Comparison of Navigation Methods in Augmented Reality Guided Assembly

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ABSTRACT

The US military is one of the largest engineering service entities in the world; however, due to the nature of its workforce, it does not have a large pool of service personnel with years of on-the-job experience. Often young and inexperienced warfighters need technologies to help them quickly and efficiently learn assembly and maintenance skills on engineered products. Augmented reality (AR) shows promise delivering work instructions in a user centered format, improving first time assembly accuracy over traditional 2D interfaces. However, building an effective AR instruction system faces many challenges. This paper addresses a critical one: navigation around an assembly area using AR. The work in this paper compares three different navigation methods: points of interest (POI), path planning gates, and a 3D directed arrow. The POI interface consisted of a simplified 2D top down view of a work cell showing stations and the user's position in relation to those stations (like a radar map). The path planning gates used a technique adopted by some flight simulators: a series of yellow squares marking the path from the user's position to the area of interest. The third method was a floating three-dimensional arrow, which rotated in the scene to point towards the participant's next area of interest. To test these three navigation methods studies were conducted. Participants were asked to assemble a mock aircraft wing twice. Their performance was recorded via subjective self-report and by objective sensor-collected data. The dependent variables included assembly time, errors, movements within the assembly area, net-promoter score and time spent looking at instructions. Findings indicated that for navigating around a work area, the gates interface was the best, resulting in lower completion times, decreased time spent looking at the instructions, and ratings by users, compared with the other interface methods.

ABOUT THE AUTHORS

Anastacia MacAllister is a graduate student in Mechanical Engineering and Human-Computer Interaction at Iowa State University's Virtual Reality Applications Center. She is working on developing Augmented Reality work instructions for complex assembly and intelligent team tutoring systems.

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.

Joseph Holub is a graduate student in Computer Engineering and Human-Computer Interaction at Iowa State University's Virtual Reality Applications Center.

Eliot Winer, Ph.D., is an associate director of the Virtual Reality Applications Center and associate professor of Mechanical Engineering and Electrical and Computer Engineering at Iowa State University. He is currently co-leading an effort to develop a next-generation mixed-reality virtual and constructive training environment for the U.S. Army. Dr. Winer has over 15 years of experience working in virtual reality and 3D computer graphics technologies on sponsored projects for the Department of Defense, Air Force Office of Scientific Research, Department of the Army, National Science Foundation, Department of Agriculture, Boeing, and John Deere.

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

The United States military maintains over 8,000 tanks and 13,000 aircraft (Nye, 2015). Each of these pieces of equipment have specific assembly and maintenance needs that require specialized equipment and training; however, the military does not always have the opportunity to train personnel via prolonged on-the-job training and mentorship. Often recruits are required to acquire knowledge quickly and are expected to perform maintenance and repairs accurately and efficiently even in harsh environments. Knowing how to perform an engineering assembly or maintenance task correctly the first time is necessary to minimize equipment down time and to make the most efficient use of the resources on hand. Augmented Reality (AR), which superimposes virtual computer-generated content onto the physical world, may serve as a job aid that can help technicians learn and perform tasks more efficiently with fewer errors. An example of AR is shown in Figure 1. In this figure, the real world is captured through the tablet's video camera and displayed, with virtual geometry (i.e. blue "spar" piece) embedded to provide information to the user (e.g., where to put the part in this assembly). This fusion of the physical and virtual worlds through AR has shown promise helping to reduce errors and improve assembly time in industrial environments (Friedrich, 2002; Nakanishi, Ozeki, Akasaka, & Okada, 2007; Regenbrecht, Baratoff, & Wilke, 2005).

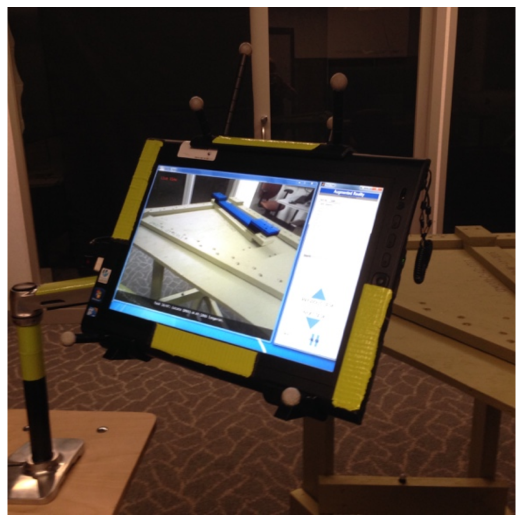

Figure 1. Example of Augmented Reality

Specific AR implementations can incorporate a wide range of technologies, depending on the needs of the task. However, according to Azuma's seminal paper, AR must include three main elements (Azuma, 1997). The first is a display with a combined view of both real and virtual objects. The second is real-time view interaction with virtual objects and the physical world, this allows the correct viewpoint of the virtual part to be displayed to the user on the AR device. The final element requirement is a system to align real and virtual objects with a common coordinate system. The benefits of using AR for assembly and maintenance has been studied repeatedly (Caudell & Mizell, 1992; Gavish & Gutiérrez, 2013; Hou & Wang, 2013), however, little attention has focused on evaluating AR interface elements to establish user-centered standards. In a review of the current state of AR, Wang, Ong, and Nee (2016) point out that AR interfaces have a number of elements such as: part picking indicators, tool picking, part and tool placements, navigation, and depth perception interface elements. The part picking indicators show a user what part to select for the next assembly step. Part and tool placements serve to show the user how to assemble parts or use a tool to complete an operation. The navigation elements serve to direct a participant's interest in a work cell, and depth perception elements show a user how parts' positions relate to each other in space. AR interfaces, however, do not always have all the same elements. Instead, elements are based on the unique needs of the assembly and the operators. Deciding what elements to include in an interface can be highly context dependent. As a result, the most accurate ways to implement AR interfaces have yet to be established (Wang, Ong, & Nee, 2016). Closer study of these elements will aid in the construction of user friendly interfaces that more clearly convey assembly procedures to operators (Radkowski, Herrema, & Oliver, 2015).

This paper examines the relative effects of three different interface methods for guiding users safely between areas in an assembly work cell. Guiding a user safely around a work cell is an important aspect of navigation in and around an assembly. In addition to safety, parts for an assembly task are often in different locations across a work area or maintenance bay. Knowing where to locate these components is an integral part of conducting an assembly procedure. To study this, a series of studies was conducted examining three different navigation methods. Participants were asked to assemble a mock aircraft wing twice. Their performance was recorded via subjective self-report and objective sensor-collected data. The dependent variables included assembly time, errors, movements within the assembly area, time spent looking at instructions, and net-promoter score. Net-promoter score is an industry accepted measure of customer satisfaction provided through answering the question, “How likely is it that you would recommend our company/product/service to a friend or colleague?” Collected measures were analyzed and compared for differences among navigation methods.

BACKGROUND

AR Work Instructions

Much research exists showing the benefits of AR systems over standard 2D manuals for assembly tasks. This previous research served to demonstrate the effectiveness of AR in a manufacturing and assembly setting. However, work proving the feasibility of AR does not often study the user impact of specific individual instruction components that make up an AR system for assembly, such as navigation around a work cell or part picking. Previous work in assembly is mainly focused on showing the benefits of AR over 2D standard instructions. While this previous work does not include studies on navigation in AR, valuable knowledge about building and using AR systems has been gained.

Wiedenmaier et al. created an AR system for assembling an automobile door (Wiedenmaier, Oehme, Schmidt, & Luczak, 2003). They compared this AR system with standard paper instructions and a human instructor. They found that AR helps reduce errors and assembly time compared to paper instructions when the assembly step complexity is high. Seok and Kim constructed an AR system for assembling a computer motherboard (Seok & Kim, 2008). They found that AR reduced completion time by sixty-percent compared with paper instructions. However, they found no difference in errors between the two methods. This result paired with Wiedenmaier et al. suggested that AR outperforms standard 2D instructions when the assembly steps are complex enough to warrant the added overhead of AR. Richardson et al. looked at comparing an AR instruction delivery system on a tablet with 2D instructions delivered on a monitor and a mobile tablet (Richardson et al., 2014). Participants in the study were asked to assemble a mock aircraft wing twice. Results indicated that participants completed the first trial faster with significantly fewer errors using AR. Users also indicated that they did not like the tablet 2D work instructions even though they committed fewer errors and completed the assembly faster than when using the desktop display. Richardson et al. showed the importance of eliciting qualitative user feedback along with quantitative user measurements like errors and time to effectively evaluate an instruction delivery system. Additional work in AR for assembly also includes (Azuma et al., 2001; Baird & Barfield, 1999; Capozzi & Sacco, 2013; Cheng & Tsai, 2013; Shen, Ong, & Nee, 2010; Wild et al., 2014).

Work has also been done comparing different delivery devices for AR systems. Henderson and Feiner developed a proof of concept AR system for military mechanics (Henderson & Feiner, 2011). They conducted a user study comparing AR on a head-mounted display to monitor-delivered instructions and non-AR instructions delivered on a head-mounted display. They found AR helped reduce the time required to locate the assembly task, as well as head movements. However, they indicated that more work was necessary to intuitively display the assembly steps. Zhu et al. developed a proof of concept system called AR-Mentor for teaching maintenance tasks (Zhu et al., 2014). The system used visual and audio based instructions for guided assembly and disassembly of a launcher tube. While wearing the heads-up display unit a user interacted with instructions using voice commands to ask questions or navigate between steps. However, they did not formally evaluate the interface with users after constructing the prototype.

Navigation in AR

With the increased interest in AR for assembly and maintenance, figuring out how to safely and accurately navigate using an AR assembly aid is an important research topic. However, little user-centered research has been conducted in terms of comparing AR navigation interface elements in engineering assembly and maintenance settings. There does exist a body of work on navigating using AR outside of the manufacturing and assembly realm. This work can help guide the selection of navigation interface elements for assembly. However, to understand how users will perceive these elements when in a manufacturing assembly environment, requires careful study in order to develop an intuitive user centered system. The work presented in this paper drew from the existing research in AR navigation and applied it towards building and testing an AR interface for navigating around an assembly work cell. An overview of relevant navigation work is presented.

Work in AR navigation using two-dimensional graphics includes Koch et al. who developed an AR system for maintenance on an iPad (Koch, Neges, König, & Abramovici, 2014). The system navigates a user to the location of the repair and then walks them though the process. To navigate a user to the repair site, the application used 2D arrows aligned to physical objects and arrows unaligned to physical objects. They did not, however, test their application with a formal user study. Pfannmüller et al. developed a heads-up AR vehicle navigation system using a single 2D arrow projected onto the road or a 2D boomerang shape curved along a 3D navigation path (Pfannmüller, Kramer, Senner, & Bengler, 2015). This boomerang concept was similar to the path planning gates which were a series of yellow squares starting from the user's position and leading to the area of interest, like a 3D breadcrumb path. They formally evaluated both concepts in a thirty participant user study. They found statistically significant evidence that 2D arrow directions were considered by participants to be more ambiguous, more difficult to interpret, and less intuitive than the boomerang concept. Based on the results Pfannmüller et al. recommends using the 3D boomerang navigation path for navigation. Yokoi et al. developed a POI interface on a smart phone for navigating though underground tunnels (Yokoi, Yabuki, Fukuda, Michikawa, & Motamedi, 2015), but did not formally evaluate the interface. This lack of formal investigation does not provide any quantifiable evidence on how this POI interface would compare to others such as a 3D path navigation aid.

Work investigating three-dimensional navigation interface elements includes Biocca et al. who looked at developing a method to direct users gaze outside their current field of view while wearing an HMD to perform a task (Biocca, Owen, Tang, & Bohil, 2007). They conducted several studies comparing the difference between an attention funnel, highlighting objects in the scene, and audio cues. The attention funnel was a series of square shapes following a 3D path, starting at the user's current position and ending at the next area of interest. This concept was nearly identical to the gates concept described above in the Introduction. Biocca et al. found that the attention funnel significantly decreased mental workload by eighteen percent over the audio and highlighting cues. In addition, they found that the overall search time was twenty-two percent less for the funnel than the other two methods. However, they compare audio, which is not an interface element, and highlighting cues, which are not visible to the user when an object is off screen. As a result they do not compare strictly visual aids that the user can see at all times such as an arrow or POI which make up a good portion of prototype AR systems. Schwerdtfeger et al. developed an AR application for comparing picking via tunnel and arrows (Schwerdtfeger, Reif, Gunthner, & Klinker, 2011). Their task had users select a specified part from an array of parts bins using one of the navigation aids. The tunnel for their study was a series of circular shapes starting at the users current position and ending at the next area of interest. Based on the number of picking interface variations and part container setups tested, they concluded that picking parts for a task and navigation to areas of interest in a work area are complex, context dependent tasks requiring user testing to ensure visual matching with the conducted operations. However, for their picking from bins task, they concluded that the tunnel produces significantly fewer errors than the arrow and is often quicker.

While there has been research on general navigation in AR, there lacks a direct comparison of visible interface elements that are often used, unevaluated, in AR work cell assembly applications. For the work presented in this paper, the authors selected the three promising navigation interface elements (gates, 3D arrow, and POI). Selection of these interface elements was based on reviewing previous work on navigation in AR. The work showed that the three interface elements could possibly help reduce the time required to navigate to an area in a work cell (Biocca et al., 2007; Schwerdtfeger et al., 2011) and that some of these elements were common in previous AR systems for assembly (Henderson & Feiner, 2011; Richardson et al., 2014).

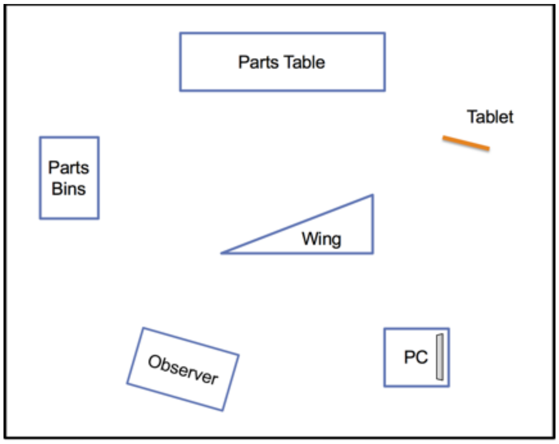

Figure 2. Participant Work Cell

USER TESTING AND AR SYSTEM DEVELOPMENT

To test the AR interfaces, a manual assembly task was created. The task needed to be complex enough to warrant the use of AR, as indicated by previous AR studies (Seok & Kim, 2008; Wiedenmaier et al., 2003). Participants were asked to assemble a mock aircraft wing made of painted wood components and metal threaded fasteners. The study setup 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. There was a designated assembly area, along with areas where workers could find needed assembly parts and required fasteners. Figure 2 shows the layout of the work cell area. All assembly tasks were performed at the wing, found in the center of the work area.

The wing was approximately 4 feet high and had a fixed base, shown in Figure 3. The wing had 12 large wooden components, three wires, and 14 fastener sets, which contained different varieties of bolts and nuts. The larger components of the assembly were fabricated from wood and were located on a parts table. The nuts and bolts were located in an array of labeled plastic bins.

Figure 3. The Wing Assembly

Data Collection and Hardware

For the study, the tablet used to deliver the POI and gate instructions was an 11-inch Dell Venue 11 Pro tablet running a 1.60 GHz Intel Core i5 processor. For testing the arrow interface, a 12.1-inch Motion Computing tablet running an Intel Core i7 processor was used. The arrow interface required the Motion Computing tablet because the secure encrypted device ensured the security of the Boeing AR program source code. To minimize any impact, the difference in tablets had on the user, both tablets were mounted on the same arm using the same tablet holder. For the study, tablets were mounted on an Ergotron adjustable desktop arm mount with a custom 3D printed tablet holder attached to the arm, which was fastened to 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.

A Vicon IR tracking system was used by the AR applications to accurately align the 3D virtual models with the physical wing assembly. 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 of the AR instructions in the event of some incidental contact which displaced objects from their original position.

The study observers sat behind a desk in the area labeled "Observer" in Figure 2, where they recorded participant errors by hand on a paper chart. The AR application recoded when a participant moved between steps using a time stamped log file.

Navigation Interface Elements

To test the different navigation methods, an AR interface was designed with a focus on studying the usability of specific navigation interface elements. However, to test navigation in a work cell assembly environment a complete AR instruction delivery system, including elements such as part picking and part installation graphics was required. The selection of each element was guided by a heuristic review. A heuristic review evaluates visual features based on

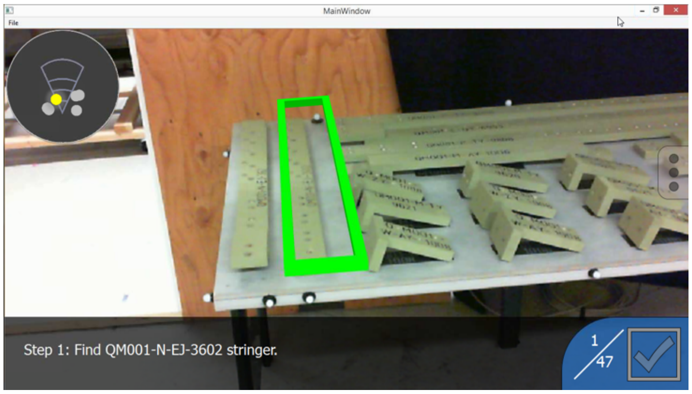

Figure 4. POI Interface

user experience (UX) experts, UX ISO standards, accepted standards for mobile interface design, gestalt principles, and other UX standards (Usability.gov, 2016). The tasks within assembly instruction software have been categorized as follows: 1) part-picking instruction, 2) work cell navigation, 3), assembly instruction and part installation, and 4) assembly step selection.

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.-a, n.d.-b).

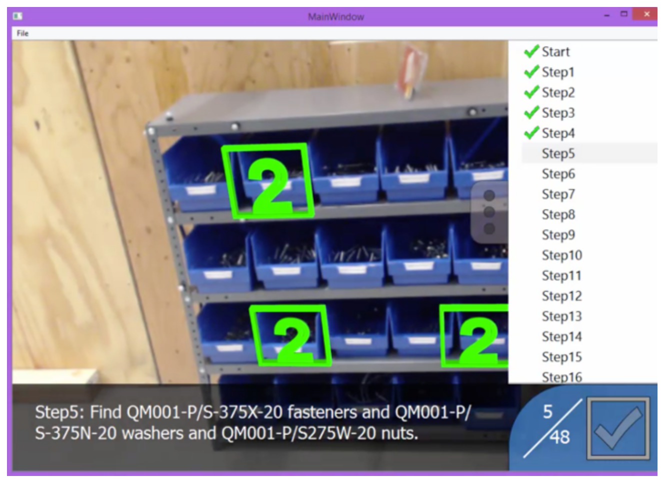

Figure 5. Assembly Step Selection and Bin Selection

Work Cell Navigation

Work cell navigation interface elements serve to direct the user around the assembly area to various stations of interest. The goal of the presented work was to investigate how users responded to different navigation interface elements. Navigation interface elements selected for the study were the POI (points of interest), 3D arrow, and path planning gates. The POI interface was selected because of its popularity in navigation applications like global-positioning systems and video games. The POI interface is shown in Figure 4. The conical shaped portion in the center of the upper left circle represents the area a user views through the tablet (i.e. viewable area). The user's, and tablet's, viewpoint are represented by the bottom point of the cone in the POI display. The positioning of elements in the work cell (i.e. parts table, parts bin) are represented by grey dots. The yellow dot represents where the user needs to go for the current assembly step. For example, in Figure 4 the user is being guided to the parts table to select a specific part (shown in the green outline). Once the user picks up the part and hits the checkbox in the lower right of the figure, the yellow dot is updated to the next location the user needs to navigate too. Users are instructed to rotate the tablet until the yellow dot is inside the viewable area in order to complete the next assembly step. When developing this interface, the decision was made to allow the points to rotate while the representation of the viewable area remained stationary. This was to aid in a user's spatial awareness of the work cell. If the user sees a point to the right of the view cone display, then the point in physical space is also to their right.

Figure 6. 3D Arrow Interface

Figure 7. Path Planning Gates Interface

A floating three-dimensional arrow that appears in the middle of the interface to point towards the participant's next area of interest was considered. The 3D arrow interface is shown in Figure 6.

Lastly, the path planning gates were a series of 3D yellow squares starting from the user's position and leading to the area of interest, which is a method used in some flight trainers, shown in Figure 7. The path planning gates were selected because previous work on attention direction and picking indicated they were easy to process and the most accurate at directing a user's gaze (Biocca et al., 2007; Schwerdtfeger et al., 2011).

The study of the three navigation interface elements was conducted over a period of three years and followed an iterative approach. The first study used the 3D arrow for navigation. However, users in the study complained of becoming confused as to where the arrow was pointing. This spawned the second study using the path planning gates. This method was more well-received by users due to its accuracy and precision. Although, some users mentioned that for the small work cell the precise 3D path planning of the gates between the user's current position and the next position maybe unnecessary. These comments spawned the third study investigating the use of the POI interface. The authors hoped the POI interface could provide the accuracy of the gates but with less screen space taken up by the arrow.

Assembly Instruction and Part Installation

To show a user how to assemble a part, the authors selected a textual instruction paired with an animated opaque 3D model of the part to be assembled. This animated virtual part was shown overlaid on to the physical assembly when the user looked at the tablet. This virtual overlay for Step 2 is shown as the blue rectangle in Figure 8. For Step 2 a user would see an animation on the tablet showing the part to be assembled (in blue) following the correct 3D path into its final position. To install the part correctly, a user would follow the on screen animations using the physical part. 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; Watson, Butterfield, Curran, & Craig, 2010). 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.-b).

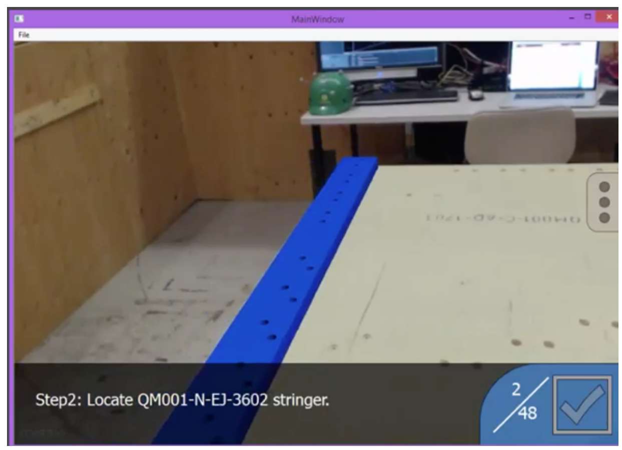

Figure 8. Assembly Instruction

Assembly Step Selection

Moving between assembly steps is another necessary component of an 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). This aspect of the interface, illustrated in Figure 8 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 also signifies that that step has been completed. Once a step has been completed, a corresponding step in the slide out menu shown at the right of the screen receives a green check. The user can slide out the menu by clicking on the three-dot semi-transparent interface element on the right side (which can be seen in Figures 5 and 8). The slide out menu allows the user to navigate to any step by clicking on the corresponding menu item whereas clicking the check mark only moves the user forward one step. 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.-c, n.d.-d).

Application Development

Two separate applications were developed to implement the different navigation methods. Limitations in some of the APIs precluded using just one application for testing. Overall, the interfaces developed were very similar. The arrow navigation method was developed using D'Fusion and MatLab. Both the POI and gates navigation methods were developed using the Metaio software development kit (SDK). 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.

Participants

Participants were recruited mainly from undergraduate engineering classes. Each participant signed an informed consent form approved by the Iowa State University Institutional Review Board. All of the recruitment and informed consent documents made clear to participants that participation in the study was voluntary and that it would not impact course grades. Data analyzed in this paper were collected over three different studies. Throughout the three studies the wing assembly task was held constant. However, the first study using the arrow interface was slightly different than the gates or POI interface. The first study interface with the arrow had a move back a step button and the step selection menu was up at all times. After the first study, data analysis indicated that participants rarely used the back button or the menu, so for subsequent studies the menu was hidden and the back button removed. This allowed similar screen space for the gates and POI interfaces which used the smaller Dell rather than the larger Motion Computing tablet. Data from the studies was analyzed for the navigation interface elements impact on completion metrics. Over each study iteration numerous observers were used to record data and they followed explicit scripted instructions to minimize any variation that could impact results. In addition, participants were recruited from the same participant pool, freshman to sophomore level engineering students. This similar participant pool minimized variation between studies since samples had similar skill levels and demographics.

Study Procedure

In total, the study was scheduled for 2-hours and participants were compensated 20 dollars for their time. Each participant used the same AR interface for the practice and two wing-assembly tasks. To start, a participant completed a survey focused on demographic information such as experience and confidence with assembly tasks. Then an observer read, from a script to minimize variation, participant instructions on how to complete the assembly task and about how to use the interface. Also, before the practice trial the participant was shown a live demonstration by the observer on how to use the interface and was allowed to ask any questions about the task or interface. After the survey and verbal instructions, the participant performed a different practice assembly task to acclimate to the work cell and instruction method. Following this, the participant was instructed to assemble the wing and received verbal instructions on how to complete the task and on how to use the interface. At the end of the first trial an observer graded the completed assembly based on the following criteria:

1. Are the correct components present? A participant may use the correct bolt with an incorrect nut, which counted as a single error.
2. Is each component installed in the correct orientation? A participant installing the correct nut and bolt pair in an incorrect orientation (i.e. upside down) was two errors.
3. Are any additional components included that are not specified in the instructions?

At no point during the study was this grading shared with the participant. Between Trial 1 and Trial 2 participants were provided with a paper folding test (Ekstrom, French, Harman, & Dermen, 1976) to assess spatial ability while an observer graded the first assembly. After the observer graded the first assembly, the participant completed a second wing assembly trial, following the same format as the first. When Trial 2 was finished, the participant completed a written feedback survey, and then departed. The feedback survey asked questions about the participant's satisfaction with the work instructions and the assembly task. After completing the feedback survey participants were escorted out of the study area and compensated.

RESULTS AND DISCUSSION

The study was conducted with a total of 35 participants. There were 16 3D arrow, 14 gate, and 5 POI participants. Overall, study participants were 72 percent male and 75 percent were between 18 and 22 years old. Results from the study are split into the following sections below: 1) assembly errors, 2) assembly time, 3) number of tablet looks and duration, 4) engineering indicators and assembly time, and 5) net-promoter score.

Assembly Errors

By running a Shapiro-Wilk test for normality and inspecting the distribution plots the researchers determined the data did not conform to a normal distribution. After determining the distributions of the recorded errors were similar, a non-parametric Kruskal-Wallis test was performed to determine if there were significant differences between the median recorded errors for Trial 1. While assembly errors did increase from Arrow method *Mdn* = 1.5) to POI (*Mdn* = 2.0) to Gates (*Mdn* =2.0), the difference was not statistically significant, $\chi2$ (2) = 1.316, p = .518. However, the Kruskal-Wallis test indicated that for Trial 2 there was a statistically significant difference in errors between methods, $\chi2(2)$ = 6.333, p = .042. Pairwise comparisons performed using Dunn's procedure with a Bonferroni correction for multiple comparisons indicated that users in the POI method made significantly more errors (*Mdn* = 2.0) than those in the 3D arrow method (*Mdn* = 1.0, p = .040). This suggests that the POI navigation may have been more difficult for the users to interpret than the 3D arrow.

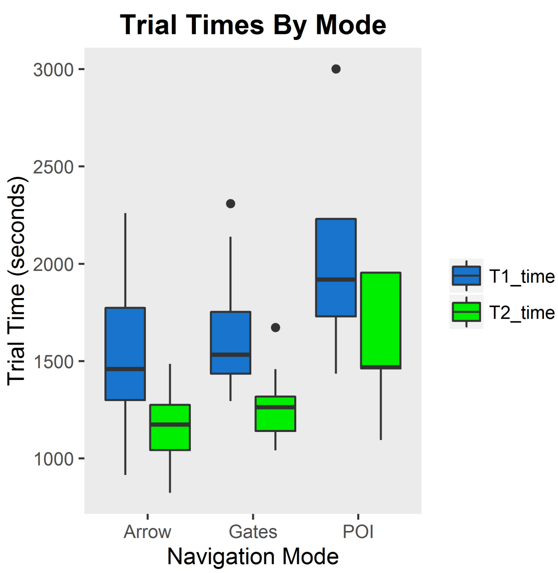

Figure 9. Trial Times by Method

Assembly Time

Looking at total assembly time by method for the trials, the authors find that for Trial 2, 3D arrow participants (*Mdn* = 1460.0 seconds) were significantly faster than POI participants (*Mdn* = 1920.0 seconds); the median completion times for participants using the 3D arrow interface were 23.96% faster than those of participants using the POI interface. Although the Shapiro-Wilk test indicated normalized data, a Kruskal-Wallis H test was run to keep statistical analysis methods consistent across measures. A statistically significant differences in median assembly times were found between the three methods in Trial 2, $\chi2(2)$ = 6.589, p = .037. Pairwise comparisons were made using Dunn's procedure and a Bonferroni correction. This post hoc analysis showed a statistically significant difference between Trial 2 POI (*Mdn* = 1469.0 seconds) and arrow completion times (*Mdn* = 1174.5 seconds, p = .031), but not between the gates (*Mdn* = 1264.0 seconds) completion times or any other group combination. The authors hypothesize that the significant difference in Trial 1 times is due to the mapping required to align the POI view frustum to objects in the room. Participants may have had a harder time or taken more cognitive resources to use the POI navigation method. Figure 9 shows box plots representing the data distribution and the median times (dark horizontal lines), with the small dots signifying outliers. The lower line on the box plot represents the first quartile, the second line is the median, and the third is the third quartile. The vertical lines coming out of the boxes represent the range of values that are not outliers, where outliers are considered values that lie more than one and a half times the range of a single interquartile above the third quartile (the top of the box) or below the first quartile (the bottom of the box). A single interquartile range is the distance between the bottom (or top) of the box to the middle line, which is the median. Looking at this plot shows that even with the small number of POI participants, the data suggest higher completion times for POI. Also, POI does not show the decrease in completion times displayed by the gates or the arrow methods in Trial 2. This could suggest that users find directional cues like the 3D arrow and gates to be more intuitive and less cognitively loading than requiring them to map between the POI display and the objects in the work cell. Looking at the two macro measures of performance, errors and time, do not provide a high level of insight into the performance differences among interface elements.

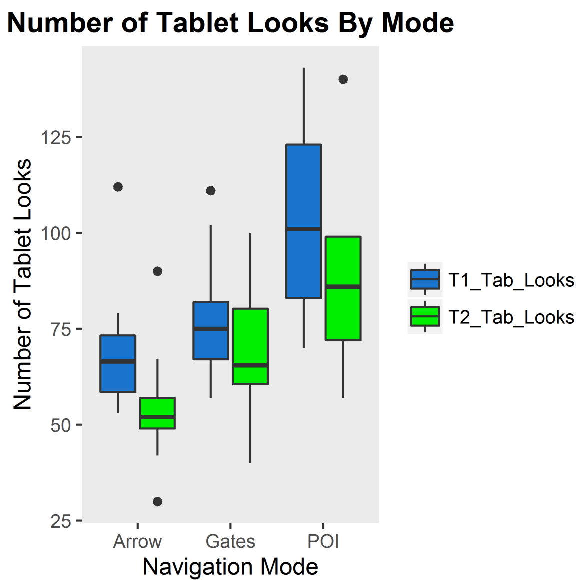

Figure 10. Number of Looks by Method

Number of Tablet Looks and Duration

Using the tracking system data, the number of looks at the tablet by method can be calculated as well as how long participants spent looking at the tablet. This can provide insight into how much time people needed to process the information provided. It was assumed that more looks and longer look times indicated that users experienced more cognitive load when interpreting the instructions or may have been confused by the instructions. The boxplot of the distribution of looks by method and trial is shown in Figure 10. A Kruskal-Wallis H test indicated differences in look times between modes for each trial, Trial 1: $\chi2(2) = 8.010$, $p = .018$ and Trial 2: $\chi2(2) = 12.503$, $p = .002$. The Dunn's procedure post hoc tests (with Bonferroni corrections) reveal that for Trial 1 the POI (*Mdn* = 101.0) had significantly more looks than the 3D arrow (*Mdn* = 66.5, $p = .006$). The trend of significantly more looks for POI held for Trial 2, where POI (*Mdn* = 86.0) had significantly more looks than the 3D arrow interface (*Mdn* = 52.0, $p = .007$). In Trial 2, the gates interface (*Mdn* = 65.5) was also found to have significantly more looks than the 3D arrow interface, $p = .020$.

The total amount of time participants spent looking at the instructions by mode was also analyzed. For total tablet look time, the authors found differences in look time in Trial 1, $\chi2(2) = 11.043$, $p = .004$ and in Trial 2, $\chi2(2) = 6.219$, $p = .045$. Because the distributions of the data were dissimilar, mean ranks, rather than medians, were used in comparisons. Post hoc analyses indicated that for Trial 1 the POI (26.0) required significantly more total look time than the 3D arrow interface (10.93, $p = .003$), but not the gates interface (16.55) or any other combination. For Trial 2, the post hoc analyses also revealed that the POI (24.80) resulted in significantly more look time than the 3D arrow interface (12.93, $p = .043$), but not the gates interface (17.50). This result illustrates that POI participants required more time with the instructions than those using the gates or 3D arrow navigation aids. Looking at the data analysis, the POI seems to require longer to interpret than the arrow or the gates. However, no statistically significant difference is seen between tablet look times for the 3D arrow and gate navigation. This suggests further metrics are needed to provide insight into which interface elements users prefer when presented with the choice between gates and arrow.

Engineering Indicators and Assembly Time

The paper folding test data (Ekstrom et al., 1976), considered a proxy for spatial ability, provides insight into how different spatial abilities faired using the three interface variations. To gain this insight, the authors looked for a linear correlation between the paper folding test data and measures of performance. Finding a correlation would allow the authors to predict how well someone can complete the assembly based on their paper folding score. This prediction indicates that the interface may not be meeting the needs of all users, specifically those of lower spatial ability, and should be adapted. To conduct this analysis, the authors looked for a linear correlation between paper folding score and total assembly time. Using Spearman's Rank-Order Correlation, the data indicated that each navigation method had a significant negative correlation at some point in the trials between paper folding score and assembly completion time as shown in Table 1. This result is expected because those with higher spatial ability should be able to complete the assembly more quickly than those with lower spatial abilities, especially for the first trial where users are unfamiliar with the assembly actions they must conduct. However, as participants learn steps required for the assembly and how to use the interface one would expect a high spatial ability participant's advantage to disappear. Looking at the data for Trial 2, there is no significant negative correlation between paper folding test and total assembly time for the POI and gate interfaces, also shown in Table 1. For the 3D arrow interface there is a statistically significant negative correlation between paper folding score and assembly time for Trial 2. Finding significance for the arrow interface in Trial 2 seems to suggest that users who have low spatial ability are still having trouble completing the assembly in a timely manner. Since this was not seen for POI and gate methods, this could suggest that the spatial ability required by the 3D arrow method is a challenge for users throughout the assembly process. This could create issues in military assembly and maintenance settings where a wide range of workers would be using an AR system.

Table 1. Paper Folding Score and Completion Time Correlations

	Trial 1 Time	Trial 2 Time
POI	-.894*	-.671
Arrow	-.706*	-.850*
Gates	-.521*	-.412

* = statistically significant at $p < .05$ level

Net-Promoter Score

Among the self-reported data gathered was the Likert survey question, "I would recommend work instructions like this to a friend." This single question is called the net-promoter score and is an industry accepted measure of customer satisfaction (Reichheld, 2003). Responses to this question on a 1-5 agree-disagree scale can be 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 -100% (worst) to 100% (best). Looking at industry scores, a baseline can be established to compare the AR interface scores and gauge user perception. 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 methods were: 3D Arrow, 44%; 3D Gate Navigation, 73%, and POI, 80%. The difference between 3D arrow and the gates is substantial. The results aligned with expectations, since the 3D arrow received complaints about being confusing, supported by the correlation above. The 3D gate navigation sought to alleviate these complaints by using a more intuitive navigation method. The increase in net-promoter score for the 3D gate navigation indicates that participants viewed the navigation method much more favorably than the arrow interface, likely because it alleviated navigation confusion. However, the POI interface received the highest net-promoter score even with the quantitative data suggesting the opposite. Since the net-promoter score is very sensitive to sample size, one would hesitate to compare the POI score (based on only five participants) to the other two methods, thus placing more weight on the quantitative analysis. Looking at the 3D arrow and gate interfaces, it seems that users greatly prefer the gates over the 3D arrow. This is a helpful piece of information when deciding between two interfaces that were very close when running the quantitative analysis. This result also aligns with previous literature demonstrating the accuracy of a gate based navigation (Biocca et al., 2007; Schwerdtfeger et al., 2011).

CONCLUSION AND FUTURE WORK

Based on the results, the authors would use the gate interface for navigation in an AR assembly instruction delivery system in a work cell setting. Quantitative data indicated that participants using the POI interface took significantly longer in some cases to compete the assembly. POI users also required more looks at the instructions than the arrow and gates participants. In addition, correlation analysis revealed that for arrow, spatial ability was an important deciding factor in assembly time. This suggests that the arrow interface may not be the best choice for a work force with varying skill levels and spatial abilities. In addition to the quantitative measures, previous work in the background section indicated that quantitative measurements may not take into account user preferences. Gauging user's responses to interface elements is an integral part of deploying a system. Ensuring that an interface is intuitive and easy to use is important for developing AR work instructions. Qualitative net-promoter score data suggests that participants preferred the gates interface over the 3D arrow.

Moving forward, the knowledge that 3D path planning gates are an accurate and well received method of AR navigation in a work cell can help direct the creation of AR systems for today's warfighter. This work, while promising, was limited to a work cell environment and should be applied with caution outside of this domain. In the future, the authors would like to continue improving and testing the system. The environment they would like to test in is a dispersed work setting. The environment for this paper was a contained work cell, however, in many cases workers have to travel across a warehouse or to another building to grab a part or a tool. With this movement comes challenges like avoiding obstacles and other hazardous situations. The authors believe that the path planning gates have an advantage over the other methods in this regard. However, as always it requires careful study and user testing.

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