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Comparing Visual Assembly Aids for Augmented Reality Work Instructions

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Abstract

Increased product complexity and the focus on zero defects, especially when manufacturing complex engineered products, means new tools are required for helping workers conduct challenging assembly tasks. Augmented reality (AR) has shown considerable promise in delivering work instructions over traditional methods. Many proof-of-concept systems have demonstrated the feasibility of AR but little work has been devoted to understanding how users perceive different AR work instruction interface elements. This paper presents a between-subjects study looking at how interface elements for object depth placement in a scene impact a user's ability to quickly and accurately assemble a mock aircraft wing in a standard work cell. For object depth placement, modes with varying degrees of 3D modeled occlusion were tested, including a control group with no occlusion, virtual occlusion, and occlusion by contours. Results for total assembly time and total errors indicated no statistically significant difference between interfaces, leading the authors to conclude a floor has been reached for optimizing the current assembly when using AR for work instruction delivery. However, looking at a handful of highly error prone steps showed the impact different types of occlusion have on helping users correctly complete an assembly task. The results of the study provide insight into how to construct an interface for delivering AR work instructions using occlusion. Based on these results, the authors recommend customizing the occlusion method based on the features of the required assembly task. The authors also identified a floor effect for the steps of the assembly process, which involved picking the necessary parts from tables and bins. The authors recommend using vibrant outlines and large textual cues (e.g., numbers on parts bins) as interface elements to guide users during these types of "picking" steps.

Disciplines

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ABSTRACT

Increased product complexity and the focus on zero defects, especially when manufacturing complex engineered products, means new tools are required for helping workers conduct challenging assembly tasks. Augmented reality (AR) has shown considerable promise in delivering work instructions over traditional methods. Many proof-of-concept systems have demonstrated the feasibility of AR but little work has been devoted to understanding how users perceive different AR work instruction interface elements. This paper presents a between-subjects study looking at how interface elements for object depth placement in a scene impact a user's ability to quickly and accurately assemble a mock aircraft wing in a standard work cell. For object depth placement, modes with varying degrees of 3D modeled occlusion were tested, including a control group with no occlusion, virtual occlusion, and occlusion by contours. Results for total assembly time and total errors indicated no statistically significant difference between interfaces, leading the authors to conclude a floor has been reached for optimizing the current assembly when using AR for work instruction delivery. However, looking at a handful of highly error prone steps showed the impact different types of occlusion have on helping users correctly complete an assembly task. The results of the study provide insight into how to construct an interface for delivering AR work instructions using occlusion. Based on these results, the authors recommend customizing the occlusion method based on the features of the required assembly task. The authors also identified a floor effect for the steps of the assembly process, which involved picking the necessary parts from tables and bins. The authors recommend using vibrant outlines and large textural cues (e.g., numbers on parts bins) as interface elements to guide users during these types of "picking" steps.

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Stephen Gilbert, Ph.D., is an associate director of the Virtual Reality Applications Center and assistant professor of Industrial and Manufacturing Systems Engineering at Iowa State University. His research interests focus on technology to advance cognition, including interface design, intelligent tutoring systems, and cognitive engineering. He is a member of IEEE and ACM and works closely with industry and federal agencies on research contracts. He is currently PI on a project supporting the U.S. Army Research Laboratory STTC in future training technologies for teams.

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Paul Davies is an electrical engineer specializing in digital signal processing, and works in the Production Systems Technology group in Boeing Research & Technology. Since joining Boeing in 2003 he has supported the Advanced Tactical Laser, Homeland Security & Services, Delta II and B1B programs in addition to multiple IRAD and CRAD projects in Signal Processing, Augmented Reality and Machine Vision. He currently develops technology for Augmented Reality in manufacturing and investigates new methods of person-machine interaction for technician support. Paul received a BS degree in Electrical Engineering from Rochester Institute of Technology in May 2004, and a MS degree in Electrical Engineering from California State University Long Beach in May 2008.

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INTRODUCTION

Today's economy is placing ever more stringent requirements on engineered products. The combination of accelerated product release cycles and increasing design complexity are creating challenges for both engineers and manufacturers (Elmaraghy, Elmaraghy, Tomiyama, & Monostori, 2012). To meet these requirements new human assembly aids are needed to keep costs and defects down (Xu, Wang, Bi, & Yu, 2012). One such technology, augmented reality (AR), is showing increasing promise in an industrial, complex assembly environment (Friedrich, 2002).

Augmented reality is a technology that superimposes virtual computer-generated content onto images of the physical world. The term "augmented reality" encompasses a wide range of applications using a variety of technologies. However, according to Azuma (one of the earliest researchers in AR), AR applications are generally expected to include three components: 1) a display with a combined view of both real and virtual objects, 2) real-time view interaction such as head tracking, and 3) a system to align real and virtual objects with a common coordinate system (Azuma, 1997).

Previous research points to AR's ability to positively impact many phases of the design, manufacture and repair process (Baratoff & Regenbrecht, 2004; Nee, Ong, Chryssolouris, & Mourtzis, 2012; Raghavan, Molineros, & Sharma, 1999). However, until recently the computing power required to create an AR system, integrating Azuma's requirements in a manufacturing assembly setting, was not available (Azuma et al., 2001; Caudell & Mizell, 1992). With the jump in computing power, existing literature has demonstrated prototype AR systems incorporating Azuma's principles (Richardson et al., 2014). The aim of these prototypes was to show that the technology is capable of addressing the challenges identified in some of the pioneering AR research such as high fidelity imagery and real time head-tracking (Azuma, 1997; Caudell & Mizell, 1992). By addressing these technological challenges, the researchers aimed to help facilitate AR transfer into a manufacturing environment where its benefits can be fully realized.

While these prototype systems have made great strides in facilitating AR's transfer into industry, barriers to adoption still exist, namely in the field of user experience and usability. Wang, Ong, and Nee conducted a thorough review of current AR work and concluded that previous research had demonstrated technology capable of producing a robust AR experience (Wang, Ong, & Nee, 2016). However, they also identified some underserved areas of AR research, namely in standards and usability. They conclude that because AR is still in its infancy, the interface standards have yet to be developed and evaluated robustly with human subjects. This lack of testing and evaluation results in limited standards for interface development, negatively impacting the usability of AR systems.

The work presented in this paper aims to investigate the effectiveness of different AR interface elements for complex assembly in a manufacturing work cell environment. Specifically, the authors examined depth perception (often referred to as occlusion). For this work, an interface was developed using previous literature and current usability guidelines for digital displays. The sections below detail the design justifications for selection of elements and testing data. In order to assess the effects on depth perception, three different variations of occlusion were compared. The results discussed below will serve to help establish guidelines for navigation and occlusion elements in AR interfaces.

BACKGROUND

Augmented reality is a technology that adds digitally generated visual cues like 3D models, static images, or textual based information onto a view of the physical world. The following section explores previous research concerning AR assembly instructions and interface design.

AR Assembly Instructions

Much research exists on comparing traditional 2D work instructions with AR. These comparisons demonstrate AR's effectiveness over current practice, justifying the added complexity and cost of AR. Even early AR interfaces showed increased speed and accuracy over paper instructions for assembly processes (Baird & Barfield, 1999). Other similar studies comparing AR and paper work instructions also found advantages to using AR for assembly tasks, but they determined that AR was most helpful when applied to very complex assembly tasks rather than simple ones and that simple assembly tasks yielded a floor effect when comparing paper and AR instructions (Seok & Kim, 2008; Wiedenmaier, Oehme, Schmidt, & Luczak, 2003).

Richardson et al. looked at comparing an AR instruction delivery system with no occlusion against traditional model based instructions (MBI) (Richardson et al., 2014). The MBIs were displayed to the user on either a desktop or tablet. The research found that most AR participants completed the assembly task faster the first time than with other modes, and that users greatly preferred the AR instructions over the MBIs on either the tablet or desktop. They also found that certain assembly steps were challenging for users to complete correctly because of the lack of occlusion.
Previous research demonstrates the ability of AR to reduce error rates and in some cases assembly time over traditional 2D instructions. However, the complexity of the task, and the presence of occlusion, along with other interface design issues, need to be addressed before the technology is ready for industry.

The studies described demonstrated positive AR results in a laboratory setting. However, performance in a real-world industrial environment requires more research. A few studies looked at the feasibility of AR systems for assembly assistance and training in industry (Friedrich, 2002). One by Caudill and Mizell looked at using transparent HMDs for wiring assemblies in a Boeing factory in 1992 (Caudell & Mizell, 1992). However, they noted that the lack of real time head-tracking to align virtual images with the physical part was a strong barrier to adoption. While the technology of the time limited this work, it demonstrated the feasibility of using AR in a factory assembly environment.

AR Interface Element Design and Usability Testing

Pathomaree and Charoenseang created an AR system that aided users in a 2D or 3D assembly task (Pathomaree & Charoenseang, 2005). This work investigated different instructional interface elements for an AR assembly system and identified which ones helped the user perform tasks more accurately in less time. However, they indicated that the reasoning was not clearly understood and that more testing was needed to fully understand the influence of these image, text, or object name combinations.

Radkowski, Herrema, and Oliver looked at different types of visual interface elements for table top AR instructions (Radkowski, Herrema, & Oliver, 2015). Based on qualitative results, the researchers concluded that photorealistic aligned parts and aligned animations improved the effectiveness of the AR instructions. In addition, results showed that using AR improved users' confidence in their abilities.

AR SYSTEM DEVELOPMENT

To test the different occlusion modes, an AR interface was designed with a focus on studying the usability of specific interface elements. The sections below use a heuristic review to discuss the rationale for each interface element and briefly touch on the application development.

Assembly Instruction and Occlusion

For assembly instruction interface elements, the authors selected a textual instruction paired with an animated opaque 3D model of the part to be assembled aligned with the current physical assembly. The instruction for Step 20 of the assembly task is shown in Figure 1. The animation showed the part of interest (in blue) moving through the correct assembly path and into its final position. Animated opaque installation instructions were selected because previous work indicates users perceive this as an intuitive representation for assembly instructions (Marcus, Cleary, Wong, & Ayres, 2013; Radkowski et al., 2015). The heuristic review also indicated that animated opaque instructions are user friendly because they: 1) limit unnecessary interface elements and allow a user to interpret spatial installation information in a natural context (Gerhardt-Powals, 1996), 2) reduce a user's cognitive and short term memory load (Shneiderman & Plaisant, 2010), 3) emulate real world objects with the aligned physical part reducing required cognitive mapping (Shneiderman & Leavitt, 2003), and 4) adhere to ISO 9241-110 (Subsection 4.6.7) (ISO 9241-110:2006, n.d.).

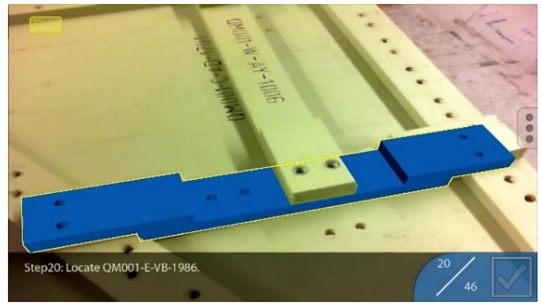
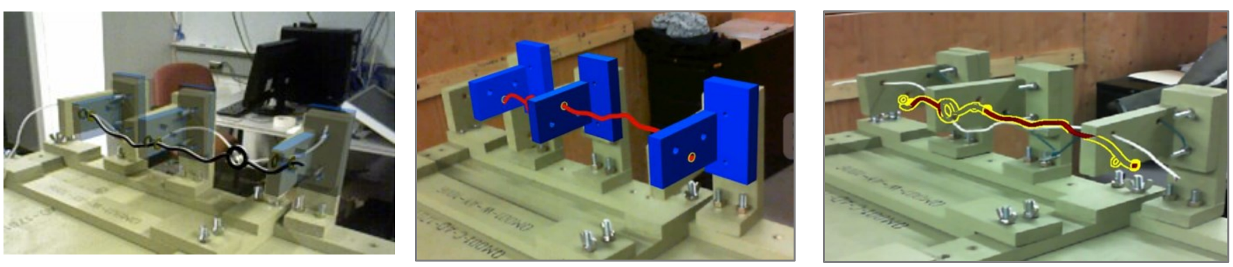


Figure 1. Opaque Model Aligned with Real Assembly Displayed Using Occlusion and Yellow Contour Lines.

Previous work in AR indicates that occlusion can be necessary for some assembly steps (Richardson et al., 2014). It is important to know whether the next part belongs in front or behind of existing subassemblies. However, showing occluded parts in an AR application on a 2D screen can be difficult. For this research, the authors created three different interface modes, each of which displayed occluded parts in a different manner. The first mode, which will be referred to as the control, displayed no occlusion in the assembly steps. Instead, the virtual parts were simply superimposed on top of the video image of the real assembly. The second mode, referred to as "Virtual Occlusion" uses a combination of un-occluded parts (like the control) and occlusion using virtual reference parts in conjunction with the part being assembled. The third mode, "Occlusion by contours", used a combination of virtual parts with cut-outs to accommodate intersecting parts, and yellow contour lines. Examples of each of these modes, for assembly step 14 involving routing wires, is shown in Figure 2.



(a) **(b)** **(c)**

Figure 2. Examples of Control (a), Virtual Occlusion (b) and Occlussion by Contours (c) for step 14 in the study designed for this research.

Direction and Guidance

Two different navigation methods were used among the three modes to guide the user through the work cell. The Control interface used a 3D arrow which pointed in the direction of the point of interest, while the Virtual Occlusion and Occlusion by Contours modes used the 3D gate method shown in Figure 3. However, in a comprehensive study of three different navigation tools conducted on this same assembly task, the 3D gates method was found to be superior (Macallister, Gilbert, Holub, Winer, & Davies, 2016). The reason for the discrepancy in navigation methods for this study is that the Control interface was developed before the navigation study was completed. Because of this inconsistency, this variable must be considered during the data analysis phase of the paper.

Figure 3. 3D Path Planning Gates.

Part-Picking Instruction

Knowing what parts to choose for a given step in an assembly process is integral to conducting a correct installation sequence. For the AR application, the authors used a simple outline shown in Figure 4 for the parts table to indicate the part to be selected. For the parts bins, the same outline was used but with quantity values as shown in Figure 5 to indicate the number of parts to be taken for subsequent assembly steps. The authors selected the bright green outline to bring attention to the specified area (Ritsos, Ritsos, & Gougoulis, 2011). In addition, the simple box shape avoids extraneous graphics and provides the user with a clean design that is easy to interpret, adhering to ISO 9241-110 (Subsections 4.5.6 and 4.5.8) (ISO 9241-110:2006, n.d.).

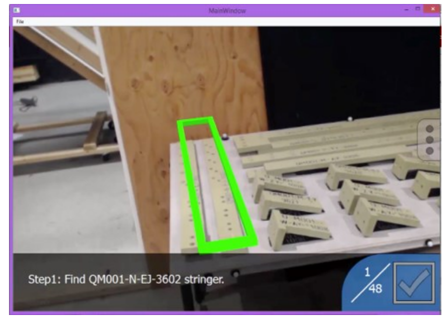


Figure 4. Part Picking with Green Outline.

Assembly Step Navigation

Moving between assembly steps is another necessary component of a AR work instruction interface. This allows users to go back and reference steps or skip ahead to future steps, letting users control the flow of system interaction (Shneiderman & Plaisant, 2010).

The interface in Figure 5 lets users interact with familiar paradigms ("Research-Based Web Design & Usability Guidelines," 2006). To move one step forward, the user clicks the check shown in the lower right-hand corner, which then triggers feedback via a green check in the navigation menu. The user can slide out the menu by clicking on the three-dot semi-transparent interface element on the right side. This slide out menu allows the user to navigate to any step by clicking on the corresponding menu item. This design allows users to control the pace of their interaction with the system, adhering to ISO 9241-110 (Subsection 4.7.1 and Subsection 4.7.4) (ISO 9241-110:2006, n.d.).

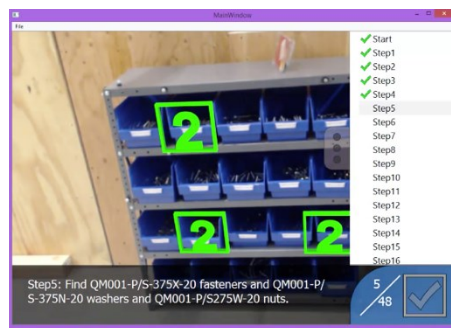


Figure 5. Assembly Step Navigation.

AR Application Development

Two separate AR systems were developed to test the direction/guidance and assembly depth perception interface elements. Table 1 below shows the interface elements for the applications along with the interface from the Control AR using a 3D directed arrow navigation interface (Richardson et al., 2014). The Virtual Occlusion interface was developed using the Metaio SDK ("Metaio," 2016). The application used Metaio's scene authoring tools and renderer. Metaio's marker based tracking was adapted to work with a Vicon infrared (IR) tracking system. The interface was constructed using Qt's windowing system for graphical user elements.

Table 1. Interface Elements by Application

	Interface Element		
	Virtual Occlusion	**Occlusion by Contours**	**Control**
Direction and Guidance	3D Gates	3D Gates	3D Arrow
Assembly Instruction	Aligned model	Aligned model	Aligned model
Part Picking	Outline	Outline	Outline
Assembly Step Navigation	Complete button and selection menu	Complete button and selection menu	Complete button and selection menu
Assembly Occlusion Method	Virtual Occlusion	Occlusion via contours	None

The Occlusion by Contours interface was based on an in-house API called ARMaker. ARMaker is composed of the ARToolKit and OpenSceneGraph libraries ("ARToolKit," 2016, "OpenSceneGraph," 2016). ARToolKit is an image based tracking AR library that was adapted to be used with a Vicon infrared tracking system ("Vicon Tracking," 2016). OpenSceneGraph is an open source computer graphics rendering framework used to create the visual display.

Although different programming libraries were used, consistency among the interfaces for the different modes was maintained. No additional interface elements were introduced other than those just described.

HUMAN SUBJECT TESTING

To evaluate the effectiveness of the different occlusion methods, human subjects testing was conducted on the interfaces. The study design and procedures are detailed in the sections below.

Study Setting

To test the AR interfaces, a manual assembly task was created. Participants were asked to assemble a mock aircraft wing made of painted wood components and metal threaded fasteners. The physical study was designed to mimic a traditional work cell found in a manufacturing environment. To ensure that the assembly task aligned with operations found on an actual manufacturing floor, the instructions and assembly were created with the co-author from The Boeing Company. For the task, there was a designated assembly area, along with areas where workers could find needed assembly parts and required fasteners. Figure 6 shows the layout of the work cell area. All assembly tasks were performed at the Wing, found in the center of the work area.

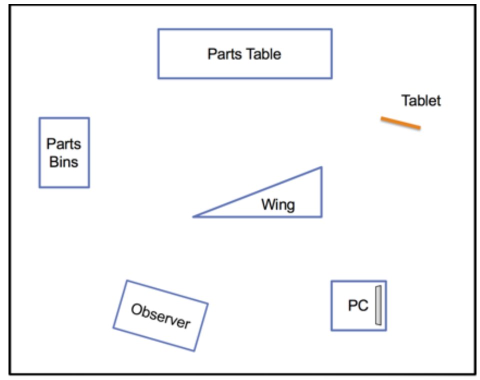


Figure 6. Participant Work Cell.

The wing was approximately 4 feet high and had a fixed base, shown in Figure 7. The final assembled wing had 12 large wooden components, three wires, and 14 fastener sets that contained different varieties of bolts and nuts. Washers were also included in four of the fastener sets. The wing assembly process was comprised of 14 major steps subdivided into a total of 46 sub-steps. The 14 major steps are the complete installation tasks; such as install a bracket. The 46 sub-steps are the more detailed instructions within an installation task, like go to the parts table and pick up a bracket then go to the parts bins and pick up 4 fasteners. Parts were labeled with a 10-character part identification number, and many parts had similar components available with a similar appearance and part number that served as distractors for the participant.

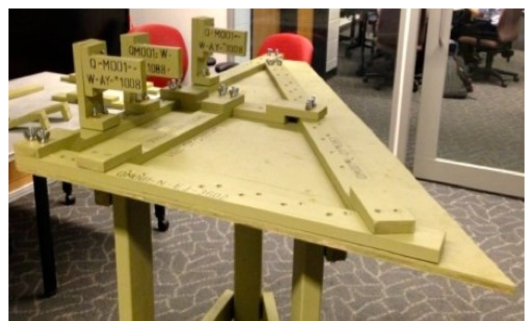


Figure 7. The Wing Assembly.

To test how AR instructions impacted a user's ability to complete the task, the authors incorporated some difficult steps into the assembly. A "twist step" forced the user to perform a complex operation making use of part occlusion. The authors also incorporated wire routing (inserting a wire through one or more channels). Wire routing is considered a difficult task for AR (Caudell & Mizell, 1992), and offered an opportunity to investigate the system's ability to tackle this challenging task.

Automatic Data Collection and Hardware

Both qualitative and quantitative data were collected. The tablet used to deliver the Virtual Occlusion and Occlusion by Contours AR instructions was an 11-inch Dell Venue 11 Pro tablet running a 1.60 GHz Intel Core i5 processor. The tablet was mounted on an Ergotron adjustable desktop arm mount with a custom 3D printed tablet holder attached to the arm, which was mounted on a mobile rolling base. This combination allowed participants to roll the tablet around the work cell and adjust the arm to achieve their ideal viewing angle.

An IR tracking system manufactured by Vicon was used by the AR applications to accurately align the 3D virtual models with the physical wing assembly. Four separate IR cameras comprised the system, which allowed tracking of the entire work cell, including the Parts Table, Parts Bins, Practice Parts, the Tablet, the Wing, and a helmet worn by the participant. Reflective IR tracking spheres were affixed to each of the tracked items. Tracking the part storage and assembly locations in the work area ensured proper spatial registration in the AR application even if incidental contact from the participant displaced objects from their original position.

The study observers sat behind a desk in the area labeled "Observer" in Figure 6, where they recorded participant errors by hand on a paper chart. The AR application also recoded when a participant moved between steps using a time stamped log file. The entire study area was recorded on video using four webcams positioned around the work cell. To keep the observer fully informed of the participant's actions in the work cell, a 27-inch Apple iMac on the observer's desk displayed a real-time view of the four video camera feeds. In addition to the live video feed, commercial screen mirroring software was used to provide a live view of the tablet's screen on the iMac. The live streams from the cameras and the instruction computer screen were saved for later analysis and to provide the ability to review what each participant did, in case of observer recording error.

Study Procedure

Participants were recruited mainly from undergraduate engineering classes. Each participant signed an informed consent form approved by the Institutional Review Board. The study was scheduled for 2-hours and participants were compensated 20 dollars for their time. First, a participant completed a pre-survey focused on demographic information as well as experience and confidence with assembly tasks. The researcher read participant instructions from a script throughout the study to minimize variation between participants.

The study design was between subjects: each participant used the same AR interface for the practice and two wing assembly tasks. After the pre-survey, the participant was instructed to perform the practice assembly to become acclimated to the work cell and instruction method. Before the practice trial, the participant received verbal instructions from the observer for the practice trial task. The participant was permitted to ask questions during the practice trial, but not during the subsequent trials.

Following this, the participant was instructed to assemble the wing and received instructions for the task. At the end of the 45-minute time limit or when the participant declared the wing to be complete, the observer assessed the assembly for errors and recorded them on a grade sheet.

When the assembly was complete, the participant was tasked with a 10-question paper folding test (Ekstrom, French, Harman, & Dermen, 1976) to assess spatial cognition ability as the observer graded the assembly from the assembly Trial 1 and reset the work cell to a standard starting configuration. The grading was not shared with the participant. Next, the participant completed a second wing assembly trial, following the same format as the first. When the second trial was finished, the participant completed a written post-survey, and then departed. The post-survey asked questions about the participant's satisfaction with the work instructions and the assembly task.

RESULTS

The study was conducted with a total of 47 participants. 16 Control participants, 14 Virtual Occlusion participants and 17 Occlusion by Contours participants. Demographically, 78% of the participants were between 18 and 22 years old and 80% were male. Also, 94% of the students participating in the study were majoring in engineering. Results from the study are detailed below.

Assembly Errors

Assembly errors were recorded by trained observers at the end of each trial. These errors were categorized as uncorrected since participants completed the assembly and did not go back to fix them. Results indicate that there was no significant difference in median number of uncorrected errors in the wing assembly between modes for either Trial 1, $\chi^2(2)=1.079$, $p=.583$ or Trial 2, $\chi^2(2)=2.787$, $p=.248$ (see Figure 8). This result suggests that we may be observing a floor effect,

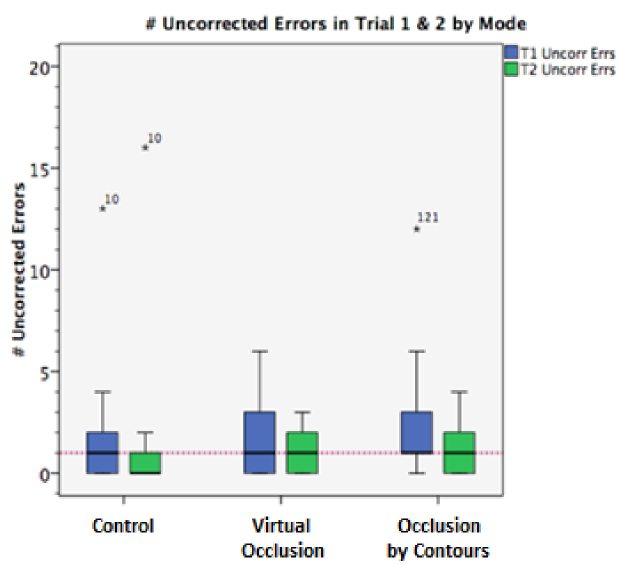


Figure 8. Assembly Errors by Mode.

especially because the median error numbers are so low for both trials. However, if we look at the errors as a strictly binary value (i.e., 0=no error, 1=error made), we can examine the percentage of participants who made errors on each step in each mode. This yielded five steps with a high number of errors in Trial 1. These are shown in Table 2.

Because only a relatively small percentage of participants made any errors, and those that did typically made only one error, the error counts were not statistically significant by step. Overall, this is believed to have occurred due to a floor effect. Using AR instructions have made this relatively complex assembly task easy at a macro level.

However, these error counts serve as valid indicators of specific instructional steps that need improvement. This can be seen for Step 5, in Table 2, where the Occlusion by Contours interface outperformed the other two interfaces, since it had no errors for this step in either trial.

Table 2. Percentage of Participants Committing Errors for Trial 1

	Step 5	Step 6	Step 12	Step 13	Step 14
Control	19%	31%	6%	6%	13%
Virtual Occlusion	14%	36%	21%	21%	21%
Occlusion by Contours	0%	53%	24%	41%	35%

Step 6 showed by far the most errors in all modes, suggesting that the AR interface does not demonstrate this task well. As we can see from the percentages for Steps 12-14, fewer participants made errors in these steps when they used Control interface than the other two modes. This suggests that the interface used to communicate this step in the Control is clearer than in the Virtual Occlusion and Occlusion by Contours modes. The Control AR interface performed better for steps 12-14 because of the special reference provided for wire stringing by the transparent brackets. A more detailed analysis of these steps is presented later in the paper.

Assembly Time

There was no significant difference between total trial completion times for any of the three modes in either trial. This again suggests a floor effect. The limiting factor may not be the quality of the instructions as in previous work (Richardson et al., 2014), but the time it actually takes to physically assemble the parts.

For Trial 1 the data were not normally distributed. To analyze the times for significance a non-parametric Kruskal-Wallis H test was performed. The results of the test indicated χ^2 (2) = 2.693, p = .260. These results show that median trial completion times were not statistically significant between modes for Trial 1.

For Trial 2 the data were normally distributed. To analyze the completion time between modes, a one-way ANOVA was performed, and there was a homogeneity of variances as assessed by Levene's test for equality of variances, p=.815. Based on the ANOVA and Levene's test, Trial 2 completion times were not significantly different between AR modes, $F(2, 44) = 1.710$ and $p = .193$. Figure 9 shows the plots of the median trial time by mode.

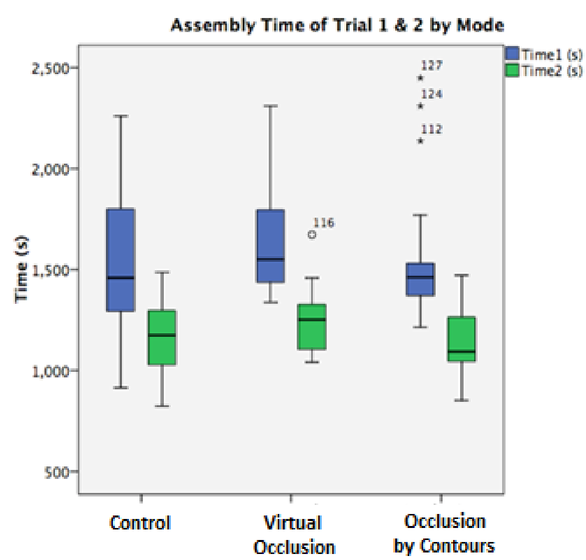


Figure 9. Assembly Time by Mode.

While there was no statistically significant difference between total completion time by mode, the results indicate that there is statistical significance between Trials 1 and 2 for each mode. In each mode participants improved upon their completion time from the first round, demonstrating the ability of AR to help facilitate training. The data looking at time improvement was found to be non-parametric, as a result a sign hypothesis test was performed. Of the 47 participants included in the analysis, all 47 showed an improvement in total trial time between trial 1 and 2. The statistically significant median decrease between trials produced $z = -5.969$ and $p < .0005$.

Step Types

For this analysis, the original 14 major steps were split into the 46 sub-step format to assess the impact of each type of instruction element on the assembly subtask. Each step was divided into its most basic component tasks: "Picking" parts from a table or bin, "Placing" parts in the correct orientation on the bench, and "Assembling" the parts using fasteners. Figure 10 shows the 46-step time breakdown for the Virtual Occlusion mode. The graph shows a floor effect for the picking steps, however, there is some variation in assembly and placing steps. While only the one graph is included the other two modes demonstrated similar floor effect for the Picking steps. This suggests that the interface elements used for the Picking steps were effective.

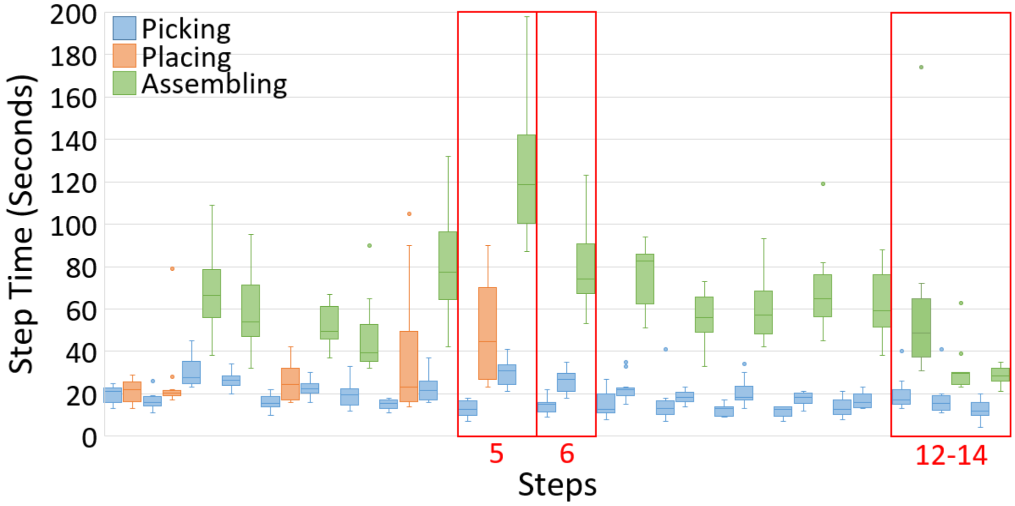


Figure 10. Picking, Placing and Assembling Times for Virtual Occlusion Interface.

Qualitative Observations

In the error reporting data and the 46-step break down graph, it was noticed that there were large variations in time and higher percentages of participants committing errors on steps 5, 6 and 12-14, as noted earlier. A more detailed analysis of these steps follows.

Overlapping Parts

Step 5 involved installing a spar under another pre-existing part. This is an instance where a part was occluded. The Control and Virtual Occlusion interfaces did not include any support for occlusion in the instructions. Figure 11 shows how Step 5 was presented to a user when using the Control and Virtual Occlusion interfaces. Notice how even though the part being installed is meant to sit under the current part at its middle left, there is no visual cue in the instructions. Alternatively, the Occlusion by Contours interface was able to depict the overlapping parts more realistically. Figure 1 displays Step 5 in the Occlusion by Contours interface. The part to be installed is shown occluded by the existing piece, and the yellow contour outline of the part indicating to the user that this instruction step deals with occluded parts.

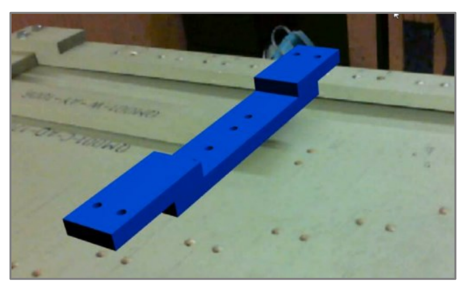


Figure 11. Step 5 in the Control and Virtual Occlusion Interfaces– With no Occlusion.

As indicated in Table 2, the error breakdown indicates that for Trial 1, 19 percent of participants using the Control AR interface made an error and about 14 percent using the Virtual Occlusion interface made at least one error on Step 5, while 0 errors were made in the Occlusion by Contours mode. The authors suggest that there were errors in the Control and Virtual Occlusion interfaces due to the absence of occlusion depth cues, indicating occlusion by contours is a particularly important feature for AR assembly on this kind of assembly step.

Occluded Fasteners

Step 6 involved using washers as spacers between a bracket and spar. The error breakdown by mode indicates that for Trial 1, around 31 percent of participants in the Control erred at least once and around 36 percent of participants in Virtual Occlusion made at least one error. Figure 12 shows the instructions as seen by the users in Control and Virtual Occlusion modes. There is no explicit cue in the instructions signifying that the washers are under the bracket or that the bolts are coming up though the table and the depth perception is lost.

Figure 12. Step 6 in Virtual Occlusion and Control.

Figure 13 below shows Step 6 in the Occlusion by Contours interface. Based on the results for Step 5, where occlusion via depth by contours helped to eliminate the errors seen in the other two modes, it was expected that a similar reduction in errors would be seen in the Occlusion by Contours mode for this step. However, in this mode, 53 percent of participants in Trial 1 made at least one assembly error.

After reviewing the instructions this is not surprising. The left side of Figure 13 is the beginning of the assembly animation for Step 6. This first image shows the bracket, the bolts and the washers. Both the bolts and the washers are shown with a yellow contour outline to signify that they are or will be occluded pieces. However, in the right side of Figure 13 at the end of the animation, the washers are no longer shown as occluded via yellow contours. This is an error in the instruction authoring. The washers are clearly occluded by the bracket and should be shown at the end of the animation as occluded. Because of this, Participants in the Occlusion mode were given two conflicting cues: the start of the animation showed the washers as spacers, while the end of the animation showed the washers as not occluded. The authors hypothesize that because of this dissonance between the two cues, participants were confused and forced to guess. This yielded the close to at-chance error rate of 53 percent. These results indicate that participants were paying attention to the occlusion by contours enough so to be confused when the instructions were authored incorrectly.

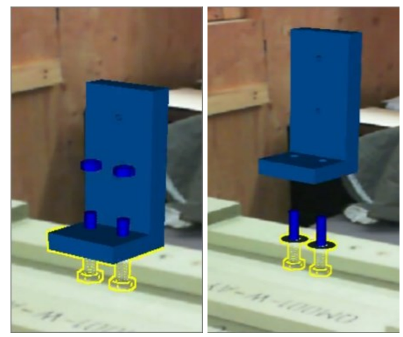


Figure 13. Step 6 in Occlusion by Contours: left show beginning of animation and right end of animation.

Wire Alignment

Steps 12, 13 and 14 dealt with installing flexible wires into a harness. Wire installation is a common procedure in today's electronically complex products. The necessity of wire installation capability in an AR system was recognized by Caudell and Mizell back in the early 1990's (Caudell & Mizell, 1992). They found from their work that flexible wires are a challenging task in AR. With the current technology, this challenge is somewhat easier, but still difficult.

In the error analysis, the authors found that for the Step 14 in Trial 1, around 13 percent of Control participants, 21 percent of participants using the Virtual Occlusion interface and 35 percent of Occlusion by Contours participants committed an error. This error pattern was similar across the other wire installation Steps 12 and 13. The hypothesized reasons for these differences are discussed below.

The Control AR interface for Step 14, shown in Figure 2a, was similar to the Virtual Occlusion interface shown in Figure 2b, however, the brackets were semi-transparent. In the Control, the semi-transparent brackets along with highlighted installation holes were shown with an animation of the wire sliding into the correct holes. Although the wire was not completely occluded by the spars, this setup led to the fewest number of errors across the three modes.

Figure 2b shows the Virtual Occlusion interface instructions for Step 14. In this interface, the authors noticed a jump in percentage of participants who committed errors, increasing from 12.5 percent (Control) to 21 percent (Virtual Occlusion). While this increase in participants making an error was not statistically significant because of the high variation in errors, the increase did indicate user confusion over this interface element. This confusion seems to have impacted the user's perception of the instruction. As a result, the authors hypothesize that the transparent parts in the Control allowed the user to map directly between the computer-generated parts and the physical model, while the Virtual Occlusion interface, prevented this direct mapping by using fully opaque parts and required the user to perform mental mapping between the physical and computer-generated parts.

Figure 2c shows the Occlusion by Contours interface for Step 14. Of the three modes, this interface had the highest percentage (35 percent) of participants who committed a wire assembly error. The authors hypothesize that the lack of brackets in the Occlusion interface contributed to the errors. Without providing virtual brackets for reference, the user must rely completely on the alignment of the AR graphics on the video image to determine the correct holes through which to string the wire. Because object tracking is often not perfectly precise, this leads to errors. Also, the authors theorize that emphasizing the shape of the wire with the yellow contours likely adds distracting cognitive noise, since only the hole location for stringing matters to the user.

The evidence in this research suggests that users found the semi-transparent brackets of Baseline AR, shown in Figure 1a, most useful for this step, possibly because the semi-transparent brackets allowed users to see both the physical part and the computer-generated guides at the same time. Including these brackets also helps a user discern the location of wires in the event of tracking system drift, a real possibility in an uncontrolled factory setting. This additional special reference seems to help the user more accurately assemble the wires, possibly because of the reduced cognitive mapping required. However, the Occlusion interface design was most helpful in other steps, suggesting that different interface standards should be applied for different types of assembly steps.

Net-Promoter Score

Among the self-reported data gathered was net-promoter score. This is collected through a Likert survey question, "I would recommend work instructions like this to a friend." Responses to this question are marked on a 1-5 agree-disagree scale. They are converted to a net promoter score by subtracting the percentage of detractors (answers of 1, 2, or 3) from the percentage of promoters (answers of 5); answers of 4 are ignored. Net promoter scores range from -0% (worst) to 100% (best). According to Reichheld, the median net promoter score for over 400 companies in 28 industries was 16% (Reichheld, 2003). Net-promoter scores for the three instruction modes were: Control, 44%; Virtual Occlusion, 71%, and Occlusion by Contours, 76%. The difference between the Control and the other two modes is notable. The results were unexpected. However, they could be a result of the disparate work cell navigation methods. As was mentioned in AR System Development section, the Control used a 3D arrow element to direct the user, while the other modes used a 3D gate system. The lower acceptance rate for the 3D arrow aligns with expectations gleaned from the study on navigation methods conducted previously, which concluded that 3D gates were more helpful than the 3D arrow for this application (Macallister et al., 2016). The Occlusion by Contours interface, while not statistically different from the Virtual Occlusion interface in net promoter score, scores slightly higher. This is to be expected since the Occlusion by Contours interface aids the user by removing ambiguity about depth perception using contours in many steps.

Engineering Indicators and Assembly Time

Using participants' responses on the surveys, an "engineering tendency" score was calculated for each participant. This score was based on responses to subjective questions and the paper folding test of spatial ability mentioned above. Spearman’s rank-order correlation was used to evaluate whether these indicators were correlated with assembly time. In Trial 1, for the Control, a higher paper folding score was significantly correlated with a lower assembly time ($r = -.706$, $p = .002$), and the engineering tendency score was also significantly correlated with a lower assembly time ($r = -.529$, $p = .035$). On the other hand, these two engineering indicators had no significant correlation with the two modes which supported occlusion. These results suggest that engineering skills aided the use of the Control interface, but that engineering skills had no effect on participants' performance when using Occlusion by Contours and Virtual Occlusion, which is desired.

CONCLUSIONS AND FUTURE WORK

While the technology associated with AR is quickly maturing, usability evaluation is an underserved area. To design and test AR interface elements, the authors started by conducting a heuristic review of interface features drawing on previous AR research, usability principles, and ISO standards. From this review, the authors constructed a platform to test three interfaces or varying occlusion principles.

The work looked at a comparison of a Control, Virtual Occlusion, and Occlusion by Contours interfaces. For completion time and errors, the authors did not find any statistically significant difference between the interface modes. This indicated that a floor effect had been reached in the difficulty of the assembly when using AR. However, after breaking down the users’ performance to specific steps, it was found that five of the steps yielded more errors than the rest. By studying these steps, the authors were able to determine which interface elements helped users accomplish certain tasks. The authors recommend providing occlusion information for placing and assembling steps, especially when parts of the assembly overlap one another. It is also important to render virtual parts in the scene that are helpful references to align a part correctly (virtual occlusion), such as steps which have many possible placement options like the wiring step used in this study. In addition, specific interface elements are better suited to the different categories of manufacturing tasks (i.e. picking, placing, and assembling). Picking tasks should use vibrant outlines and large textural cues (e.g., numbers on parts bins) as interface elements to guide users correctly, as indicated by the floor effect for time spent picking individual parts. Lastly, the authors found that, for the Control interface, there was a significant correlation between measures of engineering tendencies and assembly time. However, for Virtual Occlusion and Occlusion by Contours, this correlation disappeared. These results indicate that the Control interface required more spatial ability than the newer interfaces. This result could translate into less training and experience required for assembly workers when using interfaces like Virtual Occlusion and Occlusion by Contours.

Moving forward, the authors will investigate how additional interface elements may or may not impact these assembly categories. In addition, the possibility of tailoring work instructions to the user's skill level could be employed to decrease training time.

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