image of Roof Deck Model in Unity.

Step 5: Once the model was finalized in Unity, the model was saved and built as an application compatible with Hololens.

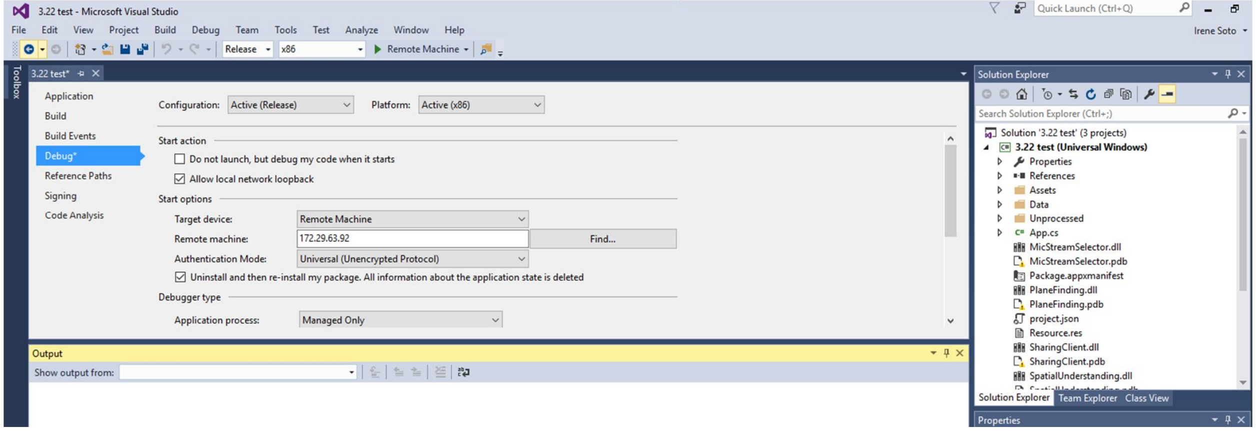


Scenes In Build
☐ 3.22 test scene
☐ 3.22 no arrow
☐ 4.11updated
☐ 4.11updates
☐ 4.24update
☑ 4.28modelonly 0

Windows Store
SDK Universal 10
Target device HoloLens
UWP Build Type D3D
UWP SDK Latest installed
Build and Run on Local Machine
Copy References ☐
Debugging
Unity C# Projects ☑
Development Build ☐
Autoconnect Profiler ☐

Figure 35. The roof deck model being saved as an application.

Step 6: The application was deployed using Microsoft Visual Studio.



Configuration: Active (Release) Platform: Active (x86)

Start action

☐ Do not launch, but debug my code when it starts

☑ Allow local network loopback

Start options

Target device: Remote Machine

Remote machine: 172.29.63.92

Authentication Mode: Universal (Unencrypted Protocol)

☑ Uninstall and then re-install my package. All information about the application state is deleted

Debugger type

Application process: Managed Only

Figure 36. Image of application about to be deployed in Microsoft Visual Studio

Figure 37. Student using Hololens after the roof deck model is deployed.

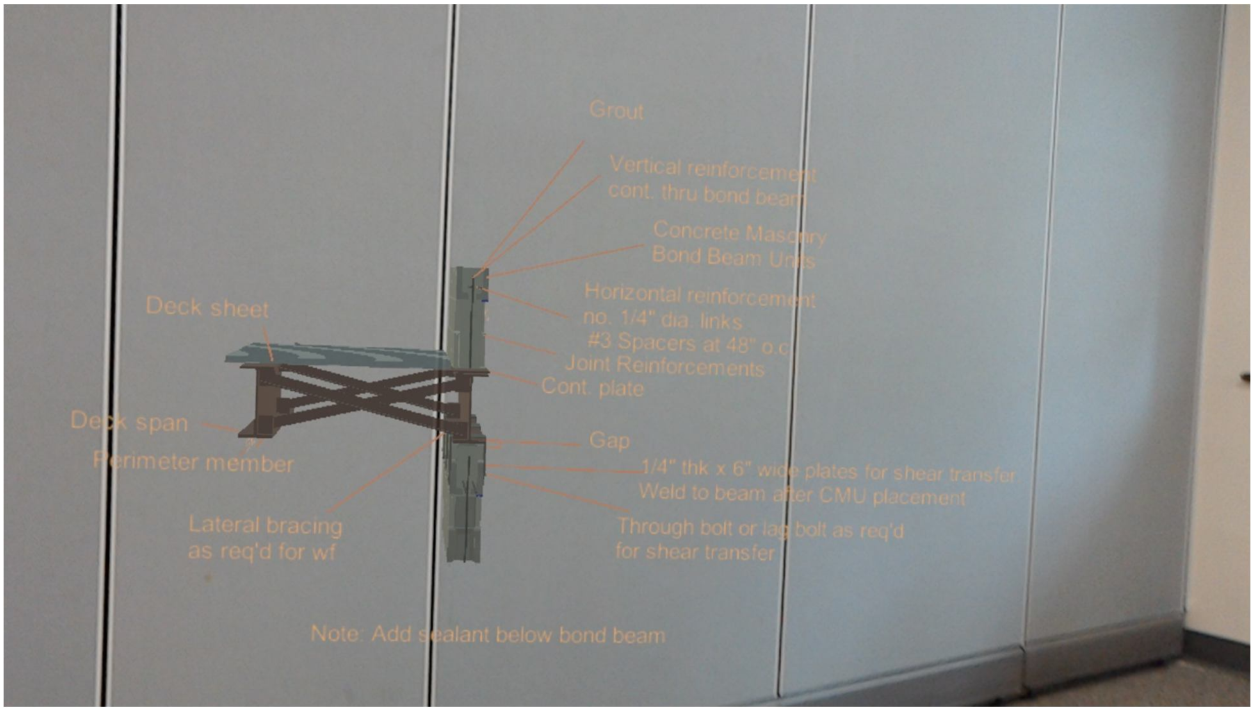


Figure 38. Roof deck model from the student’s point of view.