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Overcoming the limitations of commodity augmented reality head mounted displays for use in product assembly

by

Jack Miller

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Program of Study Committee:
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Stephen Gilbert
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ABSTRACT

Numerous studies have shown the effectiveness of utilizing Augmented Reality (AR) to deliver work instructions for complex assemblies. Traditionally, this research has been performed using hand-held displays, such as smartphones and tablets, or custom-built Head Mounted Displays (HMDs). AR HMDs have been shown to be especially effective for assembly tasks as they allow the user to remain hands-free while receiving work instructions. Furthermore, in recent years a wave of commodity AR HMDs have come to market including the Microsoft HoloLens, Magic Leap One, Meta 2, and DAQRI Smart Glasses. These devices present a unique opportunity for delivering assembly instructions due to their relatively low cost and accessibility compared to custom built AR HMD solutions of the past. Despite these benefits, the technology behind these HMDs still contains many limitations including input, user interface, spatial registration, navigation and occlusion.

To accurately deliver work instructions for complex assemblies, the hardware limitations of these commodity AR HMDs must be overcome. For this research, an AR assembly application was developed for the Microsoft HoloLens using methods specifically designed to address the aforementioned issues. Input and user interface methods were implemented and analyzed to maximize the usability of the application. An intuitive navigation system was developed to guide users through a large training environment, leading them to the current point of interest. The native tracking system of the HoloLens was augmented with image target tracking capabilities to stabilize virtual content, enhance accuracy, and account for spatial drift. This fusion of marker-based and marker-less tracking techniques provides a novel approach to display robust AR assembly

instructions on a commodity AR HMD. Furthermore, utilizing this novel spatial registration approach, the position of real-world objects was accurately registered to properly occlude virtual work instructions. To render the desired effect, specialized computer graphics methods and custom shaders were developed and implemented for an AR assembly application.

After developing novel methods to display work instructions on a commodity AR HMD, it was necessary to validate that these work instructions were being accurately delivered. Utilizing the sensors on the HoloLens, data was collected during the assembly process regarding head position, orientation, assembly step times, and an estimation of spatial drift. With the addition of wearable physiological sensor data, this data was fused together in a visualization application to validate instructions were properly delivered and provide an opportunity for an analysist to examine trends within an assembly session. Additionally, the spatial drift data was then analyzed to gain a better understanding of how spatial drift accumulates over time and ensure that the spatial registration mitigation techniques was effective.

Academic research has shown that AR may substantial reduce cost for assembly operations through a reduction in errors, time, and cognitive workload. This research provides novel solutions to overcome the limitations of commodity AR HMDs and validate their use for product assembly. Furthermore, the research provided in this thesis demonstrates the potential of commodity AR HMDs and how their limitations can be mitigated for use in product assembly tasks.

CHAPTER 1. INTRODUCTION

Purpose of Work

The goal of this research was to develop novel computer graphics techniques to mitigate the hardware limitations of commodity Augmented Reality (AR) Head Mounted Displays (HMDs) for use in product assembly tasks. To evaluate if these techniques were successful, an AR assembly application was developed to test the functionality. Furthermore, data collected during the assembly application was collected to further evaluate the success and proper delivery of assembly work instructions.

Motivation

Manual product assembly encompasses a large portion of resources, time, and cost in the manufacturing of engineered products. Among industry and military organizations alike, manufacturing, maintenance, and assembly presents a multibillion-dollar industry. In 2018 alone, The United States Military proposed a defense budget of $639 billion (Office of the Under Secretary of Defense (Comptroller), 2018a). Of this extraordinary amount, over a third, $272 billion, was allocated for Operations and Maintenance. In addition, the budget overview specifically states that the budget request includes additional funding for logistics, maintenance, training and spares (Office of the Under Secretary of Defense (Comptroller), 2018b). Due to the large amount of spending on product assembly related tasks, any opportunity to reduce these costs would have a significant impact on industry and the military.

Augmented Reality (AR) is an emerging technology that can have substantial impact on training efficiency and effectiveness for assembly tasks. In fact, Henderson & Feiner found that AR may reduce time and errors by as much as 50% for maintenance and assembly operations (Henderson & Feiner, 2011). Essentially, AR consists of computer-generated visual information overlaid on top of a view of the real world. These computer-generated visuals are often delivered via a tablet or Head Mounted Display (HMD). Traditionally, Hand-Held Displays (HHDs), such as a tablet or smartphone, have been the preferred method of delivering AR content due to technological constraints and commercial availability. HMDs of the past tended to be expensive custom-built solutions for research purposes and not viable for commercial use. However, in recent years several commercially available AR HMDs have come to market and show promise for use in assembly applications. The main advantage of AR HMDs over HHDs is that they overlay the computer-generated visuals directly over the users view of the real world while allowing them to remain hands free. This is ideal for assembly training as the user is likely to be working with their hands while receiving work instructions.

However, due to the emerging nature of this technology, many of the components that make up these AR HMDs are still under development. Therefore, there are many limitations within the technology that must be mitigated including input methods, user interface, spatial registration, navigation and occlusion. Spatial registration and occlusion are especially critical to assembly applications as the work instructions must be presented accurately with the proper depth perception cues. While there have been many advancements since the introduction of AR in the early 1990s, many of these hardware limitations have restricted the widescale adoption of AR in a variety of fields including product assembly. Understanding how to mitigate these limitations would allow for greater use and effectiveness of this technology, namely for assembly tasks. These limitations are especially pertinent to assembly tasks as it is important to ensure the user receives accurate work instructions to minimize cost and errors.

Specifically, this paper discusses the novel techniques, notably those regarding spatial registration and occlusion, employed to mitigate the limitations of commodity AR HMDs for use in an AR work instruction assembly application.

This application was also used to conduct a user study comparing the effectiveness of work instructions delivered via an AR HMD, AR tablet, tablet model-based instructions and desktop model-based instructions (Hoover, Miller, Gilbert, Winer, & Davies, 2018). For the study, due to all the custom enhancements made to the HMD system, it was necessary to validate that work instructions and other parts of the system were functioning together properly. To accomplish this, a separate data visualization application was developed. This application fused data collected from the HoloLens device, an Empatica E4 physiological wrist sensor and errors via post-process grading of the users' completed assembly. This fusion through the data visualization application allowed the analyst to better understand the training session and identify any issues in the AR application. In addition to validating the work instructions, the analyst may also discover new high-level trends about the user and the training environment through the fusion of these data sources. Through the delivery and validation of these work instructions, this work seeks to enhance the effectiveness of training for assembly operations by mitigating the limitations of a commodity HMD.

Thesis Organization

Chapter 2 will include the necessary background information to understand augmented reality, the hardware involved, the limitations of the hardware and finally its use case for delivering assembly work instructions. Chapter 3 contains a journal article that will be submitted to IEEE Access. This paper focuses on the novel solutions to mitigate the limitations of commodity AR HMDs for use in product assembly. Furthermore, it provides a methodology to ensure the mitigation techniques were effective and the work instructions were accurately delivered. Chapter 4 provides the general conclusions to this work and Chapter 5 describes the future work that will further this research.

CHAPTER 2. BACKGROUND

The following background research can be broken up into the following four categories: 1) an overview of augmented reality, 2) augmented reality hardware, 3) the limitations of augmented reality head mounted displays, and 4) augmented reality for use in delivering work instructions. These topics will each be discussed in detail and will provide the complete background information regarding augmented reality, its limitations and its use in delivering assembly instructions.

Overview of Augmented Reality

Perhaps one of the earliest applications of AR could be found in a seminal paper by Caudell and Mizell in 1992 (Caudell & Mizell, 1992). The authors saw a need to deliver wiring harness instructions in a more intuitive manner and devised a system to overlay computer generated images over a view of the real assembly station. While this, and many AR hardware systems soon after it, merely provided a heads up display with limited tracking capabilities, it paved the way to more sophisticated systems of the future. This early work provided the foundations for a large field of research which helped to better understand the fundamentals of this technology and its applications. In 1997, Azuma surveyed the state of AR, providing a thorough overview of AR and its potential for the future (RT Azuma, 1997). Azuma essentially described AR as computer generated images overlaid on a viewport of the real world with three distinctive characteristics: 1) the system must combine the real and the virtual, 2) it must be functional in real time, and 3) content must be registered in 3D. This seminal paper in the late 1990’s has served as the de facto definition of AR for research purposes.

Researchers over the years have discovered a vast amount of applications for AR in a large variety of domains. By the late 1990s, Azuma had already identified many useful applications of AR including research in the field of medicine, manufacturing and repair, visualization, entertainment and the military (RT Azuma, 1997). However, with further advancements in the technology in the years following, other application areas have been identified such as gaming, personal information systems, assembly and collaboration (Krevelen & Poelman, 2010). Furthermore, many of the areas Azuma had originally identified have been extensively researched including manufacturing (Evans, Miller, Iglesias Pena, MacAllister, & Winer, 2017) and medicine (Tepper et al., 2017). What makes these domains ideal for the adoption of AR includes many factors depending on their use case, but they all derive from the need for further information in the physical world.

Augmented Reality Work Instructions Benefits

Ever since Caudell and Mizell's seminal paper exploring the use of an AR HMD for a wire harness task, extensive research has explored the benefits of AR for use in assembly and manufacturing tasks (Caudell & Mizell, 1992). The main benefits of AR for assembly can be broken up into three main categories: 1) time savings, 2) error reductions and 3) cognitive loads. The following section will elaborate on the benefits of AR delivered work instructions for these three categories.

Time Savings

AR has been shown to be an effective way of reducing the time spent on assembly tasks (Friedrich, 2002). Friedrich developed ARVIKA on this principle, which includes an AR system for mobile use in industrial applications and significantly enhanced the efficiency of assembly tasks. One particular study by Hou et al. investigated the effectiveness of using AR work instructions against traditional 2D paper instructions for a construction piping operation (Hou, Wang, & Truijens, 2015). The authors found the AR work instructions had a 50% reduction in time compared to the 2D paper instruction counterpart. Furthermore, Henderson and Feiner found similar results when they assessed work instructions delivered on an AR HMD against an untracked heads-up display and a 2D laptop display (Henderson & Feiner, 2011). It was found that AR HMD users were 47% faster than those using a 2D laptop display and 56% faster than those using a heads-up display. The significant time savings shown by these two studies show the effectiveness of AR for use in assembly tasks. The time saved equates to substantial cost savings as the operation time is a large portion of total cost for assembly tasks.

Error Reductions

Error reduction is another benefit of AR for use in assembly applications as it drastically reduces cost associated with rework and equipment malfunctions (Hou et al., 2015). Fiorentino et al. developed an AR monitor application to deliver work instructions for an assembly of an engine (Fiorentino, Uva, Gattullo, Debernardis, & Monno, 2014). The researchers analyzed the effectiveness of this system against traditional paper instructions. They found a substantial reduction in errors when utilizing the AR system against paper instructions. For some tasks the reduction was as high as 92.4%. This research shows that AR can be especially effective for complex assemblies where paper instructions do not necessarily provide a clear representation of the task. Tang et al. showed similar results when they compared the effectiveness of AR in object assembly against paper instructions (Tang, Owen, Biocca, & Mou, 2003). The researchers found an 82% reduction in errors when using the AR system. Furthermore, they noted this may be due to the AR system removing the need for users to determine the position and orientation from pictorial diagrams on paper instructions. Despite only using LEGO bricks and being less complex than the Fiorentino et al. assembly, this conclusion was consistent across both studies.

Other researchers have shown the same reduction in errors when using a variety of AR systems and devices. Sanna et al. utilized a handheld AR device to deliver work instructions for a maintenance application (Sanna et al., 2015). They found a reduction in errors and users reported favorable reviews of the system. Blattgerste et al explored the use of AR HMDs including the Microsoft HoloLens and Epson Moverio BT-200 smart glasses against paper instructions and a smartphone for delivering AR assembly instructions (Blattgerste, Strenge, Renner, Pfeiffer, & Essig, 2017). Significantly fewer errors were found with the HoloLens (m=0.25) when picking parts than the Epson Moverio BT-200 smart glasses (m=2.08, p<.05), paper instructions (m=1.25, p<.05), and smartphone (m=1.08, p<.05). Baird and Barfield explored the use of both video see-through AR HMDs and optical see-through AR HMDs against paper instructions for an assembly task (Baird & Barfield, 1999). They found the AR systems produced 75% fewer errors than the paper instructions. However, there was no spatial registration in the assembly instructions, so the system was closer to a heads-up display than true AR. Finally, Tatić and Tešić found success in using AR assembly instructions to reduce errors leading to workplace injuries (Tatić & Tešić, 2017). Their system guides the user through the work instructions while reminding them of safety protocols along the way. Based on prior work, the authors theorize that using this system against paper instructions would reduce errors leading to reduced injuries and enhanced safety.

Cognitive Load

Due to the complexity of various assemblies, there is often a high cognitive load on the operator as they try to understand and envision various steps of the assembly process. AR has been shown to reduce the cognitive load by providing more intuitive work instructions that require less mental demand on the operator (Tang et al., 2003). By utilizing AR to display the work instructions directly over the work environment, this reduces the need for the user to mentally transform the objects from paper pictorial diagrams. The understanding of the position and orientation of the work instructions is effectively eliminated from working memory. Funk et al. explored the mental workload of users for an assembly process with work instructions delivered through an AR HMD, AR HHD, AR projector and traditional paper instructions (Funk, Kosch, & Schmidt, 2016). By using the NASA-TLX questionnaire to measure cognitive load, they found the projector condition had the lowest mental workload and was the most favorably by users. Users reported the hands-free aspect of the project was ideal to the assembly task. While the AR HMD was also hands-free, users reported the limited field of view was detrimental to the experience. Blattgerste et al. found the same results utilizing the Microsoft HoloLens for a similar assembly task (Blattgerste et al., 2017). The limited field of view was also reported as the main drawback of the AR HMD. Despite these limitations, Crescenzio et al. found success using an AR HMD to check oil levels in a small aircraft. The AR system increased task efficiency and reduced cognitive load, with mental workload ratings from the NASA-TLX survey staying under 4 points out of 10 for all participants.

Augmented Reality Hardware

As previously discussed, AR requires a view of the real world on which to overlay 3D virtual content. To achieve this, there are various hardware devices available, but generally they can be broken up into four separate categories: 1) monitors, 2) projectors, 3) hand-held displays, and 4) head mounted displays. Each of these have their own advantages and disadvantages and the optimal device should depend on the intended use case (Palmarini, 2017).

Monitors and Projectors

Monitors and projectors are two simple ways of displaying AR content. Both devices require an external system to track the environment and provide a view of the real world. This view is then augmented with virtual content. At this point, monitors will display the augmented real-world view on a stationary 2D screen. Projectors will display the augmented content directly over the real-world objects. In both cases, the use for assembly tasks remains very limited as both devices are stationary. Nevertheless, both devices have found various use cases for assembly tasks. Research has shown that monitors can be very effective for delivering work instructions when the work station is small and stationary, specifically reducing completion time and errors (Echtler et al., 2004; Fiorentino et al., 2014; Loch, Quint, & Brishtel, 2016). Similarly, Uva et al. and Marner et al. found that projectors also reduce competition time and errors for assembly tasks (Marner, Irlitti, & Thomas, 2013; Uva et al., 2017). The main drawback to both devices is that they are not feasible when the user must navigate along a larger work station where the displays may not always be present.

Hand-Held Displays

HHDs, as the name suggests, include a variety of devices which the user holds while in use. Generally, smartphones and tablets are the preferred delivery device for this category but this definition may occasionally be extended to include hand-held projectors as well (Krevelen & Poelman, 2010). HHDs work by utilizing a video see-through technique in which a camera records frames that are then augmented with virtual content (RT Azuma, 1997). These devices have been used extensively in AR research due to their accessibility and relatively low cost. In fact, Wagner et al. found that HHDs present many advantages to other AR devices as they utilize technology the user is already familiar with and therefore, reduce the learning curve (Wagner, Pintaric, Ledermann, & Schmalstieg, 2005).

Specifically, for manufacturing and assembly related applications, there has been much research utilizing and evaluating HHDs. Sanna et al. developed an AR maintenance application for an AR HHD that guides a user through the disassembly of a laptop computer (Sanna et al., 2015). A user study showed that participants assessed the technology favorably and errors were reduced substantially compared to the paper instruction control condition. Furthermore, Webel et al. found similar results exploring the use of AR HHDs in manufacturing and assembly (Webel et al., 2013). The AR HHD condition showed approximately 75% fewer errors compared to traditional methods. Additionally, after one training session, the results showed that those who trained with the AR HHD has a higher skill level as well. These results demonstrate the effectiveness of AR HDDs to deliver work instructions and training materials for manufacturing applications. However, HHDs are not without their pitfalls. Studies by Syberfeldt et al. and Aromaa et al. both received concerns from users that the HHDs were cumbersome to hold during assembly tasks and also interrupted workflows (Aromaa, Aaltonen, Kaasinen, Elo, & Parkkinen, 2016; Syberfeldt, Holm, Danielsson, Wang, & Brewster, 2016).

While AR HHDs may provide many benefits and display work instructions in a more intuitive manner, applications like manufacturing may not be ideal when the user needs to perform work manually.

Head-Mounted Displays

AR HMDs follow the same general principle as HHDs, essentially overlaying computer-generated imagery over a view of the real world. However, HMDs use specialized technology to display the AR content directly over the user's field of view. To accomplish this, two separate display techniques can be used: video see-through and optical see-through (Krevelen & Poelman, 2010). In both cases, the HMD allows for the user to remain hands free. However, both approaches have significant advantages and disadvantages, which need to be considered based on the application (Palmarini, 2017).

Video see-through HMDs capture a view of the real-world using cameras located on the device. This view of the real world is then augmented with computer generated images and displayed to a user via a binocular display directly in front of their eyes. This technique provides many advantages including low-cost, ease of implementation, brightness, contrast of virtual objects and the ability to mimic proper lighting conditions (Krevelen & Poelman, 2010). Unfortunately, video see-through HMDs have major drawbacks that limit their potential and usability. This includes parallax due to the camera's position being offset of the viewer's eye location leading to eye strain and fatigue (Biocca & Rolland, 1998; Rolland & Fuchs, 2000). Furthermore, the fixed focal distance of the display provides poor eye accommodation leading to improper depth cues (Ellis, Breant, Adelstein, Jacoby, & Manges, 1997). Lastly, any delay between capturing the video of the real-world and displaying it along with augmented content will be detrimental to the user's experience (Ong, Yuan, & Nee, 2008).

Optical see-through HMDs overcome many of the limitations of video see-through HMDs by projecting virtual content onto a transparent display in front of the user's eyes. These devices are parallax free as there is no offsetting camera to account for. In addition, natural light can penetrate the display, so the focal distance is not fixed, and proper depth cues are present (Rolland, Holloway, & Fuchs, 1995). Moreover, in the event where the equipment malfunctions, optical see-through HMDs are safer than video see-through displays as the transparent display will allow the user the ability to still see their environment while the opaque display of the video see-through would not (Krevelen & Poelman, 2010). This is especially important for manufacturing and assembly applications as a user may operate in a dangerous environment where sight is always necessary (Rolland et al., 1995). The main drawback of these devices is the limited brightness of the transparent display. Since the light of the virtual content is mixed with real-world light, the display may not be usable in bright conditions such as outdoors. Similarly, the addition of real-world light sources make occlusion very difficult as the brightness of the display struggles to occlude the real-world object (Rolland & Fuchs, 2000).

2D smart glasses are an additional class of devices that may fall under the AR HMD category. These devices are essentially optical see-through HMDs that only render 2D content, like a heads-up display. Since the content is not registered in 3D, they cannot truly be considered AR devices (RT Azuma, 1997).

Like HHDs, there has been considerable research for the use of HMDs in AR assembly applications. HMDs are especially advantageous for assembly tasks as they allow the user to remain hands free while viewing work instructions. A study by Syberfeldt et al. explored the use of HMDs against tablets and spatial projectors for an assembly task (Syberfeldt et al., 2016). Participants reported that the hands-free interaction was ideal, and the HMDs kept the view of the world intact. The main drawback of the system was due to the weight of the HMD on their head. However, the devices used in this study were bulky custom-built solutions meant for research and not availability for commercial use. The influx of new commodity AR HMDs to the market feature more sleek designs. Evans et al. evaluated the Microsoft HoloLens for use in product assembly and found it to be a viable platform for delivering assembly work instructions (Evans et al., 2017). Since then, other devices have come to market including the Daqri Smart Glasses, Magic Leap One, and Meta 2. While these devices show improvements over their bulky predecessors, there is still much to understand about their limitations and how to overcome them for use in product assembly.

Augmented Reality Limitations

AR HMDs have been proven useful in a variety of applications, namely assembly tasks. However, they still have many limitations that have plagued their full-scale adoption. Some of the most detrimental limitations include input, user interfaces, spatial registration, navigation, and occlusion (Krevelen & Poelman, 2010). These limitations are increasingly problematic for assembly applications where work instructions need to be displayed clearly and accurately (Ong et al., 2008). While improvements have been made through hardware advancements, many of these problems are still present in state of the art commodity AR HMDs (Blattgerste et al., 2017). The following sections will discuss these limitations in detail and provide a background on the key challenges.

Input and User Interfaces

One of the major issues regarding AR assembly applications is presenting clear and concise information for a complex procedure (Chimienti, Iliano, Dassisti, Dini, & Failli, 2010). Chimienti et al. explained that for AR assembly aids to be successful, the work instructions must be simple enough for a user to quickly understand. The main benefit of AR for assembly applications is to provide intuitive instructions and for the user to clearly see the virtual content in the real-world. Any addition of unnecessary information is detrimental to the task and should be avoided. Martinetti et al. suggests that the information delivered should be specific and dynamic, ensuring that the AR system provides help and not obstacles for a given task (Martinetti, Rajabalinejad, & Van Dongen, 2017). Furthermore, the AR system should keep track of the operation progress and communicate that information back to the user. This will allow the user to understand their progress, keeping them on track and enhancing learning outcomes. It was noted that wearable devices such as AR HMDs are more prone to users blindly following directions and not truly understanding the actions they are performing. By giving feedback to the user, they are less likely to form an overreliance on the device.

In additional to ensuring clarity of the AR work instructions, it is critical to consider how they will be displayed to the user. Radkowski et al. performed a study to compare the effectiveness of 3D work instructions when displayed using different graphical representations (Radkowski, Herrema, & Oliver, 2015). The task included the assembly of a pump and instructions were given as 3D virtual images of the assembly steps, abstract representations of instructions consisting of arrows and text, as well as traditional paper instructions. The researchers found that there were fewer errors when using 3D visuals of various parts moving into their correct position as opposed to abstract instructions. This was consistent with prior research showing that these 3D visuals often reduce errors and cognitive load in assembly processes (Tang et al., 2003). Furthermore, the clarity of these instructions are consistent with the guidelines set by Chimienti et al (Chimienti et al., 2010). A study by Khuong et al. explored AR work instructions displayed directly over the physical parts versus a virtual 3D model displayed next to the physical part (Khuong et al., 2014). Surprisingly to the authors, the side-by-side model outperformed the virtual overlay mode. The main reason for this was that errors associated with tracking and the display were more obvious when the virtual content was overlaid on the real-world parts. These results demonstrate the need for accuracy and clarity when delivering AR work instructions.

Input methods also play an important role in the delivery of AR work instructions. To navigate through the work instructions, the user must be able to interact with the system in an intuitive manner. Some of the most common input methods for AR include voice commands, gesture input, gaze-and-dwell, and remote controllers. Goose et al. developed an AR system that utilized speech as an input device (Goose, Sudarsky, Xiang Zhang, & Navab, 2003). While speech commands may be effective in some scenarios, they often have a limited vocabulary and do not work well in noisy environments. Gesture controls are an alternative input method that show promise to theoretically be intuitive and easy to learn (Chi, 2013). The main drawback is that, gesture control is still early in development and additional research is needed before they are truly intuitive and easy to learn (Cheng, Yang, & Liu, 2016; Rautaray & Agrawal, 2012). Fortunately, there is significant interest in this field and researchers are quickly discovering new techniques for gesture control (Wang, Ong, & Nee, 2013; Yew, Ong, & Nee, 2016). Gaze-and-dwell input is a common and simplistic method to implement on AR devices. This heavily researched method involves using the gaze direction of the user as a target and them dwelling on a specific region for a period of time as an input (Jae-Young Lee, Hyung-Min Park, Seok-Han Lee, Tae-Eun Kim, & Jong-Soo Choi, 2011). Park et al. developed a gaze interaction for use in an AR repair and maintenance task. While they found success as a proof of concept, they acknowledged the innate limitation that the user must keep still for a potentially uncomfortable period to provide input. Lastly, remote control devices are a simplistic method of providing input to AR applications. These generally consist of an additional physical device that features buttons to provide input to the AR system (RT Azuma, 1997). The main drawback of these devices is they require an additional piece of equipment and in some cases will prevent the user from remaining hands-free.

Spatial Registration

As Azuma described in his seminal survey paper on AR, spatial registration is a fundamental component of AR (RT Azuma, 1997). To properly display AR content, the AR system must have an accurate representation of the environment and its position in that environment. There are a variety of techniques to track the environment but often the best AR systems will use a hybrid of multiple tracking techniques, including visual, inertial and optical to optimize their system (Ronald Azuma et al., 2001). These systems can generally be broken up into two separate categories: marker-based registration and marker-less registration.

Marker-based registration is the most straight forward and arguably the most common method for registration in AR. This technique utilizes high-contrast image targets or fiducial markers to anchor AR content (Kato & Billinghurst, 1999). An RGB camera is then used to detect these images and calculate the orientation and position of the camera relative to the image (Davis, Clarkson, & Rolland, 2003). Once this pose is calculated, it is possible to render AR content on a given display device such as a HMD, HHD, projector or monitor. The main benefits of this tracking system are the simplicity and accuracy in spatial registration. Various computer vision algorithms have been developed to quickly identify images and calculate their pose at real time. Many commercial products are available to provide this functionality for a variety of applications, such as Vuforia (Vuforia, 2018) and ARKit (Apple, 2018) and ARCore (Google, 2018). Despite these benefits, there are many drawbacks that limit the use case of marker-based tracking. First, the image must always remain visible to the camera to be tracked. If the user shifts the view of the camera then tracking is lost, and the AR experience may be broken. Second, for any object that is to be tracked, an image must be attached to it (Kato & Billinghurst, 1999). This means that if there are multiple objects that must be tracked in a given application, it may not be feasible to attach an image to every single object. Lastly, the images and algorithms used for tracking include many variables that may interfere with the accuracy of the system. Some of the most notable variables include lighting conditions, gloss of the image, the quality of the image, the quality of the camera, the viewing angle and distance from the camera to the image (Zhu, Ong, & Nee, 2015). Any variation in these variables can be detrimental to the tracking of the system and therefore a controlled environment is best for marker-based tracking.

Marker-less tracking is a technique to understand the environment without any need for a marker or image. Instead of using an RGB camera to scan for a predefined image, this technique often utilizes visual information with inertial information to create a map of the environment. The most common technique of this form is called Simultaneous Localization and Mapping (SLAM). SLAM can dynamically find natural features in the environment and create a mesh of a that environment in real time (Martin, Marchand, Houlier, & Marchal, 2014). While this tracking technique may seem ideal, there are some critical limitations that reduce its adoption for use in many areas including assembly applications. Even though marker-less tracking techniques can generate a map of the environment, it is often very difficult to accurately define a single point in that environment. Essentially, these techniques provide a rough representation of the environment that is well suited for applications where accuracy is not critical. However, if one needs to define a specific point on an assembly part for example, this would be challenging. Furthermore, as the entire viewed scene is returned as a single tessellated model or point cloud it is very difficult to identify specific objects (Comport, Marchand, Pressigout, & Chaumette, 2006). Again, this is not conducive to the high accuracy tracking required for assembly applications.

Both marker-based and marker-less tracking techniques have unique capabilities and limitations that can be leveraged based on the intended use case and application. Platonov et al. developed a marker-less tracking system for use in maintenance and repair (Platonov, Heibel, Meier, & Grollmann, 2006). Since accuracy wasn’t crucial in this specific use case, they were able to utilize marker-less tracking for a guided maintenance task. By combining the techniques of both marker-based and marker-less tracking, the benefits of both methods become available in the environment. Yang et al. developed a vision-inertial hybrid tracking system to track specific images with high accuracy and rely on the inertial sensor when image tracking was lost (Yang, Si, Xue, Zhang, & Cheng, 2015).

Navigation

Navigation in large 3D environments presents a very difficult challenge. Not only must the spatial registration be accurate, but a user must be intuitively guided to the correct point of interest to accomplish an assembly task. Schwerdtfeger & Kilnker proposed a “tunnel” method that guided the user’s attention through a series of graphics, effectively forming a tunnel to the point of interest (Schwerdtfeger & Klinker, 2008). The researchers compared this method to a

3D arrow and found the tunnel to be significantly faster for part picking tasks. Additionally, users made fewer mistakes utilizing this method. Interesting, the authors also found that the 3D arrow performed better when using a higher quality HMD. This may be due to the arrow appearing clearer and giving a better representation of the given space. Furthermore, MacAllister et al. also explored the use of a "tunnel" against a 3D arrow and top down point of interest map for navigation in a large AR assembly environment (MacAllister, Gilbert, Holub, Winer, & Davies, 2016). The tunnel and 3D arrow system provided similar completion times, but it was found that the tunnel was favored by users. Renner and Pfeiffer performed a study to explore this "tunnel" method against a 3D arrow and found conflicting results (Renner & Pfeiffer, 2017). Users in this study found the 3D arrow to be preferable over the tunnel method for navigation. However, in this study the user remained seated and did not move over the course of the trial. Therefore, these systems were not assessed in a large 3D environment and it is uncertain if they would have similar results if the user had to move around. It is crucial to understand the capabilities of the AR system and the environment in which it will be located to implement the most useable navigation system.

Occlusion

Occlusion plays a critical role in providing depth perception cues for 3D augmented reality content (Wloka & Anderson, 1995). For the user to have a proper representation of the 3D content, they must understand the depth order in which the content appears, e.g., if a virtual object is partially behind a real object then that portion of the virtual object must not appear. The issue of occlusion is two-fold and Shah et al. describe these issues as occlusion detection and occlusion handling (Shah, Arshad, & Sulaiman, 2012). Occlusion detection refers to the tracking of the real-world environment so the AR system can distinguish the proper depth sorting of objects in the scene. This can further be broken down into real time and preprocessed systems. To perform occlusion at real time, a tracking system must constantly detect changes in the real environment. This process takes extensive computing power and often must sacrifice accuracy for performance. Preprocessed occlusion utilizes a static environment to build a model of the real-world environment already present in the application. While this is more efficient, any changes in the environment will not be represented in the model at real time. Occlusion handling refers to the display of the AR system being bright enough to fully occlude any captured background light. In optical see-through displays, natural light is mixed with the AR content. Therefore, any AR content must be bright enough to effectively occlude the natural light (Rolland & Fuchs, 2000) for proper depth sorting. For a user to gain a complete understanding of assembly instructions, these limitations must be mitigated to ensure proper depth perception cues are given (Krevelen & Poelman, 2010). Furthermore, Richardson et al. confirmed the need for occlusion in AR assembly applications by performing a study on the assembly of a mock aircraft wing (Richardson et al., 2014). It was found that users performed better with fewer errors when occlusion was present in assembly work instructions. While many AR devices are limited in their tracking and display capabilities, it is important to understand how these limitations can be mitigated to ensure occlusion and proper depth perception cues.

Research Questions

AR devices, especially AR HMDs, have limitations that prevent their full-scale adoption in many fields. Prior work has shown promise for the use of AR especially in assembly applications where they can substantially reduce time, errors and cognitive load. With the introduction of new commodity AR HMDs such as the Microsoft HoloLens, it is important to understand how the limitations of these devices can be mitigated for use in product assembly to take advantage of the many benefits this technology can provide. To investigate this, the research in this thesis will address the following questions.

1. *How can the input limitations of the Microsoft HoloLens be addressed for delivering guided assembly work instructions?*

   For AR assembly work instructions, the user should be able to interact with the user interface in an intuitive, hands-free manner to maximize the usability of the system.

2. *Can marker-based tracking augment the spatial registration capabilities of the Microsoft HoloLens to provide better results for product assembly tasks?*

   To properly deliver AR work instructions, spatial registration must be stable and spatial drift must be quantified and minimized. Marker-based tracking techniques provide high accuracy spatial registration that can augment the capabilities of the Microsoft HoloLens tracking to ultimately improve performance and reduce error.

3. *Does the Microsoft HoloLens have enough processing power and spatial registration capabilities to properly occlude virtual content and provide depth perception cues?*

   Occlusion provides the necessary depth perception cues to ensure AR assembly work instructions are properly interpreted by the user. If a device can’t provide proper occlusion, performance may decrease for assembly tasks.

CHAPTER 3. MITIGATION OF THE MICROSOFT HOLOLENS' HARDWARE LIMITATIONS FOR A CONTROLLED PRODUCT ASSEMBLY PROCESS

The follow section was submitted to the Access journal of the Institute of Electrical and Electronics Engineers (IEEE). Access is a multidisciplinary journal focused heavily on applications of various technologies.

Abstract

Studies have shown that using augmented reality (AR) reduces time and errors by as much as 50% for manufacturing and assembly operations. The use of Head Mounted Displays (HMDs) is very interesting for these situations as they free up a user's hands. However, with the technology behind these HMDs still under development, limitations in input, field of view, tracking, and occlusion exist. For AR assembly instructions to be effective, these limitations must be mitigated so that a user receives accurate instructions. To investigate this, an application was developed that guides a user through the assembly of a mock aircraft wing using AR on a Microsoft HoloLens. The application displays 3D work instructions, user interfaces, and spatially registered content. To ensure accurate instructions were displayed, techniques were developed to mitigate the HoloLens' tracking and display limitations. Image tracking was implemented to augment the HoloLens' limited position determination, stabilize spatially registered virtual content and account for spatial drift. Also, 3D augmented content was optimized for clarity through the display using specialized computer graphics methods. Lastly, the system provides raw data regarding head position, orientation and assembly step times. A visualization application was developed that combines this information with wearable sensor data, to examine trends exhibited by a user during the assembly tasks and validate the delivered instructions. The outcomes of this research provided solutions to address limitations of the HoloLens for broad use.

Introduction

Augmented Reality (AR) is an emerging technology that could greatly increase training efficiency and effectiveness. In fact, Henderson & Feiner found that AR may reduce time and errors by as much as 50% for maintenance and assembly operations (Henderson & Feiner, 2011). Essentially, AR consists of computer-generated visual information overlaid on top of a view of the real world. These computer-generated visuals are often delivered via a tablet or Head Mounted Display (HMD). Traditionally, tablets have been the preferred method of delivering AR content due to technological constraints and commercial availability. HMDs of the past tended to be expensive custom-built solutions for research purposes and not viable for commercial use (Dini & Mura, 2015; Nee & Ong, 2013; Ockerman & Pritchett, 1998). However, in recent years several commercially available AR HMDs have come to market and shown promise for use in maintenance operations. The main advantage of AR HMDs over tablets is that they overlay the computer-generated visuals directly over the user’s field of view, allowing hands free operation. This is ideal for maintenance and assembly operations and training.

AR HMDs show great potential for use in maintenance operations and training as will be shown later in the paper. However, due to the emerging nature of this technology, many of the components that make up these AR HMDs are still under development. Therefore, there are many limitations within the technology that must be mitigated including input methods, field of view, tracking and occlusion (Dini & Mura, 2015; Nee & Ong, 2013; Ockerman & Pritchett, 1998). These limitations are especially important to maintenance and assembly tasks as it is essential to ensure the user receives accurate work instructions and effective training. Therefore, augmented 3D content must be accurately spatially registered and displayed, otherwise users may misunderstand instructions leading to additional assembly time and errors.

Furthermore, as assembly tasks may take a considerable amount of time, it is important to ensure the spatial registration does not degrade via spatial drift of the devices tracking system.

This paper discusses the novel techniques employed to mitigate the limitations of the Microsoft HoloLens for use in an AR work instruction assembly application. Specifically, the methods developed to address the HoloLens' limited position determination, spatial registration of virtual content and spatial drift. This application was also used to conduct a user study comparing the effectiveness of work instructions delivered via an AR HMD, AR tablet, tablet model-based instructions and desktop model-based instructions (Hoover, Miller, Gilbert, Winer, & Davies, 2018). The focus of this current paper is not the study design and implementation, but rather addressing the HoloLens's limitations as stated earlier. Due to all the custom enhancements made to the HMD system, it was necessary to evaluate that the technical parts of the system were functioning properly. To accomplish this, a separate data visualization application was developed, which used the study data for validation. This fusion through the data visualization application allowed an analyst to better understand the training session and identify any issues in the AR application. In addition to validating the work instructions, an analyst may also discover new high-level trends about the user and the training environment through the fusion of these data sources. One of the largest limitations of the HoloLens was to ensure proper tracking when spatial drift was present. To combat tracking limitations, data was collected during the training sessions to measure the drift accumulated and validate that the techniques developed to combat this spatial drift were effective. Through the delivery and validation of these work instructions, this work seeks to enhance the effectiveness of training for maintenance and assembly operations using an emerging commodity HMD.

Background

Augmented reality is a technology that has been heavily researched since the 1990's and shows promise for a variety of applications (RT Azuma, 1997; Caudell & Mizell, 1992). AR involves merging computer-generated visuals with a view of the real world. These visuals provide additional information to what is seen in reality. In a seminal paper, Azuma surveyed the various applications of AR and found that it would have a major impact in the fields of medical, robotics, entertainment, visualization and notably manufacturing and repair (RT Azuma, 1997). Additionally, Krevelen & Poelman found similar use cases and many more including education, military training and others (Krevelen & Poelman, 2010). Manufacturing is a large area for AR research including many use cases for industry and the military. Specifically, AR guided assembly and disassembly tasks make up 30% of published research for AR manufacturing (Palmarini, Erkoyuncu, Roy, & Torabmostaedi, 2018).

Augmented Reality Assembly Applications

Numerous papers have explored the use of AR for the delivery of work instructions. One of the first AR work instruction applications was proposed by Caudell & Mizell for an aircraft manufacturing process through a transparent HMD (Caudell & Mizell, 1992). However, the technology at that time was still in its infancy and suffered from many of the same problems modern HMDs have, specifically tracking and display capabilities (Caudell & Mizell, 1992). Since this seminal paper, researchers have developed many systems to explore the possibilities of this technology.

Studies have shown that AR delivered work instructions drastically reduce errors when compared to traditional delivery methods (Baird & Barfield, 1999; Loch, Quint, & Brishtel, 2016; Tatić & Tešić, 2017). Furthermore, Baird & Barfield found that in addition to reducing errors, AR also decreased the time to complete assembly tasks. In a similar study, Henderson and Feiner found that AR delivered instructions significantly reduced: 1) the amount of time to locate tasks, 2) head and neck movements, and 3) mental workload (Henderson & Feiner, 2011). Additionally, since the instructions are presented directly over a view of the real world, the user does not have to recall the visual information from 2D instructions (De Crescenzio et al., 2011). These benefits lead to enhanced assembly performance and therefore reduced costs.

Augmented Reality Hardware

AR assembly instructions are often delivered through transparent HMDs, tablets and smartphones. Due to commercial availability and relatively low cost, tablets and smartphones have been the preferred AR platform (Wagner, Pintaric, Ledermann, & Schmalstieg, 2005). However, the main drawback of these devices for delivering assembly instructions is that typically a user must hold the device when using it. This is not ideal as the user will likely be working with their hands when receiving work instructions.

AR HMDs may overcome this issue through a hands-free experience. In the past, AR HMDs have been expensive custom-built solutions created for specific use cases. This has been a large pitfall for the use of HMDs in many applications as they are not readily available. However, in recent years numerous commercially available AR HMDs have come to market including the Microsoft HoloLens, Daqri Smart Glasses, Meta 2 and Magic Leap (Daqri, 2018; Leap, n.d.; Meta, 2018; Microsoft, 2018b). These devices can track the environment while displaying spatially located 3D content through an optical see-through display. The use of these devices allows the user to remain hands-free and view instructions directly over their field of view. Evans et al. evaluated the Microsoft HoloLens for use in an assembly application and found the device to be a viable platform (Evans, Miller, Iglesias Pena, MacAllister, & Winer, 2017). The research presented by Evans et al. showed that the HoloLens had the necessary processing power, display and tracking capabilities for use in assembly applications. However, more research was needed to further mitigate these issues and evaluate it for use in the field.

Augmented Reality Limitations

While there are many benefits for the use of AR, there are many limitations that come along with it. Tang et al. found great success with the use of AR for assembly purposes but noted that the technology was not ready for widespread use due to various limitations in the hardware (Tang, Owen, Biocca, & Mou, 2003). Some of the main hardware limitations include tracking, depth perception, and occlusion (R. Azuma et al., 2001; Krevelen & Poelman, 2010). While hardware improvements may help overcome some of these limitations, novel development techniques may additionally help mitigate the negative effects.

Tracking can be broken down into two main categories, marker-based and marker-less. The most accurate method is marker-based tracking. This method uses a high-contrast image target to provide a real-world point of reference. This image target can be identified by an RGB camera on the AR device to establish this point of reference. While marker-based tracking provides high accuracy, its main drawback is that it requires an image target for any object it is tracking. Additionally, the image target, the environment and the camera detecting the image target have many limitations including lighting conditions, gloss, contrast, camera quality, viewing angle, and distance. Marker-less tracking overcomes the issue of needing an image target through various techniques, often combining input from visual sources, depth sensors, and an inertial measurement unit (IMU) (Comport, Marchand, Pressigout, & Chaumette, 2006). The main issue with marker-less tracking, such as simultaneous localization and mapping (SLAM), is that it lacks the accuracy to register precise points in the real world. While a mesh of the general environment can be mapped, understanding specific points presents many challenges that have yet to be explored (Martin, Marchand, Houlier, & Marchal, 2014). Since it is often difficult to achieve an accurate point of reference, it is not ideal for tasks, such as assembly, that require precise registration.

Depth perception is very important to assembly applications as the user must be able to properly locate and visualize augmented instructions. Many past devices had issues with dim displays and low resolution leading to virtual objects appearing farther away than they should (Krevelen & Poelman, 2010). Even though recent advances in technology have improved resolution and opacity in many devices, there are still many improvements that can be made. Occlusion has been found to effectively give depth perception cues that may overcome limitations in resolution and opacity (Rolland & Fuchs, 2000). Through accurate occlusion, the user may better understand the proper representation of the instructions given (Shah, Arshad, & Sulaiman, 2012; Wloka & Anderson, 1995). However, to properly occlude virtual content with real world objects, the AR system must understand the environment and its geometry. As previously mentioned, tracking the environment is not a simple task and this limitation must be overcome to ensure instructions are properly displayed.

Additional research is needed to understand and mitigate these limitations for use in AR work instruction applications. While hardware improvements of emerging technology will be very beneficial in the future, many of the current limitations can be mitigated through novel development techniques. The work in this paper explores these limitations and offers solutions to overcome them.

Methodology

Hardware

Several commercially available AR HMDs currently exist on the market. For this research, the Microsoft HoloLens was chosen as the display device for the AR assembly application due to its maturity and popularity compared to the other devices. Furthermore, the HoloLens includes the necessary capabilities for an AR HMD assembly application: environment tracking, sufficient computing power, and a transparent display. Despite these capabilities, the HoloLens has limitations in input, field of view, tracking, and occlusion that must be mitigated for the delivery of AR work instructions.

The HoloLens is a completely self-contained AR HMD and is not required to be tethered to an external computing device (Microsoft, 2018a). The computing power of the HoloLens consists of a 32-bit Intel processor with a custom-built Microsoft Holographic Processing Unit. The HoloLens takes in sensor data from an inertial measurement unit, four environment understanding cameras, one depth camera, one 2MP photo / HD video camera, four microphones and one ambient light sensor. Graphics are then displayed through see-through holographic lenses using waveguide technology. An effective resolution of 1268x720 per eye is achieved through two HD 16:9 light engines.

Development Tools

Unity3D is a powerful game engine widely used for the development of 2D, 3D, VR and AR applications (Unity Technologies, 2018). The Unity3D editor allows for the rapid development of applications through a large toolset including a rendering engine, a physics engine, user interface design tools, and the Unity3D C# scripting API. In addition, support is available for a variety of build platforms including windows, mac, iOS, android, and Universal Windows Platform (UWP). Specifically, Microsoft provides ample documentation and recommends for the development of AR HoloLens applications using Unity3D (Microsoft, 2018c). Due to the vast toolset and capabilities of Unity3D, it was chosen as the development platform for the AR assembly application and data visualization tool.

The Vuforia SDK is one of the leading AR SDKs used for a variety of purposes (Soussi, Spijkerman, & Jansen, 2016). Using propriety computer vision algorithms, Vuforia provides functionality for image, text, model and object tracking. Through this tracking, Vuforia is able to deliver position and orientation data which can then be used to spatially register AR content. Like development with Unity3D, Microsoft provides documentation for, and highly recommends the use of Vuforia when utilizing image targets in a HoloLens application (Microsoft, 2018d). Furthermore, as of Unity3D 2017.2, Vuforia is built into the Unity3D engine to increase functionality and ease of use. Vuforia was chosen to augment the tracking capabilities of the HoloLens for the AR system. The functionality, wealth of documentation, and stability of the Vuforia SDK was ideal to provide image tracking capabilities for the AR assembly application, Figure 1 shows an example image target. The image tracking, accompanied by the HoloLens tracking system, allowed for all AR content to be properly spatially registered.

Figure 3.1. Image Target Example.

Effective User Input

For the AR assembly instructions to be usable, the user had to be able to interact with the application in an intuitive manner. To receive input from the user, there were a variety of options available. The HoloLens provides built-in gesture controls, the most popular being the “air tap”. While this input method is relatively hands-free, it is often difficult to teach to a new user and may lead to reduced usability of the system (Rautaray & Agrawal, 2012; Cheng, Yang, & Liu, 2016). Another input method often used in AR HMDs is the “gaze and dwell”. While this is completely hands-free, the user must keep their head unusually still and it tends to be very slow. Voice commands were another method considered, however this would not be ideal for loud manufacturing environments. To overcome the issues of these input modes and provide an intuitive experience, the authors implemented the HoloLens’ Bluetooth clicker. The clicker was paired with the HoloLens and the application received input when the clicker button is pressed. To keep the user handsfree during the assembly process, the clicker was attached to the user’s wrist by a simple strap. While the user gazed at the virtual button, they can press this clicker to deliver input to the HoloLens as shown in Figure 2. It is an intuitive method that is simple to learn.

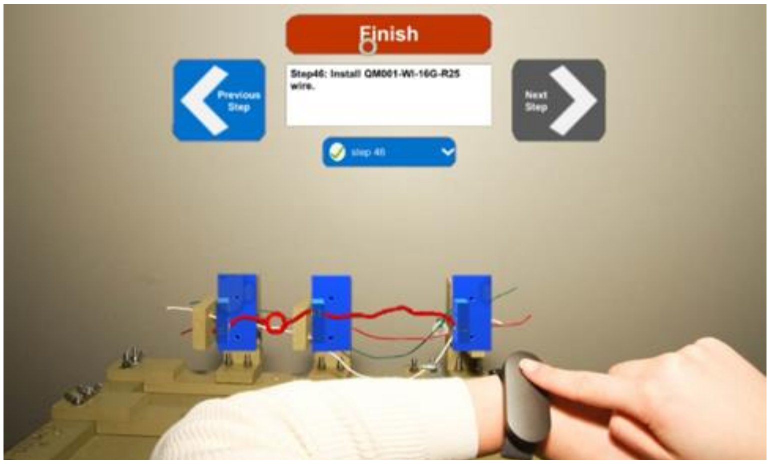

Figure 3.2. HoloLens input method and user interface.

Tracking Accuracy

The AR assembly application needed to track the environment well enough to correctly display spatially located assembly instructions. The HoloLens can generate a mesh of the environment using its proprietary tracking system in real time. To successfully track the assembly, the generated mesh had to be detailed enough to identify key feature points such as edges and corners. However, Figure 3 shows that the mesh generated for even a basic assembly is not nearly accurate enough to achieve this. In addition, the HoloLens suffers from spatial drift due to error in the propriety tracking system and IMU. This drift accumulates over time and would be detrimental to any task lasting more than a few minutes (Sekar, Santos, & Beltramello, 2015). If the AR work instructions were not accurately registered, then the user may misinterpret the instructions leading to safety concerns or errors in the assembly process. To overcome these limitations, the Vuforia SDK was used to provide image tracking capabilities. Image targets were then used to initialize the location of the stations to augment the environment tracking of the HoloLens. The UI was then placed over these image targets so when the user looked at the UI, the application seamlessly reinitialized the position and corrected the drift.

Figure 3.3. HoloLens' spatial mapping of a basic assembly.

While image targets offer additional tracking capabilities, they are not without their own inaccuracies. Lighting conditions, gloss, target image quality, camera quality, viewing angle, and distance can all lead to errors and/or false positives when detecting the target, examples of this are shown in Figure 4 and Figure 5 (Vuforia, 2018). Any error in the calculated position and orientation of the image target is subject to a lever arm, i.e., rotational error is propagated over distance. This means that even a one-degree error in the calculated rotation of the image target over the distance of one-meter would lead to almost a two-centimeter difference in the location of the spatialized content. To overcome this limitation, a calibration stage was implemented to ensure all locations were properly initialized. This stage involved the user gazing at the image targets to initialize the position and then ensuring that the UI was placed flush with the image target. The tracking system then used this initialized position and orientation as a baseline. After this point, anytime the image target was detected, the calculated orientation was compared with the initialized orientation. If the rotations were different then the image target would not update its position. This method drastically reduced false positives when detecting the image target and limited error in the tracking system.

Ensure this UI is correctly positioned and rotated. Click the toggle when properly calibrated.

Figure 3.4. UI correctly flush with image target.

Ensure this UI is correctly positioned and rotated. Click the toggle when properly calibrated.

Figure 3.5. Miscalculated orientation of image target.

Navigation

Since the user was unfamiliar with the assembly environment, a navigation system was needed to guide them to the correct location. Previous research indicates that a 3D gate system is the most usable form of navigation in large 3D environments (MacAllister et al., 2017). To accomplish this, virtual square yellow gates were placed along a Bezier curve leading to the current step's location, shown in Figure 6. Since the stations were spatially located, a Bezier curve could be generated between the user's location and the current step's location. One control point was placed in front of the HoloLens to ensure the gates were always in view of the user and a second control point was placed between the previous control point and the end point to smooth the curve. Square yellow gates were then placed along the calculated curve at equal distances. The HoloLens' processing power along with the Unity3D C# scripting API was able to perform this operation at a high framerate to ensure a smooth navigation system. The use of this navigation system was able to give the user directional cues in an unfamiliar training environment where many distractions could be prevalent.

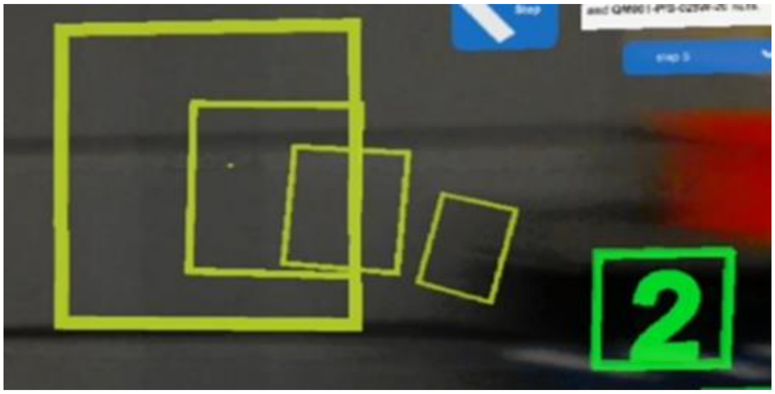

Figure 3.6. Yellow navigation gates.

Occlusion

Occlusion is crucial to an AR assembly application. The depth perception cues given by occlusion ensure the user sees the proper representation of the work instructions (Shah et al., 2012; Wloka & Anderson, 1995). Therefore, real world parts must be able to occlude the virtual parts shown in the work instructions. As previously discussed, the HoloLens can create a mesh of the real world but in very poor detail. This is not ideal for occlusion as inaccuracies may misrepresent the instructions given. To overcome this limitation, the authors utilized the augmented tracking capabilities of Vuforia with the static nature of the stations. The station positions and orientations were calculated from the Vuforia image targets. From there, the position and orientation of each assembled part was calculated relative to the station it belonged to using vector math. Finally, a virtual representation of each previously assembled part was placed in the scene with the same position and orientation as its real counterpart. A shader was then used to write this virtual part to the z-buffer but not render anything. A separate shader was used to render the work instructions a solid opaque color when in front of a real part and a yellow outline where it is occluded, see Figure 7. This custom solution allowed the user to see virtual work instructions properly occluded by real parts leading to the proper representation of the work instructions.

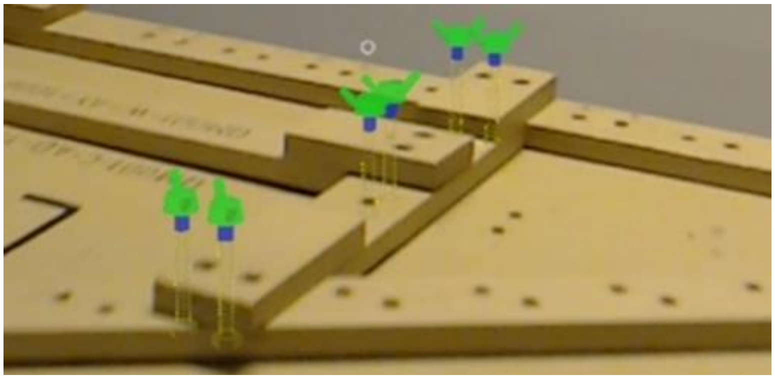

Figure 3.7. Virtual bolts occluded by real parts.

Data Collection

During the training session, data was collected on the user’s experience from the same sensors used to track the environment. This data included position data, orientation data, when input actions were performed, and how long the user spent on steps. The data was then stored locally on the HoloLens as CSV files to be easily parsed later for analysis. In addition, data could be collected from various other sources such as wearable physiological sensors and post-processed assembly error data. These rich data sets were combined to create a greater understanding of the user’s experience.

Results and Evaluation

Augmented Reality Assembly Application

To assess the hardware mitigation techniques described in this paper, an experimental setup of an assembly of a mock aircraft wing was used as shown in Figure 8. This assembly included a 46-step process of picking, placing, and assembling a variety of parts and fasteners.

These steps required the user to navigate through three separate stations: a parts table, fastener bins and assembly station. The parts table included large wooden parts to be placed and assembled, the bins contained the fasteners used to assemble the parts, and the assembly station was where the final product was put together. Each station was separated by roughly eight feet as shown in Figure 9, and the assembly station was positioned at approximately four feet high for ergonomic purposes. Physiological data was collected throughout the assembly training process using a wearable wrist device.

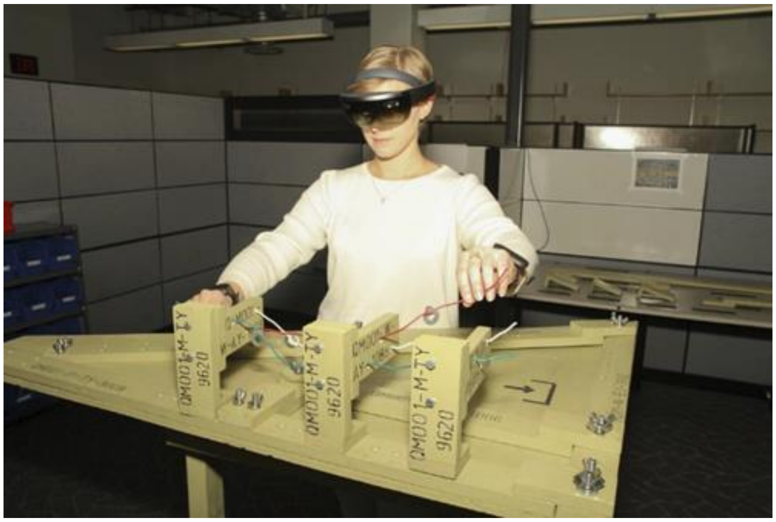

Figure 3.8. Mock aircraft wing assembly.

An AR assembly application was developed, with the methods described earlier, to guide a user through the assembly of the mock aircraft wing. The application began with a UI asking for the user's identification number to properly store the session data. Then, a large start button appeared with four large white squares in each corner of the display. These white squares were used to ensure the user was properly wearing the HoloLens device. If the user could see all four white squares it meant that they were experiencing the full field of view for the HoloLens. After the start button was pressed, the user was led through the 46-step assembly process. The UI appeared over the current station and displayed pertinent information including text directions and navigational tools. The user's attention was guided through a series of square yellow gates to the proper position. Parts that need to be acquired were outlined in green and then animations were given to demonstrate how to assemble each step as shown in Figure 2. When all steps were completed, a finish button would appear which then terminated the session and stopped the data logging.

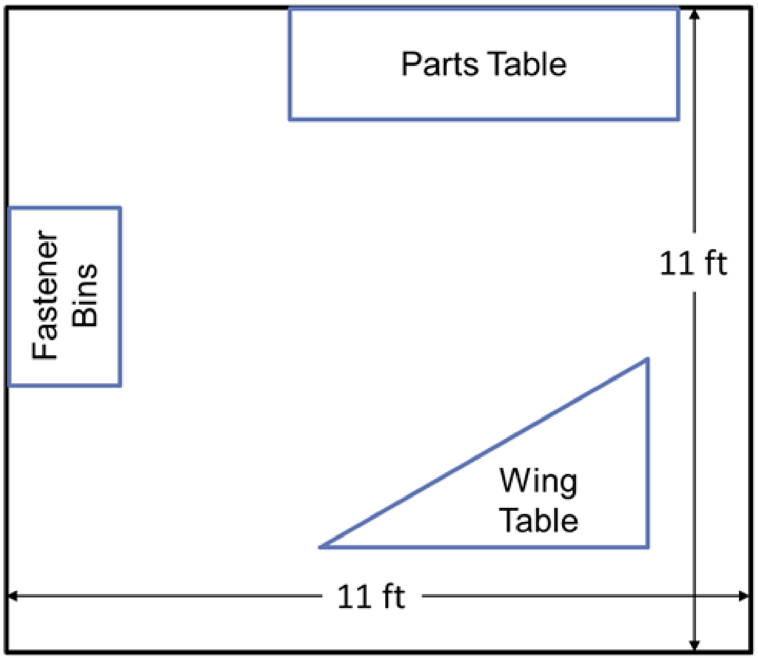

Figure 3.9. Station layout.

Wearable sensors such as Fitbit, Apple Watch, and the Empatica E4 can be used to collect important physiological data about the user. This data includes photoplethysmography, skin temperature and electrodermal activity. Specifically, the Empatica E4 was chosen for this application, as it is a high end, CE Medical 93/ 42/EEC Directive, class 2A compliant physiological sensor providing the most accurate data for health applications (Garbarino, Lai, Bender, Picard, & Tognetti, 2015). Using this device during training can lead to a better understanding of the user’s experience and readiness level through an analysis of their physiological response.

Drift Correction

As stated in the introduction, this paper focuses on addressing the hardware limitations of the HoloLens. To validate this, the data from a user study, in a parallel project, was used. This data was comprised of 83 trials of an assembly application to better understand how the spatial drift of the HoloLens affected delivered work instructions. This data was taken directly from the HoloLens without the need of a secondary tracking system. Every time the user looked at the image target, a measurement was taken from where the image target was previously located to where it was recalibrated. Since the image target was stationary in the real world, this measurement captured the drift accumulated in between recalibration events. The first 12 trials were broken up into two separate conditions, one where the drift was corrected and one where it was not. The first condition involved the AR system recalibrating and zeroing out the initialized locations each time the user viewed the image target. The second condition involved the AR system calculating the drift difference but not recalibrating and zeroing out the image target location. After these initial trials, it was found that the correction condition significantly reduced drift error and the remaining 71 trials were run with the correction condition enabled. Full details of the study can be found in a corresponding publication.

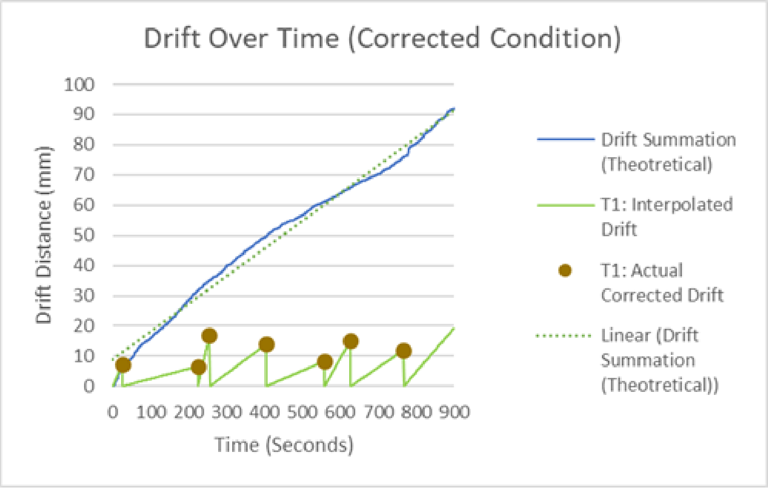

Figure 3.10. Drift over 15 minutes for corrected condition.

The data collected during the corrected drift condition consisted of the measurements taken at each recalibration event. Figure 10 shows the interpolated trend of drift built up over time and resetting at each recalibration event. In addition, by summing the recalibration distances over the course of the trial, approximately 15 minutes, it was possible to get a graph of how drift would have theoretically accumulated over time if it was not corrected. For individual trials, this resulted in a stepwise function with a step at each recalibration event. As shown in Figure 10, by periodically correcting for drift, the instantaneous drift was much lower than the theoretical drift accumulated / summated. Furthermore, by averaging all 77 trials of the summated drift it was possible to examine a general trend of how drift accumulated. Figure 10 shows the result of averaging these 77 trials with a fitted linear regression line. On average, drift tended to accumulate at a rate of 0.0459mm per second with the line fitting with a R2 value of 0.9868. Figure 10 also shows the recalibration events for a single trial. An interpolated line was included between events to show approximately how the drift accumulated. This shows that the correction method significantly reduced drift at any given time during the trial.

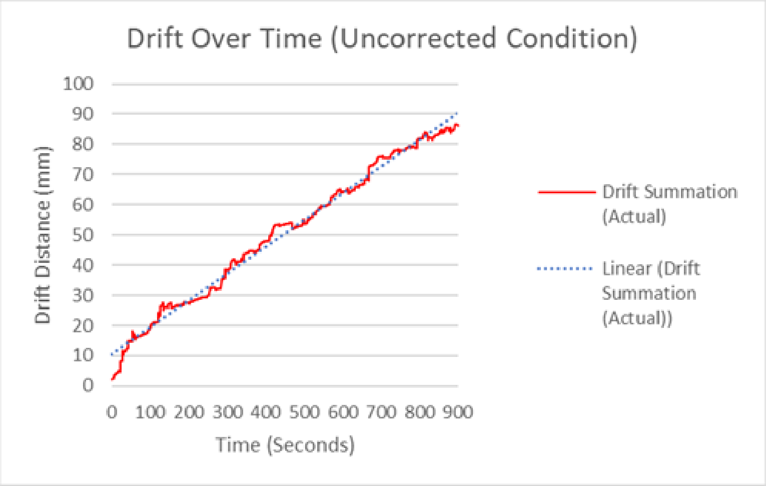

Figure 3.11. Drift over 15 minutes for uncorrected condition.

To confirm the trend of drift accumulating over time, the 6 uncorrected condition trials were analyzed. For these trials, there were no recalibration events, so the accumulated / summated drift distance was the same as the instantaneous drift distance measured. However, since the measurement was only taken when the user looked at the image target, for individual trials a stepwise function was also produced. These 6 trials were averaged together to find a general trend for the uncorrected drift condition, shown in Figure 11. Since only 6 trials were performed for this condition, small step functions are still present in the graph. However, a clear linear trend was found from the data. From the linear regression line, it was shown that drift accumulated a rate of 0.0445mm per second with a R2 value of 0.9897.

Both the corrected and uncorrected conditions of the collected drift data showed a clear linear trend as drift accumulated over time. The rate at which this drift accumulated was similar for both conditions, as shown in Figure 10 and Figure 11. This shows that correcting the drift throughout the trial is critical to ensuring the work instructions are accurately spatially located. If drift is not corrected, the error in displacement of spatially located content will follow the accumulated drift trendlines shown in Figure 10 and Figure 11. However, if drift is corrected periodically, the displacement error in spatially located content will be minimized to the small amount of drift accumulated between recalibration events, shown as T1 in Figure 10, on the order of 10mm.

Data Visualization Tool

The data visualization tool was developed to virtually recreate the user's assembly session. From this recreation, an analyst, referring to anyone who would use this tool to review the data, may validate the instructions and explore any potential trends that occurred during the session. This analysis would be highly advantageous to identify if the user is prepared but also to pinpoint inefficiencies in the assembly process. The data visualization tool was developed using Unity3D for this purpose. Data from the HoloLens, Empatica E4 and post-processed assembly error data was parsed and synced within the application.

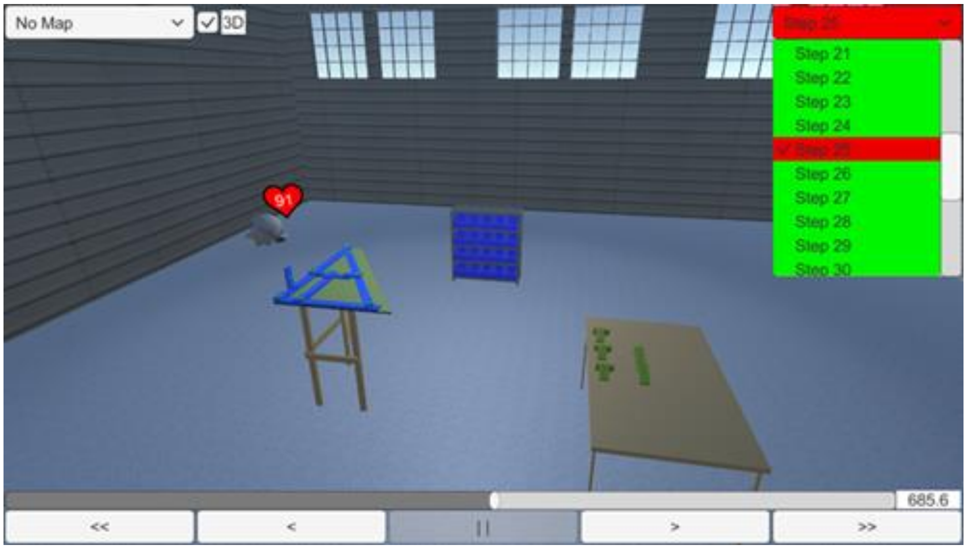

Figure 3.12. Visualization tool UI.

For the fusion of data within the application, there were various tools for analysis. A playback tool was available to scrub through the timeline of the training session, see Figure 12. A scrubber and timestamp showed the current time location. The analyst could then use buttons to pause, play, play-2x, rewind, and rewind-2x to navigate along the time line. The analyst was also able to navigate around the environment to view the session from various vantage points. To achieve this, various technical and usability challenges had to be overcome. An avatar, representing the user, was displayed and followed the same path of the user within the virtual recreation of the training environment. To accomplish this, the positional and rotational data set were parsed into the application from the CSV files generated during the trials. The pose of the avatar was then transformed relative to the new virtual environment to ensure the collected data points in the real world aligned with the virtual environment. In addition, the heart rate of the user was displayed over the avatar's head to show their physiological responses during the session, see Figure 13. To enable this functionality, the heart rate data collected from the Empatica E4 was parsed into the application and synchronized with the positional data set via the UTC timestamps. Finally, the post-processed assembly error data and step time data set was synchronized with the previously mentioned data sets using the same UTC timestamp method. This allowed the analyst to quickly navigate to specific points where the user may have struggled or misunderstood directions. The navigational tools and data represented would allow the analyst to quickly assess if the instructions were delivered accurately and identify high-level trends during the session.

To further explore these trends within the training session, heat maps were available for positional and heart rate data. To create the positional heat map, a square mesh was generated over the virtual recreation of the training environment. Each vertex of this mesh was then compared to the positional data set and was raised in the upwards y direction if it was within a threshold distance, shown in Figure 14. The height of the mesh was then normalized to enhance visibility. To generate the heart rate heat map, the same square mesh was used. However, to get positional context of the heart rate data set, the heart rate data set was synchronized with the positional data set, utilizing the UTC timestamps included in each data set. From there, the average heart rate was found for each point and the closest vertex to that location was raised to that value. 2D heat maps were also available from storing the value of each vertex in an array and not raising the vertex, shown in Figure 15. A linear interpolation of color is used to show the variation from high to low, red representing high values and blue representing low values. Since both maps represent where the participant traveled, any unusual points could represent issues within the tracking system of the HoloLens during the training session.

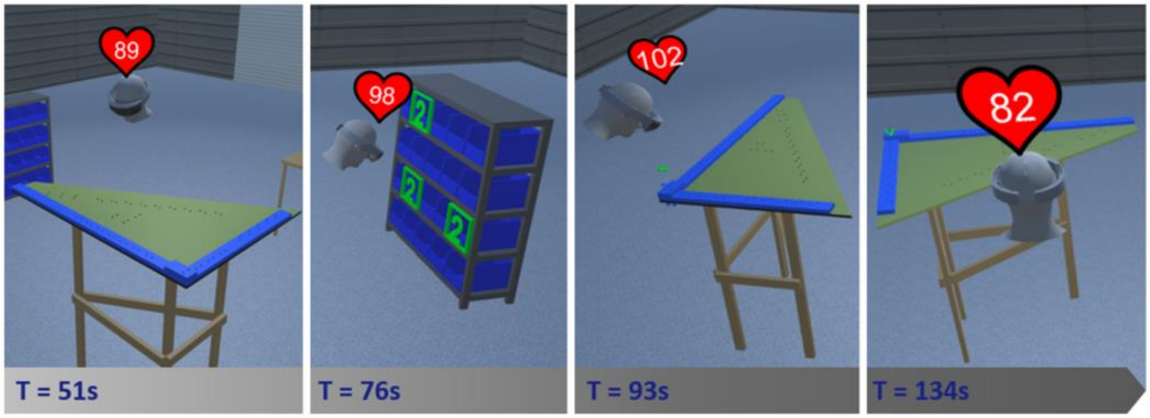

Figure 3.13. Analysis of heart rate data over time.

The development of this application using Unity3D allowed for multi-platform build support. The data visualization tool’s codebase was build-platform agnostic meaning that it could be deployed on any platform supported by Unity3D. While a major use case of this application was to give additional evidence during statistical analysis, commonly performed on a computer, it could also be highly beneficial to make a quick high-level analysis and validation in the field. For this purpose, the application was deployed on a commodity smartphone. This would allow the analyst the ability to review the session with all the collected data shortly after the training session to make sure that the instructions were being delivered accurately so adjustments may be made during the training process.

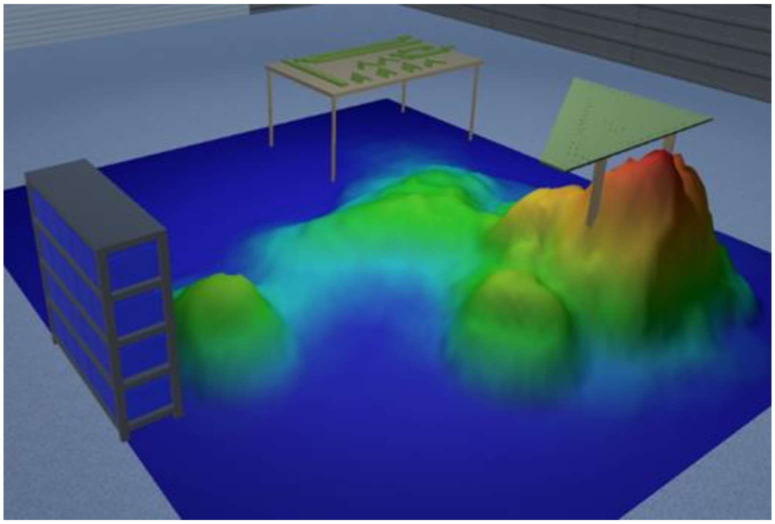

Figure 3.14. 3D positional heat map.

The capabilities of this application present many unique opportunities regarding data analysis. The purpose of this application was to provide a high-level analysis to augment traditional statistical methods by helping to explain trends already found or generating new leads to explore further. In addition, time studies would also benefit greatly from a tool of this nature. Instead of the time-consuming process of overserving how a task is performed, the analyst could quickly scrub through the session to identify major trends paired along with the heat maps generated.

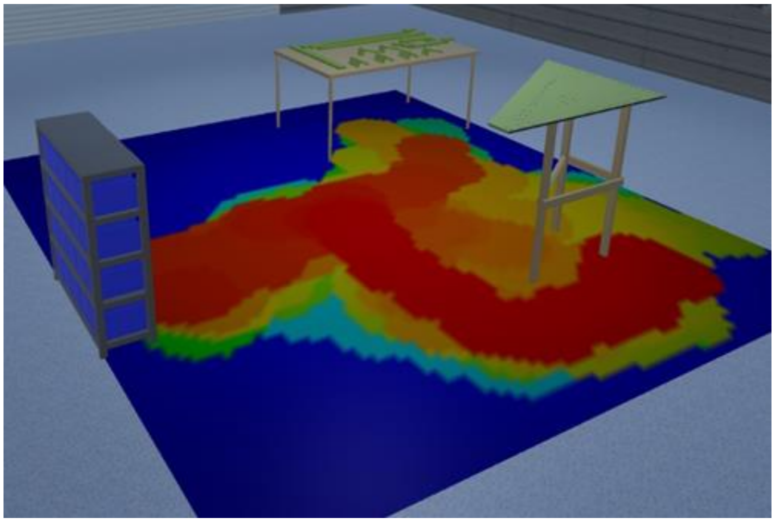

Figure 3.15. 2D average heart rate heat map.

For example, a prior study, using the same experimental setup, found that participants had significantly higher average heart rates on parts picking and assembly steps compared to parts placing steps (Hoover, MacAllister, Holub, Gilbert, & Winer, 2016). However, there was no explanation to why this had occurred. By combining positional, rotational, step time, and heart rate data into the data visualization tool, a hypothesis could be formed. Figure 13 shows a timeline of a user who experienced a change in heart rate over the course of a picking and assembly step. The user moved from a placing step to a picking step requiring them to bend down to reach the fasteners required. Their heart rate spiked, and it was possible to see this physiological response continue into the assembly following step. After this, their heart rate returned to normal. From this high-level analysis, it is possible to hypothesize that the increased heart rate was caused by poor ergonomic conditions during the picking step. While the statistical analysis in Hoover et al. showed significantly higher heart rates for picking and assembly steps, this additional evidence shows that the elevated assembly step heart rate may be due to the physiological response carrying over from the picking step preceding it (Hoover et al., 2016).

Conclusion

The research presented in this paper explored novel solutions to overcome the limitations of the Microsoft HoloLens for delivering assembly work instructions and an approach for analyzing the data collected during the training session. Due to the HoloLens' various limitations including input, field of view, tracking and occlusion, the work instructions had to be developed in a way that mitigated these issues. The approach described in this paper allowed for an accurate delivery of work instructions for a 46-step mock wing assembly. To ensure these work instructions were delivered accurately through the HoloLens, a data visualization application was developed to validate the assembly training session along with an analysis of spatial drift data collected through 83 trials. In addition, it is important to ensure the user is properly trained for the assembly task. Through the same data visualization application, an analyst may explore trends to establish the overall readiness level of the user for the field.

Future work will explore new transparent HMDs that improve upon the limitations of the HoloLens. While this paper gives a novel approach to mitigating the current limitations, improvements in hardware would likely further the success of AR delivered work instructions. The Meta 2, Daqri Smart Glasses, and Magic Leap are three such products that have been released after the HoloLens and boast improved performance. Assessing the limitations of these new transparent HMDs may allow for a better understanding of the ideal method of delivering AR work instructions. However, despite any hardware improvements that these devices may bring, additional work is needed to explore the methods of input for AR work instruction applications. Ideally, the user would be able to deliver input to the device hands-free. The input methods for current transparent HMDs often require a clicker device or unintuitive gesture controls. The usability of these systems could be greatly improved by a better understanding of how users will best interact with them.

References

Apple. (2018). ARKit - Apple Developer. Retrieved February 28, 2019, from https://developer.apple.com/arkit/

Aromaa, S., Aaltonen, I., Kaasinen, E., Elo, J., & Parkkinen, I. (2016). Use of wearable and augmented reality technologies in industrial maintenance work. In *Proceedings of the 20th International Academic Mindtrek Conference on - AcademicMindtrek '16* (pp. 235–242). New York, New York, USA: ACM Press. https://doi.org/10.1145/2994310.2994321

Azuma, R. (1997). A survey of augmented reality. *Presence: Teleoperators and Virtual Environments*. Retrieved from http://www.mitpressjournals.org/doi/abs/10.1162/pres.1997.6.4.355

Azuma, R., Baillot, Y., Behringer, R., Feiner, S., Julier, S., & MacIntyre, B. (2001). Recent advances in augmented reality. *IEEE Computer Graphics and Applications*, *21*(6), 34–47. https://doi.org/10.1109/38.963459

Baird, K. M., & Barfield, W. (1999). Evaluating the effectiveness of augmented reality displays for a manual assembly task. *Virtual Reality*, *4*(4), 250–259. https://doi.org/10.1007/BF01421808

Biocca, F. A., & Rolland, J. P. (1998). Virtual Eyes Can Rearrange Your Body: Adaptation to Visual Displacement in See-Through, Head-Mounted Displays. *Presence: Teleoperators*, *7*(3), 262–277. https://doi.org/10.1162/105474698565703

Blattgerste, J., Strenge, B., Renner, P., Pfeiffer, T., & Essig, K. (2017). Comparing Conventional and Augmented Reality Instructions for Manual Assembly Tasks. In *Proceedings of the 10th International Conference on PErvasive Technologies Related to Assistive Environments - PETRA '17* (pp. 75–82). https://doi.org/10.1145/3056540.3056547

Caudell, T. P., & Mizell, D. W. (1992). Augmented reality: an application of heads-up display technology to manual manufacturing processes. In *Proceedings of the Twenty-Fifth Hawaii International Conference on System Sciences* (pp. 659–669 vol.2). https://doi.org/10.1109/HICSS.1992.183317

Cheng, H., Yang, L., & Liu, Z. (2016). Survey on 3D Hand Gesture Recognition. *IEEE Transactions on Circuits and Systems for Video Technology*, *26*(9), 1659–1673. https://doi.org/10.1109/TCSVT.2015.2469551

Chi, H.-L. (2013). Research trends and opportunities of augmented reality applications in architecture, engineering, and construction. *Automation in Construction*, *33*, 116–122. https://doi.org/10.1016/J.AUTCON.2012.12.017

Chimienti, V., Iliano, S., Dassisti, M., Dini, G., & Failli, F. (2010). Guidelines for implementing augmented reality procedures in assisting assembly operations. *IFIP Advances in Information and Communication Technology*, *315*, 174–179. https://doi.org/10.1007/978-3-642-11598-1_20

Comport, A. I., Marchand, E., Pressigout, M., & Chaumette, F. (2006). Real-time markerless tracking for augmented reality: The virtual visual servoing framework. In *IEEE*

Transactions on Visualization and Computer Graphics (Vol. 12, pp. 615–628). https://doi.org/10.1109/TVCG.2006.78

Davis, L., Clarkson, E., & Rolland, J. P. (2003). Predicting accuracy in pose estimation for marker-based tracking. *Proceedings - 2nd IEEE and ACM International Symposium on Mixed and Augmented Reality, ISMAR 2003*, 28–35. https://doi.org/10.1109/ISMAR.2003.1240685

Echtler, F., Sturm, F., Kindermann, K., Klinker, G., Stilla, J., Trilk, J., & Najafi, H. (2004). The intelligent welding gun: Augmented reality for experimental vehicle construction. In *Virtual and Augmented Reality Applications in Manufacturing* (pp. 333–360). London: Springer London. https://doi.org/10.1007/978-1-4471-3873-0_17

Ellis, S. R., Breant, F., Adelstein, B. D., Jacoby, R., & Manges, B. (1997). Factors influencing operator interaction with virtual objects viewed via head-mounted see-through displays: viewing conditions and rendering latency. In *Proceedings of IEEE 1997 Annual International Symposium on Virtual Reality* (pp. 138–145). Albuquerque: IEEE. https://doi.org/10.1109/vrais.1997.583063

Evans, G., Miller, J., Iglesias Pena, M., MacAllister, A., & Winer, E. (2017). Evaluating the Microsoft HoloLens through an augmented reality assembly application. In J. (Jack) N. Sanders-Reed & J. (Trey) J. Arthur (Eds.) (p. 101970V). International Society for Optics and Photonics. https://doi.org/10.1117/12.2262626

Fiorentino, M., Uva, A. E., Gattullo, M., Debernardis, S., & Monno, G. (2014). Augmented reality on large screen for interactive maintenance instructions. *Computers in Industry*, *65*(2), 270–278. https://doi.org/10.1016/J.COMPIND.2013.11.004

Friedrich, W. (2002). ARVIKA-augmented reality for development, production and service. *Proceedings. International Symposium on Mixed and Augmented Reality*, 3–4. https://doi.org/10.1109/ISMAR.2002.1115059

Funk, M., Kosch, T., & Schmidt, A. (2016). Interactive worker assistance: comparing the effects of in-situ projection, head-mounted displays, tablet, and paper instructions. In *Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing* (pp. 934–939). New York, New York, USA: ACM. https://doi.org/10.1145/2971648.2971706

Google. (2018). ARCore - Google Developer. Retrieved February 28, 2019, from https://developers.google.com/ar/

Goose, S., Sudarsky, S., Xiang Zhang, & Navab, N. (2003). Speech-enabled augmented reality supporting mobile industrial maintenance. *IEEE Pervasive Computing*, *2*(1), 65–70. https://doi.org/10.1109/MPRV.2003.1186727

Henderson, S., & Feiner, S. (2011). Exploring the benefits of augmented reality documentation for maintenance and repair. *IEEE Transactions on Visualization and Computer Graphics*, *17*(10), 1355–1368. https://doi.org/10.1109/TVCG.2010.245

Hoover, M., Miller, J., Gilbert, S., Winer, E., & Davies, P. (2018). Evaluating Augmented Reality Assembly Instructions Delivered via Microsoft HoloLens (pp. 1–14). Interservice/Industry Training, Simulation, and Education Conference (I/ITSEC).

Hou, L., Wang, X., & Truijens, M. (2015). Using Augmented Reality to Facilitate Piping Assembly: An Experiment-Based Evaluation. *Journal of Computing in Civil Engineering*, *29*(1), 05014007. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000344

Jae-Young Lee, Hyung-Min Park, Seok-Han Lee, Tae-Eun Kim, & Jong-Soo Choi. (2011). Design and Implementation of an Augmented Reality System Using Gaze Interaction. *2011 International Conference on Information Science and Applications*, 1–8. https://doi.org/10.1109/ICISA.2011.5772406

Kato, H., & Billinghurst, M. (1999). Marker tracking and HMD calibration for a video-based augmented reality conferencing system. *Proceedings - 2nd IEEE and ACM International Workshop on Augmented Reality, IWAR 1999*, 85–94. https://doi.org/10.1109/IWAR.1999.803809

Khuong, B. M., Kiyokawa, K., Miller, A., La Viola, J. J., Mashita, T., & Takemura, H. (2014). The effectiveness of an AR-based context-aware assembly support system in object assembly. In *2014 IEEE Virtual Reality (VR)* (pp. 57–62). IEEE. https://doi.org/10.1109/VR.2014.6802051

Krevelen, D. W. F. van, & Poelman, R. (2010). A Survey of Augmented Reality Technologies, Applications and Limittions. *The International Journal of Virtual Reality*, *9*(2), 1–20. https://doi.org/10.1155/2011/721827

Loch, F., Quint, F., & Brishtel, I. (2016). Comparing video and augmented reality assistance in manual assembly. In *Proceedings - 12th International Conference on Intelligent Environments, IE 2016* (pp. 147–150). https://doi.org/10.1109/IE.2016.31

MacAllister, A., Gilbert, S., Holub, J., Winer, E., & Davies, P. (2016). Comparison of Navigation Methods in Augmented Reality Guided Assembly. *Interservice/Industry Training, Simulation and Education Conference (I/ITSEC)*, (16075), 1–14.

Marner, M. R., Irlitti, A., & Thomas, B. H. (2013). Improving procedural task performance with Augmented Reality annotations. In *2013 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)* (pp. 39–48). IEEE. https://doi.org/10.1109/ISMAR.2013.6671762

Martin, P., Marchand, E., Houlier, P., & Marchal, I. (2014). Decoupled mapping and localization for Augmented Reality on a mobile phone. In *Proceedings - IEEE Virtual Reality* (pp. 97–98). IEEE. https://doi.org/10.1109/VR.2014.6802069

Martinetti, A., Rajabalinejad, M., & Van Dongen, L. (2017). Shaping the Future Maintenance Operations: Reflections on the Adoptions of Augmented Reality Through Problems and Opportunities. *Procedia CIRP*, *59*, 14–17. https://doi.org/10.1016/j.procir.2016.10.130

Office of the Under Secretary of Defense (Comptroller). (2018a). DoD Fiscal Year 2018 Budget Proposal. Retrieved May 22, 2018, from https://www.defense.gov/News/News-Releases/News-Release-View/Article/1190216/dod-releases-fiscal-year-2018-budget-proposal/

Office of the Under Secretary of Defense (Comptroller). (2018b). Operation and Maintenance Overview Fiscal Year 2018 Budget Estimates. Retrieved May 29, 2018, from http://comptroller.defense.gov/Portals/45/Documents/defbudget/fy2018/fy2018_OM_Overview.pdf

Ong, S. K., Yuan, M. L., & Nee, A. Y. C. (2008). Augmented reality applications in manufacturing: a survey. *International Journal of Production Research*, *46*(10), 2707–2742. https://doi.org/10.1080/00207540601064773

Palmarini, R. (2017). An Innovative Process to Select Augmented Reality (AR) Technology for Maintenance. *Procedia CIRP*, *59*, 23–28. https://doi.org/10.1016/J.PROCIR.2016.10.001

Platonov, J., Heibel, H., Meier, P., & Grollmann, B. (2006). A mobile markerless AR system for maintenance and repair. In *2006 IEEE/ACM International Symposium on Mixed and Augmented Reality* (pp. 105–108). IEEE. https://doi.org/10.1109/ISMAR.2006.297800

Radkowski, R., Herrema, J., & Oliver, J. (2015). Augmented Reality-Based Manual Assembly Support With Visual Features for Different Degrees of Difficulty. *International Journal of Human-Computer Interaction*, *31*(5), 337–349. https://doi.org/10.1080/10447318.2014.994194

Rautaray, S. S., & Agrawal, A. (2012). Vision based hand gesture recognition for human computer interaction: a survey. *Artificial Intelligence Review*, *43*(1), 1–54. https://doi.org/10.1007/s10462-012-9356-9

Renner, P., & Pfeiffer, T. (2017). Attention guiding techniques using peripheral vision and eye tracking for feedback in augmented-reality-based assistance systems. In *2017 IEEE Symposium on 3D User Interfaces (3DUI)* (pp. 186–194). IEEE. https://doi.org/10.1109/3DUI.2017.7893338

Richardson, T., Gilbert, S., Holub, J., Thompson, F., MacAllister, A., Radkowski, R., … Terry, S. (2014). Fusing Self-Reported and Sensor Data from Mixed-Reality Training. In *I/ITSEC* (pp. 1–12). Retrieved from http://www.frederickt.com/pubs/iitsec2014.pdf

Rolland, J. P., & Fuchs, H. (2000). Optical Versus Video See-Through Head-Mounted Displays in Medical Visualization. *Presence: Teleoperators and Virtual Environments*, *9*(3), 287–309. https://doi.org/10.1162/105474600566808

Rolland, J. P., Holloway, R. L., & Fuchs, H. (1995). Comparison of optical and video see-through, head-mounted displays. In *International Society for Optics and Photonics*. https://doi.org/10.1117/12.197322

Sanna, A., Manuri, F., Lamberti, F., Member, S., Paravati, G., & Pezzolla, P. (2015). Using Handheld Devices to Support Augmented Reality-based Maintenance and Assembly Tasks. *IEEE International Conference on Consumer Electronics (ICCE) Using*, 178–179. https://doi.org/10.1109/ICCE.2015.7066370

Schwerdtfeger, B., & Klinker, G. (2008). Supporting order picking with Augmented Reality. In *2008 7th IEEE/ACM International Symposium on Mixed and Augmented Reality* (pp. 91–94). IEEE. https://doi.org/10.1109/ISMAR.2008.4637331

Shah, M. M., Arshad, H., & Sulaiman, R. (2012). Occlusion in Augmented Reality. *8th International Conference on Information Science and Digital Content Technology (ICIDT 2012)*, *2*, 372–378.

Syberfeldt, A., Holm, M., Danielsson, O., Wang, L., & Brewster, R. L. (2016). Support Systems on the Industrial Shop-floors of the Future – Operators' Perspective on Augmented Reality. *Procedia CIRP*, *44*, 108–113. https://doi.org/10.1016/J.PROCIR.2016.02.017

Tang, A., Owen, C., Biocca, F., & Mou, W. (2003). Comparative effectiveness of augmented reality in object assembly. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 73–80). New York, New York, USA: ACM Press. https://doi.org/10.1145/642625.642626

Tatić, D., & Tešić, B. (2017). The application of augmented reality technologies for the improvement of occupational safety in an industrial environment. *Computers in Industry*, *85*, 1–10. https://doi.org/10.1016/j.compind.2016.11.004

Tepper, O. M., Rudy, H. L., Lefkowitz, A., Weimer, K. A., Marks, S. M., Stern, C. S., & Garfein, E. S. (2017). Mixed reality with hololens: Where virtual reality meets augmented reality in the operating room. *Plastic and Reconstructive Surgery*, *140*(5), 1066–1070. https://doi.org/10.1097/PRS.0000000000003802

Uva, A. E., Gattullo, M., Manghisi, V. M., Spagnulo, D., Cascella, G. L., & Fiorentino, M. (2017). Evaluating the effectiveness of spatial augmented reality in smart manufacturing: a solution for manual working stations. *The International Journal of Advanced Manufacturing Technology*, *94*(1–4), 509–521. https://doi.org/10.1007/s00170-017-0846-4

Vuforia. (2018). Optimizing Target Detection and Tracking Stability. Retrieved May 22, 2018, from https://library.vuforia.com/articles/Solution/Optimizing-Target-Detection-and-Tracking-Stability.html

Wagner, D., Pintaric, T., Ledermann, F., & Schmalstieg, D. (2005). Towards Massively Multi-user Augmented Reality on Handheld Devices (pp. 208–219). Springer, Berlin, Heidelberg. https://doi.org/10.1007/11428572_13

Wang, Z. B., Ong, S. K., & Nee, A. Y. C. (2013). Augmented reality aided interactive manual assembly design. *The International Journal of Advanced Manufacturing Technology*, *69*(5–8), 1311–1321. https://doi.org/10.1007/s00170-013-5091-x

Webel, S., Bockholt, U., Engelke, T., Gavish, N., Olbrich, M., & Preusche, C. (2013). An augmented reality training platform for assembly and maintenance skills. *Robotics and Autonomous Systems*, *61*(4), 398–403. https://doi.org/10.1016/J.ROBOT.2012.09.013

Wloka, M. M., & Anderson, B. G. (1995). Resolving occlusion in augmented reality. In *Proceedings of the 1995 symposium on Interactive 3D graphics - SI3D '95* (pp. 5–12). New York, New York, USA: ACM Press. https://doi.org/10.1145/199404.199405

Yang, X., Si, X., Xue, T., Zhang, L., & Cheng, K.-T. (Tim). (2015). Vision-Inertial Hybrid Tracking for Robust and Efficient Augmented Reality on Smartphones. *Proceedings of the 23rd ACM International Conference on Multimedia*, 1039–1042.

https://doi.org/10.1145/2733373.2806396

Yew, A. W. W., Ong, S. K., & Nee, A. Y. C. (2016). Towards a griddable distributed manufacturing system with augmented reality interfaces. *Robotics and Computer-Integrated Manufacturing*, *39*, 43–55. https://doi.org/10.1016/j.rcim.2015.12.002

Zhu, J., Ong, S. K., & Nee, A. Y. C. (2015). A context-aware augmented reality assisted maintenance system. *International Journal of Computer Integrated Manufacturing*, *28*(2), 213–225. https://doi.org/10.1080/0951192X.2013.874589

CHAPTER 4. CONCLUSIONS

The research presented in this thesis presented novel solutions to overcome the hardware limitations of commodity AR HMDs for use in product assembly applications. These limitations included issues with input, user interface, spatial registration, navigation, and occlusion. A variety of input devices were considered for an assembly application. However, the Microsoft Bluetooth clicker was chosen as it would allow the user to remain hands free during the assembly process while providing an intuitive input method. Prior user interface research was taken into consideration to make the most of the HoloLens' limited field of view and display capabilities. The spatial registration capabilities of the HoloLens' were augmented using Vuforia to allow for image target tracking capabilities. This additional tracking functionality allowed for enhanced accuracy and stabilization of spatial content. To navigate within large 3D environments, a navigational gate system was developed which intuitively guides users to points of interest. Finally, proper occlusion of virtual and physical parts was necessary to ensure that work instructions are displayed with the proper depth perception cues. By utilizing the enhanced tracking capabilities, virtual representations of physical parts were generated to allow for accurate occlusion.

In addition, data regarding how drift accumulated during the assembly task was collected from 83 trials. This data was then analyzed to better understand how drift may affect the registration of the work instructions and assess if the techniques implemented to mitigate this drift was effective. It was found that when the drift correction technique was enabled, the spatial drift at any given point was lower than the uncorrected counterpart. These results show that this technique was effective in mitigating the spatial drift, allowing for the accurate delivery of work instructions over an extended period of time.

Finally, this research includes an approach to fuse data collected from different sources during the assembly process and provide a means to validate that work instructions were accurately delivered. During the assembly process, data was collected from the sensors on the HoloLens including head position, orientation, step completion times and an estimation of the drift accumulated. This data, along with physiological sensor data from the Empatica E4 and post processed error data, was synchronized and fused within a visualization application. This application allows an analyst to ensure that work instructions were properly displayed while also providing tools to discover new trends with in the data. The data from disparate sources were synchronized and displayed in an intuitive manner for this to be achieved. 3D and 2D heat maps were dynamically generated over a view of the virtual training environment to provide a new perspective and what trends occurred during the training scenario.

CHAPTER 5. FUTURE WORK

Future work on this topic should explore new commodity AR HMDs that come to market and their use case in delivering product assembly work instructions. Since the technology behind these devices is still under development, many of the current hardware limitations may be resolved in the future, providing enhanced functionality. Furthermore, if hardware limitations persist, it would be beneficial to deploy the hardware mitigation techniques described in this paper to these new HMDs and assess their effectiveness.

A large area of research that would benefit from additional work is input methods for AR and specifically delivering work instructions in AR. Currently, there is no widely accepted input method for AR devices and further research is needed to understand how users may interact with AR content and what provides the best user experience. Furthermore, AR assembly instructions have additional limitations as it is ideal to keep the user hands-free so they may work while receiving directions. A user study would provide critical insight on what input methods may be the most efficient, effective and usable for delivering work instructions in AR.

Additionally, the data visualization application described in this paper would benefit tremendously from user testing and refinement. The approach described in this paper focuses on the technical challenges to fuse data from disparate sources to provide functionality for an analyst to understand a training session. By performing user research on how an analyst may use a tool of this nature, a greater understanding of what features are necessary may be achieved. This would drastically increase the usability and effectiveness of the analysis tool.

Finally, the drift estimation analysis was based on data collected from the HoloLens itself and may therefore include error from a variety of sources. To further validate the tracking capabilities of the HoloLens, it would be ideal to use a third-party high-end tracking system, such as a VICON tracking system, to compare the tracking data against the HoloLens' perceived spatial registration. This additional analysis would both evaluate the HoloLens in whole as well as the mitigation techniques developed for this research.

REFERENCES

Apple. (2018). ARKit - Apple Developer. Retrieved February 28, 2019, from https://developer.apple.com/arkit/

Aromaa, S., Aaltonen, I., Kaasinen, E., Elo, J., & Parkkinen, I. (2016). Use of wearable and augmented reality technologies in industrial maintenance work. In *Proceedings of the 20th International Academic Mindtrek Conference on - AcademicMindtrek '16* (pp. 235–242). New York, New York, USA: ACM Press. https://doi.org/10.1145/2994310.2994321

Azuma, R. (1997). A survey of augmented reality. *Presence: Teleoperators and Virtual Environments*. Retrieved from http://www.mitpressjournals.org/doi/abs/10.1162/pres.1997.6.4.355

Azuma, R., Baillot, Y., Behringer, R., Feiner, S., Julier, S., & MacIntyre, B. (2001). Recent advances in augmented reality. *IEEE Computer Graphics and Applications*, *21*(6), 34–47. https://doi.org/10.1109/38.963459

Baird, K. M., & Barfield, W. (1999). Evaluating the effectiveness of augmented reality displays for a manual assembly task. *Virtual Reality*, *4*(4), 250–259. https://doi.org/10.1007/BF01421808

Biocca, F. A., & Rolland, J. P. (1998). Virtual Eyes Can Rearrange Your Body: Adaptation to Visual Displacement in See-Through, Head-Mounted Displays. *Presence: Teleoperators*, *7*(3), 262–277. https://doi.org/10.1162/105474698565703

Blattgerste, J., Strenge, B., Renner, P., Pfeiffer, T., & Essig, K. (2017). Comparing Conventional and Augmented Reality Instructions for Manual Assembly Tasks. In *Proceedings of the 10th International Conference on PErvasive Technologies Related to Assistive Environments - PETRA '17* (pp. 75–82). https://doi.org/10.1145/3056540.3056547

Caudell, T. P., & Mizell, D. W. (1992). Augmented reality: an application of heads-up display technology to manual manufacturing processes. In *Proceedings of the Twenty-Fifth Hawaii International Conference on System Sciences* (pp. 659–669 vol.2). https://doi.org/10.1109/HICSS.1992.183317

Cheng, H., Yang, L., & Liu, Z. (2016). Survey on 3D Hand Gesture Recognition. *IEEE Transactions on Circuits and Systems for Video Technology*, *26*(9), 1659–1673. https://doi.org/10.1109/TCSVT.2015.2469551

Chi, H.-L. (2013). Research trends and opportunities of augmented reality applications in architecture, engineering, and construction. *Automation in Construction*, *33*, 116–122. https://doi.org/10.1016/J.AUTCON.2012.12.017

Chimienti, V., Iliano, S., Dassisti, M., Dini, G., & Failli, F. (2010). Guidelines for implementing augmented reality procedures in assisting assembly operations. *IFIP Advances in Information and Communication Technology*, *315*, 174–179. https://doi.org/10.1007/978-3-642-11598-1_20

Comport, A. I., Marchand, E., Pressigout, M., & Chaumette, F. (2006). Real-time markerless tracking for augmented reality: The virtual visual servoing framework. In *IEEE Transactions on Visualization and Computer Graphics* (Vol. 12, pp. 615–628). https://doi.org/10.1109/TVCG.2006.78

Davis, L., Clarkson, E., & Rolland, J. P. (2003). Predicting accuracy in pose estimation for marker-based tracking. *Proceedings - 2nd IEEE and ACM International Symposium on*

Mixed and Augmented Reality, ISMAR 2003, 28–35. https://doi.org/10.1109/ISMAR.2003.1240685

Echtler, F., Sturm, F., Kindermann, K., Klinker, G., Stilla, J., Trilk, J., & Najafi, H. (2004). The intelligent welding gun: Augmented reality for experimental vehicle construction. In *Virtual and Augmented Reality Applications in Manufacturing* (pp. 333–360). London: Springer London. https://doi.org/10.1007/978-1-4471-3873-0_17

Ellis, S. R., Breant, F., Adelstein, B. D., Jacoby, R., & Manges, B. (1997). Factors influencing operator interaction with virtual objects viewed via head-mounted see-through displays: viewing conditions and rendering latency. In *Proceedings of IEEE 1997 Annual International Symposium on Virtual Reality* (pp. 138–145). Albuquerque: IEEE. https://doi.org/10.1109/vrais.1997.583063

Evans, G., Miller, J., Iglesias Pena, M., MacAllister, A., & Winer, E. (2017). Evaluating the Microsoft HoloLens through an augmented reality assembly application. In J. (Jack) N. Sanders-Reed & J. (Trey) J. Arthur (Eds.) (p. 101970V). International Society for Optics and Photonics. https://doi.org/10.1117/12.2262626

Fiorentino, M., Uva, A. E., Gattullo, M., Debernardis, S., & Monno, G. (2014). Augmented reality on large screen for interactive maintenance instructions. *Computers in Industry*, *65*(2), 270–278. https://doi.org/10.1016/J.COMPIND.2013.11.004

Friedrich, W. (2002). ARVIKA-augmented reality for development, production and service. *Proceedings. International Symposium on Mixed and Augmented Reality*, 3–4. https://doi.org/10.1109/ISMAR.2002.1115059

Funk, M., Kosch, T., & Schmidt, A. (2016). Interactive worker assistance: comparing the effects of in-situ projection, head-mounted displays, tablet, and paper instructions. In *Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing* (pp. 934–939). New York, New York, USA: ACM. https://doi.org/10.1145/2971648.2971706

Google. (2018). ARCore - Google Developer. Retrieved February 28, 2019, from https://developers.google.com/ar/

Goose, S., Sudarsky, S., Xiang Zhang, & Navab, N. (2003). Speech-enabled augmented reality supporting mobile industrial maintenance. *IEEE Pervasive Computing*, *2*(1), 65–70. https://doi.org/10.1109/MPRV.2003.1186727

Henderson, S., & Feiner, S. (2011). Exploring the benefits of augmented reality documentation for maintenance and repair. *IEEE Transactions on Visualization and Computer Graphics*, *17*(10), 1355–1368. https://doi.org/10.1109/TVCG.2010.245

Hoover, M., Miller, J., Gilbert, S., Winer, E., & Davies, P. (2018). Evaluating Augmented Reality Assembly Instructions Delivered via Microsoft HoloLens (pp. 1–14). Interservice/Industry Training, Simulation, and Education Conference (I/ITSEC).

Hou, L., Wang, X., & Truijens, M. (2015). Using Augmented Reality to Facilitate Piping Assembly: An Experiment-Based Evaluation. *Journal of Computing in Civil Engineering*, *29*(1), 05014007. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000344

Jae-Young Lee, Hyung-Min Park, Seok-Han Lee, Tae-Eun Kim, & Jong-Soo Choi. (2011). Design and Implementation of an Augmented Reality System Using Gaze Interaction. *2011 International Conference on Information Science and Applications*, 1–8. https://doi.org/10.1109/ICISA.2011.5772406

Kato, H., & Billinghurst, M. (1999). Marker tracking and HMD calibration for a video-based augmented reality conferencing system. *Proceedings - 2nd IEEE and ACM*

International Workshop on Augmented Reality, IWAR 1999, 85–94. https://doi.org/10.1109/IWAR.1999.803809

Khuong, B. M., Kiyokawa, K., Miller, A., La Viola, J. J., Mashita, T., & Takemura, H. (2014). The effectiveness of an AR-based context-aware assembly support system in object assembly. In *2014 IEEE Virtual Reality (VR)* (pp. 57–62). IEEE. https://doi.org/10.1109/VR.2014.6802051

Krevelen, D. W. F. van, & Poelman, R. (2010). A Survey of Augmented Reality Technologies, Applications and Limittions. *The International Journal of Virtual Reality*, *9*(2), 1–20. https://doi.org/10.1155/2011/721827

Loch, F., Quint, F., & Brishtel, I. (2016). Comparing video and augmented reality assistance in manual assembly. In *Proceedings - 12th International Conference on Intelligent Environments, IE 2016* (pp. 147–150). https://doi.org/10.1109/IE.2016.31

MacAllister, A., Gilbert, S., Holub, J., Winer, E., & Davies, P. (2016). Comparison of Navigation Methods in Augmented Reality Guided Assembly. *Interservice/Industry Training, Simulation and Education Conference (I/ITSEC)*, (16075), 1–14.

Marner, M. R., Irlitti, A., & Thomas, B. H. (2013). Improving procedural task performance with Augmented Reality annotations. In *2013 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)* (pp. 39–48). IEEE. https://doi.org/10.1109/ISMAR.2013.6671762

Martin, P., Marchand, E., Houlier, P., & Marchal, I. (2014). Decoupled mapping and localization for Augmented Reality on a mobile phone. In *Proceedings - IEEE Virtual Reality* (pp. 97–98). IEEE. https://doi.org/10.1109/VR.2014.6802069

Martinetti, A., Rajabalinejad, M., & Van Dongen, L. (2017). Shaping the Future Maintenance Operations: Reflections on the Adoptions of Augmented Reality Through Problems and Opportunities. *Procedia CIRP*, *59*, 14–17. https://doi.org/10.1016/j.procir.2016.10.130

Office of the Under Secretary of Defense (Comptroller). (2018a). DoD Fiscal Year 2018 Budget Proposal. Retrieved May 22, 2018, from https://www.defense.gov/News/News-Releases/News-Release-View/Article/1190216/dod-releases-fiscal-year-2018-budget-proposal/

Office of the Under Secretary of Defense (Comptroller). (2018b). Operation and Maintenance Overview Fiscal Year 2018 Budget Estimates. Retrieved May 29, 2018, from http://comptroller.defense.gov/Portals/45/Documents/defbudget/fy2018/fy2018_OM_Overview.pdf

Ong, S. K., Yuan, M. L., & Nee, A. Y. C. (2008). Augmented reality applications in manufacturing: a survey. *International Journal of Production Research*, *46*(10), 2707–2742. https://doi.org/10.1080/00207540601064773

Palmarini, R. (2017). An Innovative Process to Select Augmented Reality (AR) Technology for Maintenance. *Procedia CIRP*, *59*, 23–28. https://doi.org/10.1016/J.PROCIR.2016.10.001

Platonov, J., Heibel, H., Meier, P., & Grollmann, B. (2006). A mobile markerless AR system for maintenance and repair. In *2006 IEEE/ACM International Symposium on Mixed and Augmented Reality* (pp. 105–108). IEEE. https://doi.org/10.1109/ISMAR.2006.297800

Radkowski, R., Herrema, J., & Oliver, J. (2015). Augmented Reality-Based Manual Assembly Support With Visual Features for Different Degrees of Difficulty.

International Journal of Human-Computer Interaction, *31*(5), 337–349. https://doi.org/10.1080/10447318.2014.994194

Rautaray, S. S., & Agrawal, A. (2012). Vision based hand gesture recognition for human computer interaction: a survey. *Artificial Intelligence Review*, *43*(1), 1–54. https://doi.org/10.1007/s10462-012-9356-9

Renner, P., & Pfeiffer, T. (2017). Attention guiding techniques using peripheral vision and eye tracking for feedback in augmented-reality-based assistance systems. In *2017 IEEE Symposium on 3D User Interfaces (3DUI)* (pp. 186–194). IEEE. https://doi.org/10.1109/3DUI.2017.7893338

Richardson, T., Gilbert, S., Holub, J., Thompson, F., MacAllister, A., Radkowski, R., … Terry, S. (2014). Fusing Self-Reported and Sensor Data from Mixed-Reality Training. In *I/ITSEC* (pp. 1–12). Retrieved from http://www.frederickt.com/pubs/iitsec2014.pdf

Rolland, J. P., & Fuchs, H. (2000). Optical Versus Video See-Through Head-Mounted Displays in Medical Visualization. *Presence: Teleoperators and Virtual Environments*, *9*(3), 287–309. https://doi.org/10.1162/105474600566808

Rolland, J. P., Holloway, R. L., & Fuchs, H. (1995). Comparison of optical and video see-through, head-mounted displays. In *International Society for Optics and Photonics*. https://doi.org/10.1117/12.197322

Sanna, A., Manuri, F., Lamberti, F., Member, S., Paravati, G., & Pezzolla, P. (2015). Using Handheld Devices to Support Augmented Reality-based Maintenance and Assembly Tasks. *IEEE International Conference on Consumer Electronics (ICCE) Using*, 178–179. https://doi.org/10.1109/ICCE.2015.7066370

Schwerdtfeger, B., & Klinker, G. (2008). Supporting order picking with Augmented Reality. In *2008 7th IEEE/ACM International Symposium on Mixed and Augmented Reality* (pp. 91–94). IEEE. https://doi.org/10.1109/ISMAR.2008.4637331

Shah, M. M., Arshad, H., & Sulaiman, R. (2012). Occlusion in Augmented Reality. *8th International Conference on Information Science and Digital Content Technology (ICIDT 2012)*, *2*, 372–378.

Syberfeldt, A., Holm, M., Danielsson, O., Wang, L., & Brewster, R. L. (2016). Support Systems on the Industrial Shop-floors of the Future – Operators' Perspective on Augmented Reality. *Procedia CIRP*, *44*, 108–113. https://doi.org/10.1016/J.PROCIR.2016.02.017

Tang, A., Owen, C., Biocca, F., & Mou, W. (2003). Comparative effectiveness of augmented reality in object assembly. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 73–80). New York, New York, USA: ACM Press. https://doi.org/10.1145/642625.642626

Tatić, D., & Tešić, B. (2017). The application of augmented reality technologies for the improvement of occupational safety in an industrial environment. *Computers in Industry*, *85*, 1–10. https://doi.org/10.1016/j.compind.2016.11.004

Tepper, O. M., Rudy, H. L., Lefkowitz, A., Weimer, K. A., Marks, S. M., Stern, C. S., & Garfein, E. S. (2017). Mixed reality with hololens: Where virtual reality meets augmented reality in the operating room. *Plastic and Reconstructive Surgery*, *140*(5), 1066–1070. https://doi.org/10.1097/PRS.0000000000003802

Uva, A. E., Gattullo, M., Manghisi, V. M., Spagnulo, D., Cascella, G. L., & Fiorentino, M. (2017). Evaluating the effectiveness of spatial augmented reality in smart manufacturing: a solution for manual working stations. *The International Journal of*

Advanced Manufacturing Technology, *94*(1–4), 509–521. https://doi.org/10.1007/s00170-017-0846-4

Vuforia. (2018). Optimizing Target Detection and Tracking Stability. Retrieved May 22, 2018, from https://library.vuforia.com/articles/Solution/Optimizing-Target-Detection-and-Tracking-Stability.html

Wagner, D., Pintaric, T., Ledermann, F., & Schmalstieg, D. (2005). Towards Massively Multi-user Augmented Reality on Handheld Devices (pp. 208–219). Springer, Berlin, Heidelberg. https://doi.org/10.1007/11428572_13

Wang, Z. B., Ong, S. K., & Nee, A. Y. C. (2013). Augmented reality aided interactive manual assembly design. *The International Journal of Advanced Manufacturing Technology*, *69*(5–8), 1311–1321. https://doi.org/10.1007/s00170-013-5091-x

Webel, S., Bockholt, U., Engelke, T., Gavish, N., Olbrich, M., & Preusche, C. (2013). An augmented reality training platform for assembly and maintenance skills. *Robotics and Autonomous Systems*, *61*(4), 398–403. https://doi.org/10.1016/J.ROBOT.2012.09.013

Wloka, M. M., & Anderson, B. G. (1995). Resolving occlusion in augmented reality. In *Proceedings of the 1995 symposium on Interactive 3D graphics - SI3D '95* (pp. 5–12). New York, New York, USA: ACM Press. https://doi.org/10.1145/199404.199405

Yang, X., Si, X., Xue, T., Zhang, L., & Cheng, K.-T. (Tim). (2015). Vision-Inertial Hybrid Tracking for Robust and Efficient Augmented Reality on Smartphones. *Proceedings of the 23rd ACM International Conference on Multimedia*, 1039–1042. https://doi.org/10.1145/2733373.2806396

Yew, A. W. W., Ong, S. K., & Nee, A. Y. C. (2016). Towards a griddable distributed manufacturing system with augmented reality interfaces. *Robotics and Computer-Integrated Manufacturing*, *39*, 43–55. https://doi.org/10.1016/j.rcim.2015.12.002

Zhu, J., Ong, S. K., & Nee, A. Y. C. (2015). A context-aware augmented reality assisted maintenance system. *International Journal of Computer Integrated Manufacturing*, *28*(2), 213–225. https://doi.org/10.1080/0951192X.2013.874589