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Evaluating the Microsoft HoloLens through an augmented reality assembly application

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ABSTRACT

Industry and academia have repeatedly demonstrated the transformative potential of Augmented Reality (AR) guided assembly instructions. In the past, however, computational and hardware limitations often dictated that these systems were deployed on tablets or other cumbersome devices. Often, tablets impede worker progress by diverting a user's hands and attention, forcing them to alternate between the instructions and the assembly process. Head Mounted Displays (HMDs) overcome those diversions by allowing users to view the instructions in a hands-free manner while simultaneously performing an assembly operation. Thanks to rapid technological advances, wireless commodity AR HMDs are becoming commercially available. Specifically, the pioneering Microsoft HoloLens, provides an opportunity to explore a hands-free HMD's ability to deliver AR assembly instructions and what a user interface looks like for such an application. Such an exploration is necessary because it is not certain how previous research on user interfaces will transfer to the HoloLens or other new commodity HMDs. In addition, while new HMD technology is promising, its ability to deliver a robust AR assembly experience is still unknown. To assess the HoloLens' potential for delivering AR assembly instructions, the cross-platform Unity 3D game engine was used to build a proof of concept application. Features focused upon when building the prototype were: user interfaces, dynamic 3D assembly instructions, and spatially registered content placement. The research showed that while the HoloLens is a promising system, there are still areas that require improvement, such as tracking accuracy, before the device is ready for deployment in a factory assembly setting.

Keywords: Microsoft HoloLens, Augmented Reality, Augmented Reality Assembly, Head Mounted Display

1. INTRODUCTION

AR's forecasted market revenue of $80+ billion by 2021 has not gone unnoticed by entrepreneurs and investors. Many companies such as Microsoft, Google, Apple, and DAQRI are taking an interest in this technology. Consequently, AR's user and consumer community could potentially increase well into the millions.[1-3] This potentially revolutionizing technology is characterized as any display that overlays spatially registered 3D content, including computer-generated models, onto a user's view of the environment in real time.[4] This technology has experienced acceptance, and popularity in domains from consumer gaming to industrial applications. Specifically, technological development for AR in manufacturing and assembly is fueled by its proven benefits such as improved first time quality and reduced training times.[5-8] AR assembly studies have shown that one advantage of superimposing digitally rendered objects in the real world is that they help guide the positioning of different assembly parts to their respective location. AR, also, eliminates the need to read long and detailed instructions by replacing that information with 3D models, signifiers, animations, and visual feedback. This allows a user to focus on the assembly task at hand.[7,9-12]

Although AR has shown great potential in assembly-based applications, previous delivery methods have restricted the technology from reaching its full potential. Many systems referenced in literature were built for research purposes rather than for commercial use, meaning that these devices are not commercially available for purchase and are not stable enough to distribute to consumers.[13-15] Also, until recently, AR has been developed for use on tablets, mobile phones, and bulky HMDs due to technological constraints. As a result, many AR content delivery devices do not allow for hands free operation, constraining the user's movements and ability to interact with the physical world. This impedes the user's process by diverting their hands and focus away from the assembly, forcing them to alternate between the assembly tasks and the instructions. However, with recent advances in computing power and display technologies, new devices that offer hands free see-through Head Mounted Displays (HMDs), like the Microsoft HoloLens and the DAQRI Smart Helmet, are becoming commercially available.[16,17] By implementing an assembly-based application on a hands-free

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device, the user would then be able to reduce their unnecessary movements, no longer having to switch their attention between the instruction delivery device and the assembly task.[18,19]

While the benefits of HMDs are clear, moving away from handheld devices to hands free HMDs introduces another problem: 3D user interfaces. Unlike in past AR delivery devices, HMDs do not rely on the use of touch screens or a mouse and keyboard to navigate the application. This suggests that HMD devices for AR will likely focus on implementing gesture interactions. Unfortunately, there is a shortage of User Interface (UI) guidelines for AR HMDs. Most of these guidelines are found through experimental reports as developers or content creators have tested their product during the development process. This suggests that many guidelines are not necessarily reinforced by scholarly articles. Even with the limited research-based UI guidelines for AR applications, it's uncertain how they translate to new commercially available HMD devices. Fortunately, using research from the field of Virtual Reality (VR) can help guide the creation of a user-friendly AR assembly instruction interfaces.

Virtual Reality (VR) is a similar type of technology that uses computer generated content to create a virtual world that users can interact with. In contrast to AR, VR environments are isolated from the real world as all content is computer generated and the user's view is completely occluded form the physical world. VR technology is often implemented and used in fully occluded HMD devices, such as the Oculus Rift. As a result of VR's consistent implementation in HMD devices, 3D UI and interaction guidelines have been developed and explored over the years. This is in contrast with AR, where the implementation of its content on HMD devices is less developed. Due to the similarities in content and now delivery devices, drawing on VR's previous knowledge can help develop more user friendly AR interfaces. This can ultimately lead to an enhanced user experience, increasing the likelihood of AR adoption. Specifically, VR principles like affordances, visibility, feedback, usability, 3D user interfaces, and interactions can help guide AR interface creation.[20,21] In addition to VR guidelines and design principles, it's possible to glean information from current AR UI guidelines for tablet and mobile devices.[8,22] Additionally, Microsoft has also provided some guidelines for the HoloLens, gathered through their own internal testing and user studies.[23-26] However, Microsoft's guidelines only provide case studies and general guidelines for developers. By fusing available research on user interfaces for HMDs with a prototype HoloLens AR assembly application, valuable insight can be gained on the feasibility of creating a user-friendly hands free interface.

Even with the proven benefits of AR, many opportunities still exist to increase its effectives. One such area of opportunity is to explore the development of an AR application on a commercial HMD and to investigate creating a user-friendly interface for such an application. This paper focuses on the design and development of a manufacturing-based assembly application. The chosen AR device was the Microsoft HoloLens because of the system's commercial availability and numerous unique features such as a high-resolution display, ability to spatially map objects, gesture interface, gaze, and voice recognition control mechanism. The HoloLens is the only commercially available AR HMD capable of spatially mapping its environment that is currently on the market. That commercial availability allows researchers and developers to experiment and discover the capabilities the system provides. Unfortunately, because of the recent and rapid development of HMDs, only a minimal amount of academic research has pointed out how to build an assembly application for AR HMDs. For that reason, there is a limited amount of information about possible issues that might come up during the development process. To investigate those issues, this application is intended to be a proof of concept design, focused on implementing a user-friendly interface, supported through established guidelines and research. The developed application includes AR instructions for a tabletop assembly built using the Unity3D game engine and deployed onto the HoloLens.[27] The proof of concept application intends to demonstrate the use of a simple and intuitive user interface, use and integration of 3D models, and spatially registered object positioning.

2. BACKGROUND

Academic research on users performing assembly tasks illustrated the first-time quality improvements and time savings benefits that Augmented Reality (AR) work instructions provided over their traditional 2D manual counterparts. A vast majority of that research highlighted the advantages of AR for training individuals on a tablet or digital 2D interface, but lacked an evaluation of AR instructions on a wireless, commodity, HMD. The lack of research covering AR instructions on HMDs is largely due to ergonomic and technical constraints that have traditionally made research on that specific topic infeasible. Those roadblocks include bulky or tethered HMDs, low-resolution displays, short battery life, and inadequate computing power on mobile platforms. However, recently there have been many advances in high fidelity displays and computing capabilities on mobile platforms. These advances have led to a commodity see-through HMD which may have the ability to deliver AR instructions on a hands-free device. Unfortunately, due to the aforementioned roadblocks, past AR work doesn't provide adequate guidance on the design of 3D User Interfaces and the corresponding 3D user interactions. Understanding how to develop a UI for AR instructions on a HMD is extremely important because the interface, and the corresponding 3D user interactions, drastically differs from the traditional 2D Windows Icons Menus Pointer (WIMP) system. Fortunately, research in VR emphasizes the key components of an effective 3D UI while also alluding to the challenges associated with 3D user interactions. Implementing a 3D interface on a commodity HMD in order to ultimately display AR instructions would provide many added benefits to the user. With the aforementioned technological advances, the development community may now be able to break through the barriers that have restricted such research in the past. The following section will discuss previous work on AR in manufacturing, challenges with previous technologies, and the design requirements for a gesture based 3D UI that would be necessary to support AR assembly instructions on an HMD.

2.1 Augmented reality for manufacturing and assembly

Augmented Reality affords a user many benefits when compared to traditional 2D work instructions. In a manufacturing or training environment this technology allows the user to dynamically see exactly where a part, fastener, or tool must go.[4] An analysis of the system's effectiveness and proposed benefits must be tested in a controlled academic study before that system can be implemented in industry. To analyze the benefits of tablet based AR, Richardson et al. conducted a between-subjects experiment. Quantitative and qualitative data were gathered, measuring the effectiveness of three modes of instruction delivery for an AR assembly training application. The modes included traditional model based instructions (MBI) on a stationary desktop, the same MBI on a moveable tablet, and finally AR work instructions on a tablet. The AR instructions guided the user to assemble the product with eight times greater first time quality when compared to the traditional desktop MBI. In addition, the users completed the assembly in 33% less time while using the AR work instructions.[8] Richardson also collected user location data by tracking the head position of the user during the study. The results of that data showed that participants using desktop and tablet MBI spent more time traveling about the work cell than the participants using tablet AR instructions. The reduction in travel for those using AR instructions granted them more time to spend focusing on the assembly itself.[8] Baird and Barfield studied 4 modes of manual assembly instructions and determined that the two AR methods were superior to the two traditional delivery methods in terms of completion time.[19] Additionally, Chryssolouris evaluated the use of AR assembly instructions in manufacturing and found that they contributed to reduced product development times and cost savings while simultaneously improving first time quality and market response times.[28] In addition to the sources mentioned above, numerous other studies point to the effectiveness of AR work instruction delivery.[19,29,30,12]

While the benefits of AR are proven, certain ergonomic and usability restrictions impede them from reaching wide adoption. Baird and Barfield's evaluation of AR instructions in manufacturing, which showed substantial time savings, also noted that the AR methods faced usability issues due to ergonomic factors. These ergonomic considerations include, but are not limited to, heavy headsets, laptop powered displays, and wired devices which cause tripping hazards. Furthermore, work by Starner and Mann, and Wagner, revealed that traditional AR work instructions have been limited to using a tablet or a bulky, tethered, HMD as the display device due to technical and ergonomic constraints.[31,32] Additional work by Dunleavy et al. showed that the HMDs used for AR work instructions have had relatively low graphical fidelity, hindering the effectiveness of such devices.[33] While tablets mounted on an arm or movable stand are effective at displaying the AR work instructions, they often lack the mobility required for an assembly task at a workstation. Mounted tablets used for AR work instructions restrict the number of accessible vantage points due to tablet holder constraints. Through a user study Aromaa et al. found that when a participant performed an assembly task while using AR work instructions on a tablet without a holder they had to put the tablet down, momentarily disconnecting them form the spatially registered instructions.[34] Although AR work instructions are highly beneficial, the aforementioned restrictions imposed by the previously utilized delivery devices have prevented wide adoption of AR technology in manufacturing.

Many of the limitations associated with tablet AR work instructions can be addressed by delivering the AR instructions on a wireless optical see through HMD. Caudell and Mizell demonstrated how this type of device's hands free capability allows the user to perform assembly operations while simultaneously changing their vantage point and the position of the dynamic AR instructions.[35] Research from the late 1990s showed the potential for AR instruction delivery through an

HMD but at the time many crucial elements had yet to be addressed. Azuma found that in order for such a device to be feasible in assembly operations it must be lightweight, computationally powerful, able to display high fidelity graphics, and finally be able to interpret specific user input and the environment.[36] Unfortunately, due to insufficient technology, at least one of those criteria was compromised in one way or another during previous studies.[4] However, Reed and Dongarra found that, over the past two decades, computing power has grown substantially.[37] In addition, high-resolution displays now provide levels of graphical fidelity that were unfathomable in the late 1990s. Those advances address two of the important criteria that Azuma noted would be necessary for the widespread adoption of AR technology.[36] Finally, the development community and researchers alike are beginning to see commodity HMD devices that may capable of providing the functionality necessary to successfully display AR assembly instructions. Using previous research as a guide, the authors developed an AR assembly instructions application to explore a commodity HMD's ability to deliver AR work instructions.

2.2 Designing User Interfaces in Virtual Environments

Traditional work on AR instructions delivered via HMDs is limited due to previous technological shortcomings, however, the vast research covering 3D UIs and user interactions in Virtual Environments (VEs) can afford insight into potential solutions. While technology has hindered HMD development in the past, a 2015 article by Reed and Dongarra attests to the recent advances in computing power and high-resolution displays.[36] With this progress, it is conceivable that HMDs will be both ergonomically friendly and technically capable in the next 5 years. Consequently, the development community must address the challenges associated with designing user friendly UIs and physical button free 3D user interactions in order for a complete system to be feasible. The main issue regarding 3D UIs is the necessary transition from a 2D WIMP system to 3D menus and interactions without a customary mouse. All user interactions must be intuitive and for optimal functionality they should be accessible by hand gestures, not a wand, controller, or another physical device. Harnessing the plethora of research covering UI design in VEs provided guidelines for the development of a research based 3D UI for this application.

While the processing power, resolution, battery life, and ergonomics of a device are extremely important, an appropriately designed user interface and realistic looking models are also necessary for a robust and user-friendly AR system. Sherman and Craig discovered the necessity of carefully designing the elements in a 3D UI in order to achieve the highest levels of presence and immersion in a VE.[38] AR and Virtual Reality (VR) simulations are designed to trick the user into believing that the models and animations are almost identical to what they would experience in real life. Without adequate presence and immersion, the VE a user will be able to distinguish the stark contrast between the simulation and reality, ultimately diminishing the user experience. Pausch et al. conducted research to quantify those required levels of immersion based on the type of visual and auditory feedback users received while interacting with their environment.[39] In addition to providing natural feedback, Crison et al. found that utilizing high fidelity models, which accurately represent their real life counterparts, was crucial for an immersive VE.[40] To further elevate the level of immersion for a user, Argelaguet found that in VR training simulations the specific menu types, input options, and user interactions must be carefully chosen to fit the use case at hand.[41] Leveraging this, and a plethora of other knowledge gained from VR research, provides insight into what can be done to address the challenges associated with displaying AR instructions on an HMD. McMahan backed up Argelaguet's statement that selection techniques must be tailored to specific applications in addition to mentioning that the Field of View (FoV) must be adequate for the designated use case.[41,42] Bowman et al. conducted various user studies in order to determine what content a proper 3D UI should contain as well as how the user should interact with it in various scenarios.[20] His work lays out guidelines for the design and development of 3D UIs in addition to covering 3D interaction techniques such as selection and object manipulation. Finally, he covers the evaluation of 3D interfaces based on their defining characteristics and specific metrics.[20]

In light of the rapid advances in computing capabilities and high-resolution displays that were noted by Reed and Dongarra, it is proposed that the development community has reached a time at which it is beneficial to evaluate AR instructions on an HMD.[37] An innovative design and the aforementioned technological advances have yielded an ergonomic and highly capable optical see-through HMD in the form of the Microsoft HoloLens. It will be necessary to utilize the 3D design guidelines dictated by Bowman et al. and the plethora of other authors who laid the groundwork for 3D user interfaces on such a device. Melding that knowledge into an AR assembly instructions application deployed on the HoloLens will allow for feasibility testing of such as system. This paper aims to evaluate the effectiveness of a cutting edge wireless HMD's ability to display AR instructions. The HMD application will ultimately be compared to the research-based benefits of tablet based AR instructions.

3. METHODOLOGY

The methodology section discusses the hardware selection, UI development, and application development processes. The hardware section describes why the Microsoft HoloLens was chosen over its competitors and the key features that allow it to be a suitable device for an assembly application. The UI development section describes the design of the UI and the choices made based on prior academic research. Finally, the application development section describes the tools used to develop this application and the challenges that had to be overcome.

3.1 Hardware

While AR HMD's have been used in the past, they are often expensive and custom made for research. The Microsoft HoloLens is the first commercially available AR HMD to reach the market. The HoloLens was first released as a development edition in 2016 and is now available as a consumer version. Since this device is so new, and the HoloLens is first to market in this area, there are little to no competitors for consumer grade wireless AR HMDs. The Google Glass was marketed as an AR device, however it is merely a transparent display lacking many necessary features, such as spatial mapping and a usable display, to interact with the real world and provide true AR capabilities. Another AR HMD, the Daqri Smart Helmet, is designed for industrial use but is currently still in development. Since the Smart Helmet is being designed for manufacturing use cases, it may be beneficial to explore AR assembly applications on this device in the future. Since the Google Glass is not capable of running AR assembly applications and the Daqri Smart Helmet is not yet released, the Microsoft HoloLens is the ideal choice for investigating an AR assembly application on a commercially available device.

The decision to use the HoloLens to investigate an AR assembly application on a HMD is strengthened by its' state of the art capabilities. Unlike AR HMDs in the past, the Microsoft HoloLens is a completely self-contained HMD, i.e, it does not require the HMD to be tethered to a separate computing device. The HoloLens features four Intel Atom x5-Z8100 1.04 GHz Intel Airmont Logical Processors, a HPU/GPU Holographic Processing Unit, 64 GB Flash, 2 GB RAM and 2-3 hours of active battery life that allows standalone operation of this device. All of this processing power is used to run 2 HD 16:9 light engines that project light through holographic lenses leading to a total resolution of 2.3 million light points. High resolution spatially located 3D content is generated by this system. The HoloLens also includes an Inertial Measurement Unit (IMU), 4 environment-processing cameras, a RGB camera, and 1 depth camera to map its surroundings and allow interaction between the real and virtual world while tracking the device's position. Other features include 4 microphones, gaze tracking, gesture input, spatial sound and voice support. The HoloLens is shown in Figure 1 below.

Figure 1. The Microsoft HoloLens.

3.2 UI Development and Development Principles

When considering the implementation of the HoloLens in a factory environment, specifically when developing the UI, the following aspects need to be kept in mind: the expected user, the use case, intended interactions, and the user's surroundings. By catering the application's interface design to the intended user and implementing design standards, potential user harm or desired task complications can be avoided. Hence, with the help of aforementioned guidelines from similar technologies, developers can start building an assembly application with a user friendly UI. This section provides an overview of different established guidelines in AR user interfaces and VR best practices. The established guidelines helped develop a better understanding of what the proof of concept application implements, along with a set of suggestions for developing an AR assembly application for the HoloLens.

The expected user, factory workers or assembly technicians, are constantly surrounded by busy and noisy spaces, therefore, the different UI components should be accessible, simple, and visible for the user to employ, regardless of the environment. If the UI fails to be simple and clear, the worker could potentially be harmed or cause an incident, raising uncertainty about the application's usability and safety. Hence, poor UIs hinder the user's work or progress, which is the opposite of what a UI should do. However, there are very few specific protocols that help guide the design of AR interfaces on HMDs. Fortunately, there is work that can be drawn on to guide a friendly UI. These guidelines provided their insights on user considerations, 3D graphical UIs and graphical design standards, gestural interface UI interactions, and VR implementations on 3D elements in order to build a foundation. The exploration of those sources led to a list of necessary requirements for creating the UI. Microsoft's Senior Holographic Designer acknowledged that there aren't any strict best practices for 3D UI and interaction design pertinent to the HoloLens, and much of their discoveries and suggestions are based off on their own internal testing.[16] Furthermore, the HoloLens applications' interfaces are considered to be a mixture between 2D and 3D, mainly due the lack of AR UI design principles or standardization. However, this hybrid combination of 3D interfaces and 2D GUIs can help facilitate navigational structures as it provides a softer transition to a new technology (AR HMDs) with familiar UI elements in order to avoiding frustrating or scaring the user away.[43] There are some basic design principles that every new user-based technology should follow: visibility (or affordances), feedback, consistency, non-destructive operations (e.g., undo), discoverability, scalability, and reliability.[44] Even as AR enters a more interactive and gestured based phase, developers can always rely on these principles in order to help create a successful interface.

Due to the expected type of environment the application will be used on, the application designers opted not to use voice commands. By not using the voice command, the application minimized the user's need to remember commands, reducing their cognitive load. Hence, the application only focused on the HoloLens gaze and gesture actions, which allows users to navigate and interact with the UI. To aid in the application's simplicity, any unnecessary information was stripped out and only the essential elements to guide an assembly task were implemented. The application focused on the following elements: next and previous step, description of the current step, guided animation of current step, and the ability to verify the list of steps and jump to any on those.[8] These elements indicate their functionality through the incorporation of basic graphic design principles, such as distinguishing something that is a button versus something that it's not, allowing the UI to maintain cohesiveness throughout the application. Additionally, the UI elements incorporated visual guidelines such as color, form, size and the implementation of icons. The combination of all of the presented guiding principles can influence the application's interface design.

3.3 UI Implementation

With the guidance of the previous suggestions the following section presents the different UI elements in the prototype system. These sections include the reasoning behind element placement, text, color choices, feedback, element shape and form, buttons, icons, and the steps menu, all of which affect a user's experience and interaction with the application.

Element Placement – All elements, including buttons, descriptions, arrows, etcetera, are placed at a comfortable distance (anything between 1m -10meters) from the user. These distances are derived from VR HMDs that have initial screens (optional first screen that allows the user to enter or edit data/options before moving on) and interactive elements; such research concluded that anything less than 0.5 meters is considered the "no-no zone" or an uncomfortable placement area.[25,26,45,46] By placing the elements in an accessible and away from possible intrusive zones, the user can comfortably use the UI, reducing eye-strain and intrusiveness. Additionally, one tradeoff was aligning the elements within the factory worker's field of view, defined by the HoloLens. An overview of the elements in the UI is shown in Figure 2 below.

Figure 2. Initial User Interface.

Text – Font size was decided to be 20pt in order to provide legibility within the application.[47] Also shown in Figure 3 below, the application uses a popular and widely available sans serif font, Arial. A sans serif font was chosen because serif fonts do not render well on screens and users seem to prefer sans serif fonts when reading computer generated text since it can help minimize confusion and eye-strain.[48,49,51] With the aid of a bigger text size and screen-friendly text, the assembly technician can easily read and understand the information that the text presents to them, avoiding possible confusion, eye-strain, and system render issues. These guidelines transferred well in to the HoloLens application, due to the font's wide standardization and usage in digital or non-print media content.

Figure 3. Button on "Selected" state.

Color Choices - Taking into account the different environments the application could be used in, the integrated colors manage to keep a high contrast between each other for legibility. It should also be noted to avoid using black, as it is perceived as "transparent" in AR and avoid using pure white, as it appears as too "bright".[23,47] The selected colors reflected the choice of providing a combination of both bright and calming colors. The brighter or lighter colors are implemented to stand out from the environment and calming colors are meant to not distract the user while providing a sense of presence. No major issues were encountered when transferring from a computer screen to an HMD; brightness, hue, and saturation were relatively true. Since pure black and white have proven to be at a disadvantage in AR, the designers avoided using pure RGB colors, and provide a more harmonious combination of colors. The following colors were selected from Microsoft's color palette and other AR application color schemes: RGB blue 0,120,215 (used for buttons and backgrounds; shown in Figure 2), RGB dark blue 0,77,11 (for descriptive text on white backgrounds; shown in Figure 2 and Figure 4), RGB green 16,124,16 (feedback change when button is pressed; shown in Figure 3), Bright green RGB 0, 255,44 (for object location; shown in Figure 4), RGB white 242,242,242 (used for icon, text, and background; shown in Figure 2 and Figure 4), RGB yellow 255, 255, 0 (used to indicate direction and gazing cursor; shown in Figure 5 and Figure 6), and RGB orange 216, 59, 1 (for hover button state, the eye is focused but item has not been selected; shown in Figure 6).[23,47,51,52] As a result, providing different colors to specific behaviors and elements, along with other UI aspects, the user is able to frame, identify, and distinguish different UI elements in the real world.

When applied to the HoloLens, these colors did not present any brightness or saturation issues and were able to be captured well in the applications UI.

Figure 4. Parts table UI

Figure 5. Directional Gates

Feedback – Feedback is a way of assuring the user, in this case through visual cues, that a performed action has been executed. By ensuring that different elements provide feedback to the user, the elements become visible and provide a good conceptual model to the user.[21] The application focuses on the implementation of color change or highlight (user focuses or selects an element; shown in Figure 3 and Figure 6), animation and movement (open and close of the menu; shown in Figure 2 and Figure 6), and appending (checkmark to indicate completeness; shown in Figure 7). Through feedback, the factory worker is assured that some sort of action has been performed, avoiding possible feelings of confusion and frustration. The different types of behaviors or feedback had to be simplified or generalized in order to execute them in the HoloLens, due to the restrictions within the provided HoloLens coding. This means that manipulating various elements within a specific area proved to be too complicated due to the scarcity of specific documentation and development case studies.

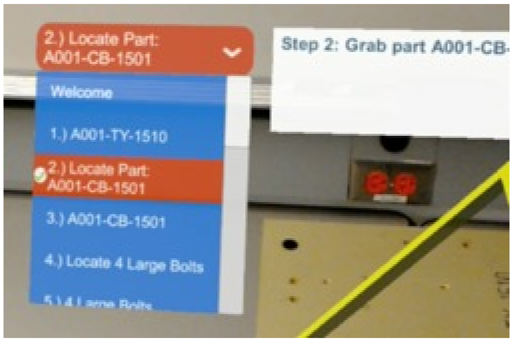

Figure 6. Steps Menu UI and gaze cursor.

Framing and Billboard Styling – Billboard style or "framing" is the surrounding shape in an UI element, allowing any text-based or icon-based UI element to stand out from the background. This style was used for the both the buttons and descriptive-text in order to differentiate from other elements in the environment. Figure 2, 4, and 6 show how the descriptive-text was designed with a white background and blue text with a straight edged billboard. AR text integration research shows that blue and white provides to best combination when there is not a plain environment background.[51,52] Figure 2 and 4 demonstrate how the buttons have a blue background and rounded billboard with white text and icon whenever it's idle, differentiating them from the descriptive-text billboards. By having the buttons look different in both color choices (inverted) and form, visual differences for the assembly technician to pick up on are established, along with helping frame the UI from the real world. Additionally, the development of different forms and billboards proved to be an easy transferable guide for the HoloLens.

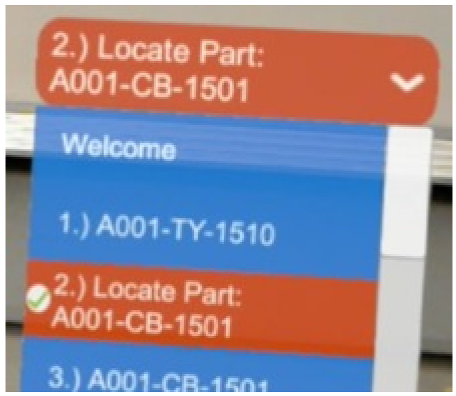

Figure 7. Steps Menu step checkmark.

UI Elements – The UI elements the application focuses on are icons and buttons. The application emphasizes on implementing 2 simple icons, along with appropriate identifiable labels, which minimize user memorization and cognitive overload.[22,53] The first icon is an arrow based element (Figure 2 and 8). Arrows are usually associated with directions, similarly, they are heavily used in WIMP applications, allowing the user to quickly familiarize with them. The arrow in the step menu (Figure 2 and 6), provides a static downward arrow to indicate the user that more information can be accessed, and new options appear if the user has selected and opened the menu. Similarly, the arrow in the buttons (Figure 2, 4 and 8) do not move, however, they indicate direction or the cognitive understanding or going to the previous or next step in the assembly (back and forward). The second icon is a checkmark enclosed in a circle (Figure 7), meant to be used in the step menu as additional feedback for the user. The checkmark icon is meant to express an indication of completeness, due to its positive association with good, correct, or success.[54] The implementation of icons and labels help the factory worker quickly understand what each element does, reducing the time they take to familiarize with the application. The implementation of different icons within separate elements proved to be an easy task within the HoloLens application development, however, performing an icon movement within the element proved to be a harder task in the HoloLens, which only allows for static icons to populate the UI.

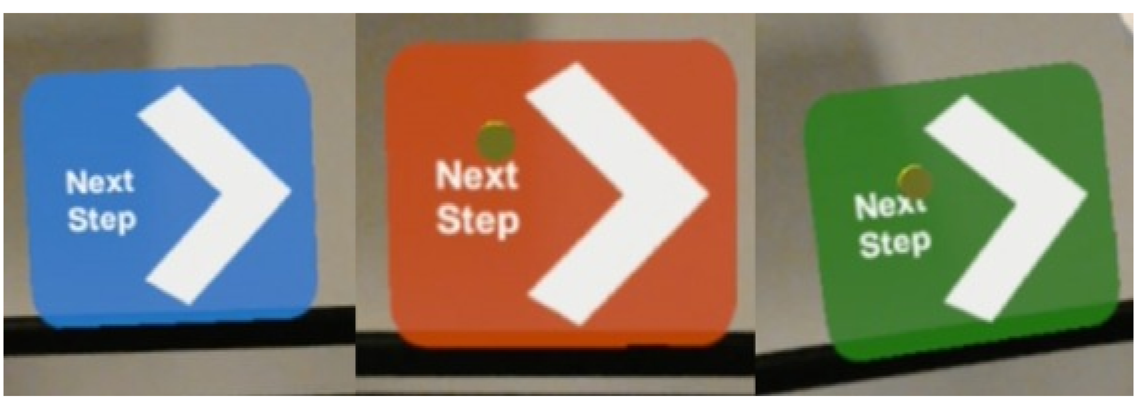

Figure 8. Button states: Idle, Hovering, Selected.

Graphical User Interface (GUI) based buttons are the visual representations that symbolize a possible user action in the environment. By implementing clear affordances and signifiers such as color, feedback, and a different shape from other elements, it can help user to understand their intended actions, even in an AR.[21] The buttons incorporate both text and the arrow icon; the direction of the icon allows the user to understand direction, (going back/forward) and the text label clarifies the button's intended action. Similarly, the implemented button actions are represented through their behavior: idle, user is focused/hovering, and user selection, shown in Figure 8 above. The idle state is portrayed as a rounded billboard with a blue background with a white icon and text. The focused/hovering state denotes that the user's eyes are gazing on top of the button but has not yet been selected. This provides a contrasting color from the idle state (orange background with a white icon and text). The selected state, performed with a hand gesture, has a green background with white text and icon, to indicate a completed action.[45] There's an ongoing debate to as how much WIMP integration should be used in 3D environments, but for now, users don't seem to favor one side entirely. By keeping the UI simple, and adding the appropriate signifiers and affordances, the implementation within the HoloLens application did not present any issues.

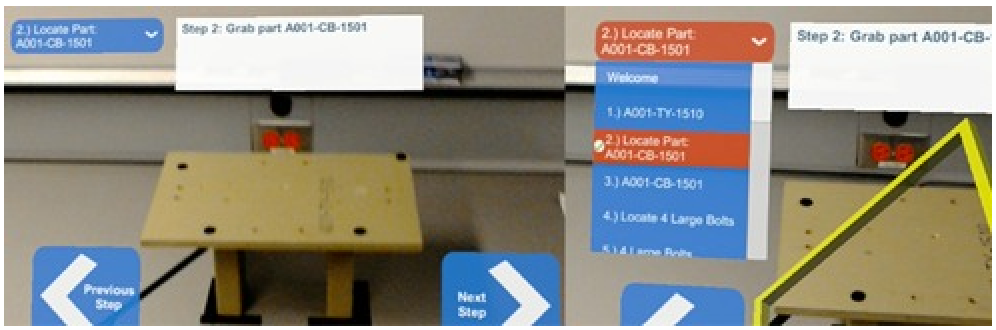

Figure 9. Steps Menu; Left: when menu is closed. Right: when menu is open.

The Steps Menu – The steps menu is modeled after collapsible web menus (shown in Figure 9). The steps menu has similar states as the buttons, due to its interactive nature.[21,22,45,53] Additionally, the checkmark icons appear as supplementary feedback. If the checkmark is present next to a step, this indicates that the user has completed that step (Figure 7).[54] The checkmark icon is a combination of a white circle with a green checkmark. Briefly explained in the icon section, the steps menu also contains an arrow icon, used as a signifier to open and display more of the assembly's steps.[21] The steps menu combines previously discussed elements, creating a uniform and cohesive understanding of what the different elements do even if placed in different zones. The menu is meant to be simple and provide only quick references to the different assembly parts, along with the appropriate behavior and feedback. This allows the assembly technician to quickly refer back to any step and verify which steps have been completed, reducing their cognitive load, while simultaneously providing UI uniformity. The implementation of various steps within a single area transferred well into the HoloLens application development, capturing the idea of organizing matching information in one area.

It is crucial to always keep the user in mind and practice the implementation of founding design guidelines, regardless of any new technology, in addition to understanding how each implemented element might impact the user. Different AR HMD applications might call for other guidelines or specific assembly-related implementations that are not necessarily relatable to this assembly application. Nonetheless, by catering the application's interface to the environment, content, and user, the developers can implement a user friendly UI, reducing the likelihood of unintentionally harming the user or delivering a cumbersome application. The HoloLens has proved to have many advantageous and transferable UI implementations, but developers still need to consider the development limitations and reserved accessible coding implementations the HoloLens provides to developers outside of Microsoft.

3.4 Application Development

The application development section explains the concept of the application, what tools were used, and specific challenges that had to be overcome. The developers generated an AR assembly application in order to assess the capabilities of the Microsoft HoloLens. The following sections describe the outcomes of the assembly application which was developed for the Microsoft HoloLens.

The AR assembly application was developed using Unity3D, Vuforia and the Microsoft HoloLens. For assembly instructions, AR provides the unique advantage of displaying the assembly information over the physical assembly area. This allows for better visualization of the assembly steps over paper based instructions.

In general, this application goes through each step of an assembly process, guiding the user on which parts to pick and how to assemble those parts. For interaction and additional guidance, a UI is included over the assembly and parts area. This UI displays information about the current step along with buttons that allow navigation between steps. Users can also choose a specific step from a dropdown menu. For each step that involves obtaining a part, a green frame is rendered around the correct part to indicate which part is needed. For each assembly step, a virtual object is rendered and may be animated to show the user how the part is to be assembled. The application follows this method of having the user find parts and then assemble them until the assembly is complete.

Developing for the Microsoft HoloLens requires the use of the Universal Windows Platform and creating a Universal Windows Application. These applications need tools designed to take advantage of the Windows Holographic Application Program Interface (API). Microsoft highly recommends that Unity3D is used to do this.[55] It is also possible for developers to build their own engines using DirectX and other Windows APIs.

Unity3D is an excellent development tool for the Microsoft HoloLens. Microsoft provides ample documentation on how to develop for the HoloLens using Unity3D in addition to their guidelines on how to ensure a high quality application. Unity3D removes much of the programmer's burden; it allows for the rapid development of applications by setting up the framework and tools to allow the developer to focus on the content of the application. Developing this assembly application using Unity3D, instead of building a custom engine, allowed for quick development iterations resulting in a high quality assembly application.

The Microsoft HoloLens is able to create a virtual representation of the real world using spatial mapping. Using the depth cameras, the HoloLens is able to map out the surfaces of a room and create a mesh from this data. For many applications this technology may be sufficient for the interaction of holograms with the real world. However, for an assembly application there are intricate steps and the location of the holograms in the real world must be precise. Shown in Figure 10, the spatial mapping mesh is not detailed enough to support an assembly application. The generated mesh is not a complete and accurate representation of the final assembly. To achieve higher precision, a Vuforia plug-in was used to perform marker based tracking. Marker based tracking uses target images recognized by the computer to establish an accurate frame of reference in the real world. This is done though using the RGB camera to detect an image, registered with the application, to deduces the position and orientation of that image. Objects can then be positioned relative to the image with considerable accuracy. The downside of marker based tracking is that images must be placed to define locations in the real world. While spatial mapping does not require markers, limitations in technology do not allow it to be as accurate in defining specific locations with markers. Multiple marker images are used to define the separate locations of the assembly workspace and parts table. This is important because the directional gates guide the user between the assembly workspace and the parts table, which is the location where unassembled parts are stored. After these locations are defined, the HoloLens then takes over control of tracking using its IMU and environment-processing cameras.

Despite requiring a plug-in, the HoloLens has the proper tracking capabilities for an AR assembly application. From a hardware perspective, the HoloLens itself is capable of marker based tracking. All that was required was a simple plug-in for Unity3D to establish which markers were to be used and how they pass pertinent information to the application. Microsoft does currently suggest that if a developer wants to use marker based tracking, that the Vuforia plug-in for Unity3D should be used.[56] After the parts and assembly locations are defined using Vuforia markers, the HoloLens could properly track those positions as the user moves around in the assembly area. That is crucial because without the specific location of each component being tracked, the device cannot achieve true AR capabilities.

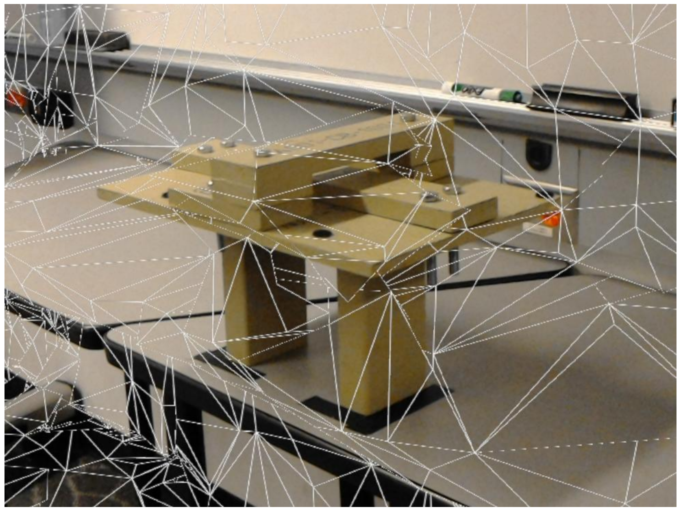

Figure 10. Spatial mapping screenshot of the assembly station through the HoloLens. The mesh does not properly represent the individual parts.

Occlusion in AR refers to one object in 3D space being blocked by another, virtual or real. Occlusion allows the user to have increased depth perception of virtual objects by showing how they are occluded by other virtual or real objects.[57] Kruijff et al. explains that the main issue with occlusion is the incorrect separation of the foreground and background, objects need to be rendered in a particular location occluded by what is in front of it.[58] The depth perception cues given by occlusion shows where an object belongs, and if done incorrectly can lead to objects being perceived in the wrong location. Richardson et al. explored a comparison of AR instruction delivery with tradition model based instructions.[8] This AR system did not include occlusion and users found it difficult to complete various assembly steps due to the lack of occlusion. If occlusion is not included in an assembly application, then users may not be able to properly locate how parts are to be assembled. A virtual part must be occluded by a real part, and vice versa, to give the user proper depth perception cues.

This AR application includes occlusion cues based on prior research done in AR assembly. The holograms of the virtual parts must be occluded by real parts to show a proper representation of how the assembly comes together. While the HoloLens spatial mapping can detect these parts, the mesh is not detailed enough for proper occlusion in an intricate assembly. The mesh may be too big or small leading to the improper occlusion of real and virtual parts. Instead, the authors can use the part locations defined by the image markers using the Vuforia plug-in to determine where parts should be occluded. The location of the assembly station is defined using the Vuforia image markers. Based on that defined position, the location and orientation of every assembled part is defined relative to that position. Therefore, for every real part already assembled, a virtual representation can be placed in that exact location. This representation needs to be completely transparent as it is acting as a virtual placeholder for the real part. To accomplish this, every virtual representation of real parts is rendered matte black, an RGBA value of 0,0,0,0. This is done because the HoloLens uses light engines to render the images on the display. Since matte black is completely void of light, nothing is rendered and the virtual representations are effectively invisible. A shader is then used to display a red mesh outline when one virtual object is occluded by another, shown in Figure 11. The end result is the assembly step holograms being almost perfectly occluded by real parts. Unity3D was able to handle this process without any issues. This workaround is necessary due to the current limits in computer vision technology. Once spatial mapping is accurate enough to define intricate parts, the mesh generated from that mapping will likely be sufficient for proper occlusion.

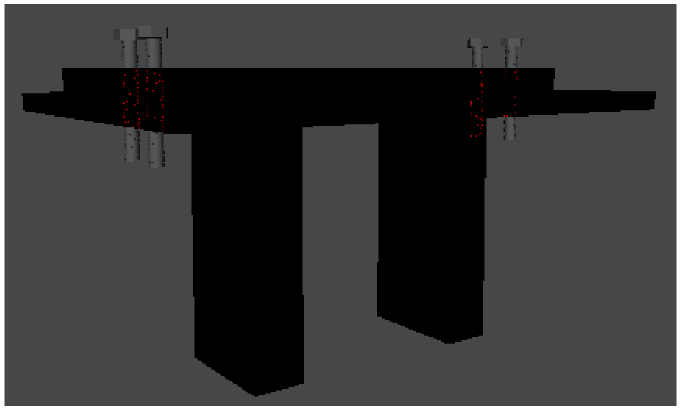

Figure 11. Bolts being occluded by previously assembled parts. The red outline shows a representation of the occluded part. The matte black parts are the virtual representation of previously assembled parts.

In an assembly application it may not always be clear where the next assembly step or part is located, part locations and assembly stations may be located in separate areas of an industrial factory. For this reason, it is necessary to include a navigation system for the user. Previous research indicates that a 3D gate system is preferred and more usable than a 3D arrow system or a heads up display.[59,60] It was found that participants were faster in finding the target object and had a decrease in mental workload while using a 3D gate system.[60] Using a cubic Bezier curve, gates are placed along a path to guide the user to the correct location, shown in Figure 12. This provides an intuitive navigation system that allows the user to find where they need to go without being distracting. These gates also disappear when the user is close to the specific step in order to avoid distractions while picking parts or assembling.

This navigation system was fairly easy to implement using Unity3D. Unity3D had no problem calculating the Bezier curve and the correct orientation of the gates at each frame to ensure a smooth performance. A simple C# script was also included to determine whether the user was within a certain distance and looking at the current part to turn off the gates. Again, Unity3D was able to handle this with ease.

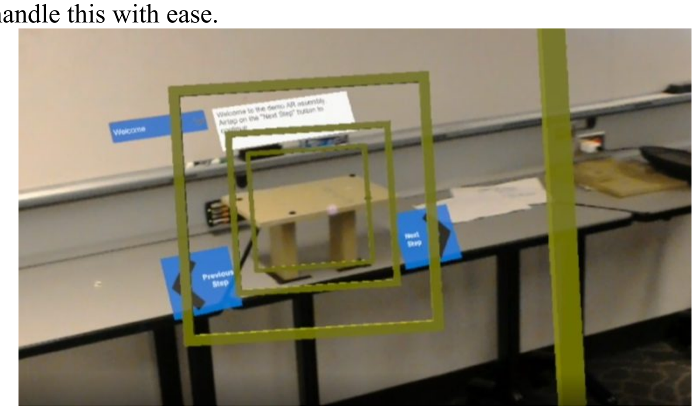

Figure 12. Gate navigation system to guide the user to the proper area.

3.5 Discussion

An AR assembly application on the Microsoft HoloLens proved to be viable using Unity3D. The Microsoft HoloLens has sufficient hardware capabilities for an AR assembly application. Using Unity3D, the authors were able to utilize these capabilities and develop an application that included features necessary for an AR assembly application. The main area of the HoloLens that seemed to be lacking robustness was its' spatial mapping. This system was not accurate enough to create a mesh of intricate parts and a marker based tracking plug-in by Vuforia had to be used. This plug-in allowed the Unity3D application to detect and handle image targets which allows the HoloLens to interpret a known location in the real world and display models at specified offsets from that location.

4. CONCLUSION AND FUTURE WORK

4.1 Conclusion

This application shows that the commercially available Microsoft HoloLens is a viable platform to deliver an application that provides AR assembly instructions. The hardware capabilities of the HoloLens allowed for virtual content to be spatially located correctly enough for assembly instructions. The display also allowed for a detailed UI. Previous academic research in UIs for AR and VR was used to create a UI that was user friendly and well suited for a factory. This included colors, text and icons that are intuitive to a user to reduce distractions and increase usability. The one area in which the HoloLens fell short was tracking the location of the parts and assembly station. An intricate assembly requires precise location capabilities. The HoloLens does have spatial mapping capabilities, however the mesh created is not accurate enough for a detailed assembly application. Vuforia was for marker based tracking to provide accurate locations of the parts and assembly stations. Since commercially available AR is so new, it is important to use previous academic research on best practices to create an application that is functional and usable.

4.2 Future Work

In the future the authors would like to perform a user study to compare this AR HMD assembly application with an AR tablet based assembly application and traditional paper instructions. Previous publications have found many benefits of AR tablet based assembly instructions over traditional paper instructions. It would be beneficial to explore whether or not AR HMD assembly instructions surpass tablet-based AR instructions.

Once released, the Daqri Smart Helmet should also be explored to see if there are benefits to using this device over the Microsoft HoloLens. The Daqri Smart Helmet was designed specifically for an industrial environment and an assembly application of this variety would fall well within its intended use. However, as it is not yet released and it is unclear if the capabilities of the Smart Helmet will be able to handle a robust AR assembly application.

REFERENCES

[1] http://www.digi-capital.com/news/2016/01/augmentedvirtual-reality-revenue-forecast-revised to-hit-120-billion-by-2020/#.WJdeBLYrJWM

[2] http://www.ptc.com/cad-software-blog/2016-the-year-for-augmented-reality-in-the-enterprise

[3] http://www.thewrap.com/mixed-year-mobile-ar-drive-108-billion-vrar-market-2021-guest-column/

[4] Azuma, R. T. "A survey of augmented reality." Presence: Teleoperators and virtual environments 6(4), 355-385 (1997).

[5] Henderson, S., and Feiner, S. "Exploring the benefits of augmented reality documentation for maintenance and repair." IEEE transactions on visualization and computer graphics 17(10), 1355-1368 (2011).

[6] Frigo, M. A., da Silva, E. C., and Barbosa, G. F. "Augmented Reality in Aerospace Manufacturing: A Review." Journal of Industrial and Intelligent Information Vol 4(2), (2016).

[7] Wang, X., Ong, S. K., and Nee, A. Y. C. "A comprehensive survey of augmented reality assembly research." Advances in Manufacturing 4(1), 1-22 (2016).

[8] Richardson, T., Gilbert, S., Holub, J., Thompson, F., MacAllister, A., Radkowski, R., Winer, E., Davies, P., and Terry, S. "Fusing Self-Reported and Sensor Data from Mixed-Reality Training" I/ITSEC, (2014).

[9] Engelke, T., Webel, S., and Gavish, N. "Generating vision based Lego augmented reality training and evaluation systems." Mixed and Augmented Reality (ISMAR), 2010 9th IEEE Int. Symp. on IEEE, 223-224 (2010).

[10] Ong, S. K., Pang, Y, and Nee, A. Y. C. "Augmented reality aided assembly design and planning." CIRP Annals-Manufacturing Technology 56(1), 49-52 (2007).

[11] Webel, S., Bockholt, U., Engelke, T., Gavish, N., Olbrich, M., and Preusche, C. "An augmented reality training platform for assembly and maintenance skills." Robotics and Autonomous Systems 61(4), 398-403 (2013).

[12] Tang, A., Owen, C., Biocca, F., and Mou, W. (2003, "Comparative effectiveness of augmented reality in object assembly" Proc. of the SIGCHI conference on Human factors in computing systems. ACM, 73-80 (2003).

[13] Piekarski, W., and Thomas, B. "ARQuake: the outdoor augmented reality gaming system." Communications of the ACM 45(1), 36-38 (2002).

[14] Schwald, B., and De Laval, B. "An augmented reality system for training and assistance to maintenance in the industrial context." (2003).

[15] Zhu, Z., Branzoi, V., Sizintsev, M., Vitovitch, N., Oskiper, T., Villamil, R., Chaudhry, A., Samarasekera, S., and Kumar, R. "AR-Weapon: live augmented reality based first-person shooting system." Applications of Computer Vision (WACV), IEEE Winter Conf., 618-625 (2015).

[16] https://www.microsoft.com/microsoft-hololens/en-us
[17] https://daqri.com/products/smart-helmet/
[18] Hou, L., and Wang, X. "A novel application in guiding assembly task: augmented reality animation" Proc. 2010 ISCCBE and The XVII EG-ICE Workshop on Intelligent Computing in Engineering, (2010).
[19] Baird, K. M. "Evaluating the effectiveness of augmented reality and wearable computing for a manufacturing assembly task." PhD diss., Virginia Polytechnic Institute and State University, (1999).
[20] Bowman, D., Kruijff, E., LaViola Jr, J. J., and Poupyrev, I. [3D User Interfaces: Theory and Practice] CourseSmart eTextbook. Addison-Wesley, (2004).
[21] Norman, D. A. [The design of everyday things: Revised and expanded edition] Basic books, (2013).
[22] Salo, K., Arhippainen, L., and Hickey, S. "Design guidelines for hybrid 2d/3d user interfaces on tablet devices" Proc. Fifth Int. Conf. on IARIA, 180-185 (2012).
[23] https://developer.microsoft.com/en-us/windows/holographic/color_design (a)
[24] https://developer.microsoft.com/en-us/windows/holographic/coordinate_systems (b)
[25] https://developer.microsoft.com/en-us/windows/holographic/designing_for_mixed_reality (c)
[26] https://developer3.oculus.com/documentation/intro-vr/latest/concepts/bp_intro/
[27] https://unity3d.com/unity
[28] Chryssolouris, G., Mavrikios, D., Papakostas, N., Mourtzis, D., Michalos, G.., Georgoulias, K., "Digital manufacturing: history, perspectives, and outlook," Proc. Inst. Mech. Eng. Part B J. Eng. Manuf. 223(5), 451–462 (2009).
[29] Gavish, N., Gutiérrez, T., Webel, S., Rodríguez, J., Peveri, M., Bockholt, U., Tecchia, F., "Evaluating virtual reality and augmented reality training for industrial maintenance and assembly tasks," Interact. Learn. Environ. 4820(November 2014), 1–21 (2013).
[30] Henderson, S., Feiner, S., "Exploring the benefits of augmented reality documentation for maintenance and repair," IEEE Trans. Vis. Comput. Graph. 17(10), 1355–1368 (2011).
[31] Starner, T., Mann, S., Rhodes, B., Levine, J., Healey, J., Kirsch, D., Picard, R. W., Pentland, A., "Augmented reality through wearable computing," Presence Teleoperators Virtual Environ. 6(4), 386–398 (1997).
[32] Wagner, D., Schmalstieg, D., "First steps towards handheld augmented reality," 7th IEEE Int. Symp. Wearable Comput., 127–135 (2003).
[33] Dunleavy, M., Dede, C., Mitchell, R., "Affordances and limitations of immersive participatory augmented reality simulations for teaching and learning," J. Sci. Educ. Technol. 18(1), 7–22 (2009).
[34] Aromaa, S., "Use of Wearable and Augmented Reality Technologies in Industrial Maintenance Work," (2016).
[35] Caudell, T. P., Mizell, D. W., "Augmented reality: an application of heads-up display technology to manual manufacturing processes," Proc. Twenty-Fifth Hawaii Int. Conf. Syst. Sci. ii, 659–669 vol.2 (1992).
[36] Azuma, R., Behringer, R., Feiner, S., Julier, S., MacIntyre, B., Baillot, Y., Behringer, R., Feiner, S., Julier, S., et al., "Recent advances in augmented reality," IEEE Comput. Graph. Appl. 21(6), 34–47 (2001).
[37] Reed, D. A., Dongarra, J., "Scientific discovery and engineering innovation requires unifying traditionally separated high-performance computing and big data analytics," *COMMUNICATIONS OF THE ACM*, *58*(7), (2015).
[38] Sherman, W. R.., Craig, A. B., "Understanding Virtual Reality", J. Doc. 59(4) (2003).
[39] Pausch, R., Proffitt, D.., Williams, G., "Quantifying immersion in virtual reality," Proc. 24th Annu. Conf. Comput. Graph. Interact. Tech. - SIGGRAPH '97, 13–18 (1997).
[40] Crison, F., Lecuyer, A., d Huart, D. M., Burkhardt, J., Michel, G.., Dautin, J., "Virtual technical trainer: learning how to use milling machines with multi-sensory feedback in virtual reality," IEEE Proceedings. VR 2005. Virtual Reality, 2005., 139–322 (2005).
[41] Argelaguet, F., Andujar, C., "A survey of 3D object selection techniques for virtual environments," *Computers and Graphics*, (2013).
[42] McMahan, R. P., Gorton, D., Gresock, J., McConnell, W.., Bowman, D. A., "Separating the effects of level of immersion and 3D interaction techniques," Proc. ACM Symp. Virtual Real. Softw. Technol. - VRST '06, 108 (2006).
[43] BenHajji, F., & Dybner, E. "3D Graphical User Interfaces." Estocolmo: Universidade de Estocolmo, Relatório Técnico, (1999).
[44] Norman, D.A. and Nielsen, J., "Gestural interfaces: a step backward in usability." interactions, 17(5), 46-49 (2010).
[45] Alger, M. "Visual Design Methods for Virtual Reality." Ravensbourne. http://aperturesciencellc.com/vr/VisualDesignMethodsforVR_MikeAlger.pdf. (2015).
[46] http://alexchu.net/Presentation-VR-Design-Transitioning-from-a-2D-to-a-3D-Design-Paradigm
[47] Witt, H., Nicolai, T., and Kenn, H. "Designing a wearable user interface for hands-free interaction in maintenance applications." PerCom Workshops 2006. Fourth Annual IEEE International Conf. on IEEE, (2006).
[48] https://www.nngroup.com/articles/serif-vs-sans-serif-fonts-hd-screens/
[49] Bernard, M. L., Chaparro, B. S., Mills, M. M., and Halcomb, C. G. "Comparing the effects of text size and format on the readibility of computer-displayed Times New Roman and Arial text." Int. Journal of Human-Computer Studies, 59(6), 823-835(2003).

[50] Jankowski, J., Samp, K., Irzynska, I., Jozwowicz, M., and Decker, S. "Integrating text with video and 3d graphics: The effects of text drawing styles on text readability." Proc. of the SIGCHI Conference on Human Factors in Computing Systems, 1321-1330 (2010).
[51] Gabbard, J. L., J Edward Swan, I. I., and Hix, D. "The effects of text drawing styles, background textures, and natural lighting on text legibility in outdoor augmented reality." Presence: Teleoperators and Virtual Environments, 15(1), 16-32 (2006).
[52] Debernardis, S., Fiorentino, M., Gattullo, M., Monno, G., and Uva, A. E. "Text readability in head-worn displays: Color and style optimization in video versus optical see-through devices." IEEE transactions on visualization and computer graphics, 20(1), 125-139 (2014).
[53] https://www.nngroup.com/articles/icon-usability/
[54] Butterworth, J., Davidson, A., Hench, S., and Olano, M. T. "3DM: A three dimensional modeler using a head-mounted display." Proc. of the 1992 symp. on Interactive 3D graphics, 135-138 (1992).
[55] https://developer.microsoft.com/en-us/windows/holographic/unity_development_overview
[56] https://developer.microsoft.com/en-us/windows/holographic/vuforia_development_overview
[57] Wloka, M., Anderson, B., "Resolving occlusion in augmented reality," Proc. of the 1995 Symp. on interactive 3D Graphics, (1995).
[58] Kruijff, E., Swan, J.E., Feiner, S., "Perceptual Issues in Augmented Reality Revisited," IEEE International Symposium on Mixed and Augmented Reality, (2010).
[59] Schwerdtfeger, B., Reif, R., Gunthner, W. A., & Klinker, G., "Pick-by-vision: There is something to pick at the end of the augmented tunnel," Virtual Reality, 15(2-3), 213–223 (2011).
[60] Biocca, F., Owen, C., Tang, A., & Bohil, C., "Attention Issues in Spatial Information Systems: Directing Mobile Users' Visual Attention Using Augmented Reality," Journal of Management Information Systems, 23(4), 163– 184 (2007).