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Overcoming Limitations of the HoloLens for Use in Product Assembly

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Abstract

Augmented Reality (AR) is an emerging technology that could greatly increase training efficiency and effectiveness for assembly processes. In fact, studies show that AR may reduce time and errors by as much as 50%. While many devices are available to display AR content, the use of Head Mounted Displays (HMDs) is the most interesting for manufacturing and assembly as they free up the user's hands. Due to the emerging nature of this technology, there are many limitations including input, field of view, tracking and occlusion. The work presented in this paper explores the use of the Microsoft HoloLens to deliver AR work instructions for product assembly. An AR assembly application was developed to guide a trainee through the assembly of a mock aircraft wing. To ensure accurate instructions were displayed, novel techniques were developed to mitigate the HoloLens' tracking and display limitations. Additionally, a data visualization application was developed to validate the training session and explore trends through data collected from the HoloLens along with wearable physiological sensor data.

Introduction

Augmented Reality (AR) is an emerging technology that could greatly increase training efficiency and effectiveness. In fact, Henderson & Feiner found that AR may reduce time and errors by as much as 50% for maintenance and assembly operations [1]. AR consists of computer-generated visual information overlaid on top of a view of the real world. These computer-generated visuals are often delivered via a tablet or Head Mounted Display (HMD). Traditionally, tablets have been the preferred method of delivering AR content due to the technological constraints of HMDs and the commercial availability of tablets. HMDs of the past tended to be expensive custom-built solutions for research purposes and not viable for commercial use. However, in recent years several commercially available AR HMDs have come to market and show promise for use in maintenance operations. The main advantage of AR HMDs over tablets is that they overlay the computer-generated visuals directly over the users view of the real world while allowing them to remain hands free. This is ideal for maintenance training as the trainee is likely to be working with their hands while receiving work instructions.

AR HMDs show great potential for use in maintenance operations and training. However, due to the emerging nature of this technology, many of the components that make up these AR HMDs are still under development. Therefore, there are many limitations within the technology that must be mitigated including input methods, field of view, tracking and occlusion. These limitations are especially important to maintenance and assembly tasks as it is important to ensure the trainee receives accurate work instructions and therefore has an effective training session.

Specifically, this paper discusses the novel techniques employed to mitigate the limitations of the Microsoft HoloLens for use in an AR work instruction assembly application. The research presented here will focus entirely on the development of the application and the novel techniques used to mitigate the limitations of the HoloLens. This application was also used to conduct a user study comparing the effectiveness of work instructions delivered via an AR HMD, AR tablet, tablet model-based instructions and desktop model-based instructions [2]. The results of this study are presented in a separate paper. For the study, due to all the custom enhancements made to the HMD system, it was necessary to validate that work instructions and other parts of the system were functioning together properly. To accomplish this, a separate data visualization application was developed. This application fused data collected from the HoloLens device, an Empatica E4 physiological wrist sensor, and errors via post-process grading of the trainee's completed assembly. This fusion through the data visualization application allowed the analyst to better understand the training session and identify any issues in the AR application. In addition to validating the work instructions, the analyst may also discover new high-level trends about the trainee and the training environment through the fusion of these data sources. Through the delivery and validation of these work instructions, this work seeks to enhance the effectiveness of training for maintenance and assembly operations using an emerging commodity HMD.

Background

Augmented reality is a technology that has been heavily researched since the 1990's and shows promise for a variety of applications. AR involves merging computer-generated visuals with a view of the real world. These visuals provide additional information to what is seen in reality. In a seminal paper, Azuma surveyed the various applications of AR and found that it will have a major impact in the fields of medical, robotics, entertainment, visualization and notably manufacturing and repair [3]. Additionally, Krevelen & Poelman found similar use cases and many more including education, military training and others [4]. Manufacturing is a large area for AR research including many use cases for industry and the military. Specifically, AR guided assembly and disassembly tasks make up 30% of published research for AR manufacturing [5].

Augmented Reality Assembly Applications

Numerous papers have explored the use of AR for the delivery of work instructions. The first AR work instruction application was proposed by Caudell & Mizell to display work instructions for an aircraft manufacturing process through a transparent HMD [6]. However, the technology at that time was still in its infancy. Since this seminal paper, researchers have developed many systems to explore possibilities of this technology.

Prior work has shown many benefits of using AR to deliver work instructions. Studies have shown that AR delivered work instructions drastically reduce errors when compared to traditional work instruction delivery methods [7]–[9]. Furthermore, Baird &

Barfield found that in addition to reducing errors, AR also decreased the time to complete assembly tasks. In a similar study, Henderson and Feiner found that AR delivered instructions significantly reduced the amount of time to locate tasks [1]. This study also found that AR reduced head and neck movements leading to reduced physical workload. Additionally, since the information is displayed when it needs to be for a task, the user does not have to recall the information from 2D instructions, decreasing mental workload [10]. These benefits lead to enhanced assembly performance and therefore reduced costs.

Augmented Reality Hardware

AR assembly instructions are often delivered through transparent HMDs, tablets and smartphones. Due to commercial availability and relatively low cost, tablets and smartphones have been the preferred AR platform [11]. However, the main drawback of these devices for delivering assembly instructions is that typically users must hold the device when using it. This is not ideal as the user will likely be working with their hands when receiving work instructions.

AR HMDs may overcome this issue through a hand-free experience. In the past, AR HMDs have been expensive custom-built solutions created for specific use cases. This has been a large pitfall for the use in many applications as they are not readily available. However, in recent years numerous commercially available AR HMDs have come to market. Some of the most popular currently available are the Microsoft HoloLens, Daqri Smart Glasses and Meta 2 [12]–[14]. These devices can track the environment while displaying spatially located content through an optical see-through display. The use of these devices allows the user to remain hands-free and view instructions directly over their field of view. Evans et al. evaluated the Microsoft HoloLens for use in an assembly application and found it to be a viable platform for this application [15]. This research shows that these commercially available HMDs have the capabilities and accessibility for use in assembly applications.

Augmented Reality Limitations

While there are many benefits for the use of AR, there are many limitations that come along with it. Tang et al. found great success with the use of AR for assembly purposes but noted that the technology was not ready for widespread use due to various limitations. [16]. The most notable of these limitations included tracking, depth perception, and user-interface issues [4], [17]. While hardware improvements may help overcome some of these limitations, novel development techniques may additionally help mitigate the negative effects.

Tracking can generally be broken down into two main categories, marker-based and marker-less. The most accurate method is marker-based tracking. This method uses a high-contrast image target to provide a real-world point of reference. This image target can be identified by an RGB camera and on the AR device to establish this point of reference. While marker-based tracking provides accurate tracking, its main drawback is that it requires an image target for any object it is tracking. Marker-less tracking overcomes this issue through various techniques, often combining input from visual sources and an inertial measurement unit (IMU) [18]. The main issue with marker-less tracking is that it lacks the accuracy to register precise points in the real world. Since it is often difficult to achieve an accurate point of reference, it is not ideal for tasks such as assembly that require precise registration.

Depth perception is very important to assembly applications as the user must be able to properly locate and visualize the instructions displayed. Many past devices had issues with dim displays and low resolution leading to virtual objects appearing farther away than they should [4]. Even though recent advances in technology have improved resolution and opacity in many devices, there are still many improvements that can be made. Occlusion has been found to effectively give depth perception cues that may overcome limitations in resolution and opacity [19]. Through accurate occlusion, the user may better understand the proper representation of the instructions given [20], [21].

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

Methodology

The methodology section describes the challenges faced when developing an AR assembly application for a commercially available AR HMD. An AR application was developed to guide a trainee through the assembly of a mock aircraft wing, shown in Figure 1. This assembly includes a 46-step process of picking, placing, and assembling a variety of parts and fasteners. These steps require the trainee to navigate through three separate stations: a parts table, fastener bins, and assembly station. The parts table includes large wooden parts to be placed and assembled. The fastener bins include the fasteners used to assemble the parts. And the assembly station was where the placing and assembling was performed. Each station was separated by roughly eight feet, diagram shown in Figure 2, and the assembly stationed was positioned at approximately four feet high for ergonomic purposes. Physiological data was collected throughout the assembly training process using a wearable wrist device.

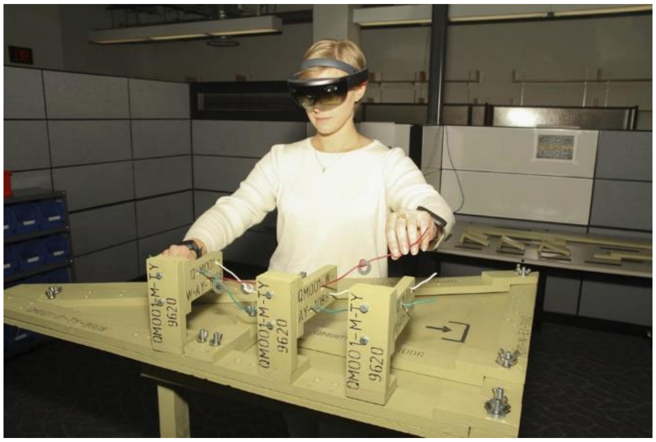

Figure 1. Mock aircraft wing assembly.

Hardware

Several commercially available AR HMDs currently exist on the market. The most notable of these devices include the Microsoft HoloLens, Daqri Smart Glasses and the Meta 2. For this research, the Microsoft HoloLens was chosen as the display device for the AR assembly application. Due to its maturity and popularity compared to the other devices, it was found to be the most suitable platform. Furthermore, the HoloLens includes the necessary capabilities for an AR HMD assembly application: environment tracking, sufficient computing power, transparent display. Despite these capabilities, the HoloLens has limitations in input, field of view, tracking, and occlusion that must be mitigated for the delivery of AR work instructions.

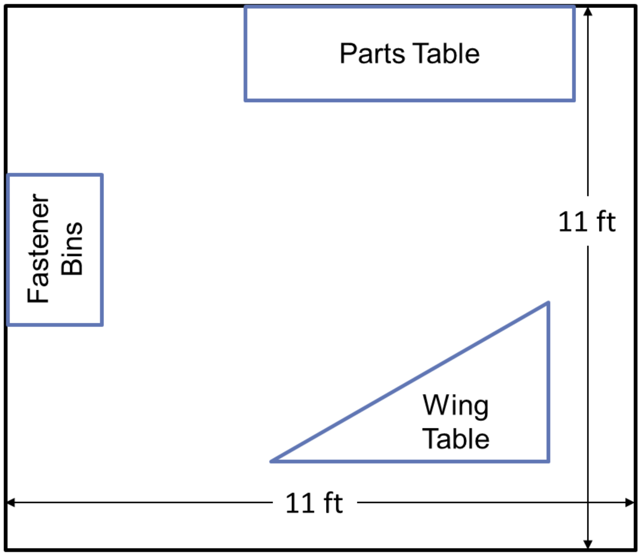

Figure 2. Station layout.

The HoloLens is a completely self-contained AR HMD and is not required to be tethered to an external computing device [22]. The computing power of the HoloLens consists of a 32-bit Intel processor with a custom-built Microsoft Holographic Processing Unit. The HoloLens takes in sensor data from an inertial measurement unit, four environment understanding cameras, one depth camera, one 2MP photo / HD video camera, four microphones and one ambient light sensor. Graphics are then displayed through see-through holographic lenses using waveguide technology. Through two HD 16:9 light engines, an effective resolution of 1268x720 per eye is achieved.

Wearable sensors such as Fitbit, Apple Watch, and the Empatica E4 are more popular than ever and collect important physiological data about the user. This data includes photoplethysmography, skin temperature and electrodermal activity. Specifically, the Empatica E4 is a high end, CE Medical 93/ 42/EEC Directive, class 2A compliant physiological sensor providing the most accurate data for health applications [23]. Using this device during training can lead to a better understanding of the trainees' experience and readiness level through an analysis of their physiological response.

Development Tools

Unity3D is a powerful game engine widely used for the development of 2D, 3D, VR and AR applications [24]. The Unity3D editor allows for the rapid development of applications through a large toolset including a rendering engine, a physics engine, user interface design tools, and the Unity3D C# scripting API. In addition, support is available for a variety of build platforms including Windows, Mac, iOS, Android, and Universal Windows Platform (UWP). Due to the vast toolset and capabilities of Unity3D, it was chosen as the development platform for the AR assembly application and data visualization tool.

In addition, since the Microsoft HoloLens was chosen as the AR hardware for this system, the functionality provided by Unity3D was very advantageous. Microsoft provides ample documentation for, and highly recommends, Unity3D for developing AR HoloLens Applications [25]. While it is possible for developers to build their own engines using DirectX and other Windows APIs, developing the application using Unity3D will result in a high-quality application in a significantly shorter development cycle.

Figure 3. Image target example.

The Vuforia SDK is one of the leading AR SDKs used for a variety of purposes [26]. Using propriety computer vision algorithms, Vuforia provides functionality for image, text, model and object tracking. Through this tracking, Vuforia is able to deliver position and orientation data which can then be used to spatially register AR content. Like development with Unity3D, Microsoft provides documentation and highly recommends, Vuforia when utilizing image targets in a HoloLens application [27]. Furthermore, as of Unity3D 2017.2, Vuforia is built into the Unity3D engine to increase functionality and ease of use. Vuforia was chosen to augment the tracking capabilities of the HoloLens for the AR system. The functionality, wealth of documentation, and stability of the Vuforia SDK was ideal to provide image tracking capabilities for the AR assembly application, Figure 3 shows an example image target. The image tracking, accompanied by the HoloLens tracking system, allowed for all AR content to be properly spatially registered.

Augmented Reality Assembly Application

The AR assembly application was developed for the HoloLens using Unity3D along with the Vuforia SDK. This application guides the trainee through the assembly of the mock aircraft wing, previously described. The application begins with a UI asking for the trainee's identification number to properly store the session data. After that has been completed, a large start button appears with four large white squares in each corner of the display. These white squares are used to ensure the trainee is properly wearing the HoloLens device. If the trainee can see all four white squares it means that they are experiencing the full field of view for the HoloLens. After the start button is pressed, the trainee is led through the 46-step assembly process. The UI appears over the current station and displays pertinent information including text directions and navigational tools. The trainee's attention is guided through a series of square yellow gates to the proper position. Parts that need to be acquired are outlined in green and then animations are given to demonstrate how to assemble each step, see Figure 4. When all steps are completed a finish button will appear which then terminates the session and stops the data logging. While the HoloLens can receive input from the user, track the environment and display spatially located content, there are still many limitations that must be overcome.

Input

For the AR assembly instructions to be usable, the trainee had to be able to interact with the application in an intuitive manner. To receive input from the user, there were a variety of options available. The HoloLens provides built-in gesture controls, namely the "air tap". While this input method is relatively hands-free, it is often difficult to teach to a new trainee and may lead to reduced usability of the system. Another input method often used in AR HMDs is the "gaze and dwell". While this is completely hands-free, the user must keep their head unusually still and it tends to be very slow. Voice commands were another method considered, however this would not be ideal for loud manufacturing environments. Finally, the chosen input method was utilizing the Bluetooth clicker that comes with the HoloLens device. This clicker can be attached to the trainee's wrist by a simple strap leaving the trainee hands-free during the assembly process. While the trainee gazes at the button then can simply press this clicker to deliver input to the HoloLens, see Figure 4. It is an intuitive method that is simple to learn.

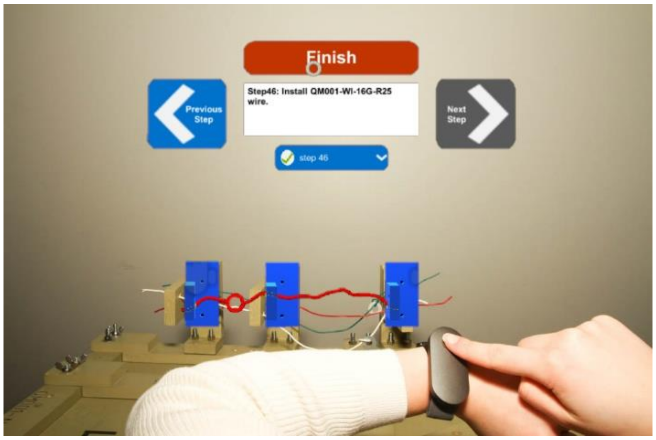
Step46: Install QM001-WI-16G-R25 wire.

Figure 4. HoloLens input method and interface.

Tracking

The AR assembly application must be able to track the environment well enough to correctly display spatially located assembly instructions. The HoloLens can generate a mesh of the environment using its proprietary tracking system. To successfully track the assembly, the generated mesh had to be detailed enough to identify key feature points: edges, corners, etc. However, Figure 5 shows that the mesh generated for even a basic assembly is not nearly accurate enough to achieve this. In addition, the HoloLens suffers from spatial drift due to error in the propriety tracking system and IMU. This drift accumulates over time and would be detrimental to any task lasting more than a few minutes. If the AR work instructions are not accurately registered, then the trainee may misinterpret the instructions leading to errors in the assembly process. These errors would only lead to additional costs and time lost. To overcome these limitations, the Vuforia SDK is used to provide image tracking capabilities. Image targets can then be used to initialize the location of the stations to augment the environment tracking of the HoloLens. The UI is then placed over these image targets so when the trainee looks at the UI, the application seamlessly reinitializes the position and corrects the drift.

While image targets offer additional tracking capabilities, they are not without their own inaccuracies. Lighting conditions, gloss, target image quality, camera quality, viewing angle, and distance can all lead to errors and/or false positives when detecting the target, examples shown in Figure 6 and Figure 7 [28]. Any error in the calculated position and orientation of the image target is subject to a lever arm, i.e., rotational error is propagated over distance. This means that even a one-degree error in the calculated rotation of the image target over the distance of one-meter would lead to almost a two-centimeter difference in the location of the spatialized content. To overcome this limitation, a calibration stage was implemented to ensure all locations are properly initialized. This stage involved the trainee gazing at the image targets to initialize the position and then ensuring that the UI is placed flush with the image target. The tracking system then used this initialized position and orientation as a baseline. After this point, anytime the image target is detected, the calculated orientation is compared with the initialized orientation. If the rotations are different then the image target will not update its position. This method drastically reduced false positives when detecting the image target and limited error in the tracking system.

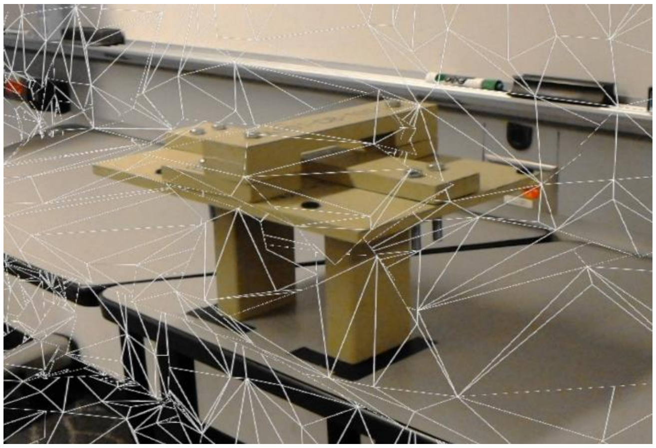

Figure 5. HoloLens spatial mapping of a basic assembly.


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

Figure 6. UI correctly located flush with image target.


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

Figure 7. Miscalculated orientation of image target.

Navigation

Since the trainee may be unfamiliar with the assembly environment, there needed to be a navigation system to guide them to the correct location. Previous research indicates that a 3D gate system is the most usable form of navigation in large 3D environments [29]. To accomplish this, virtual square yellow gates were placed along a Bezier curve leading to the current step's location, shown in Figure 8. After the stations are correctly located, a Bézier curve can be generated between the two points. The start point is the HoloLens and the end point is the current step's location. One control point is placed in front of the HoloLens to ensure the gates are always in view of the trainee and a second control point is placed between the previous control point and the end point to smooth out the curve. Square yellow gates are then placed along the calculated curve at equal distances. The HoloLens' processing power along with the Unity3D C# scripting API was able to perform this operation at a high framerate to ensure a smooth navigation system. The use of this navigation system would help give the trainee directional cues in an unfamiliar training environment where many distractions may be prevalent.

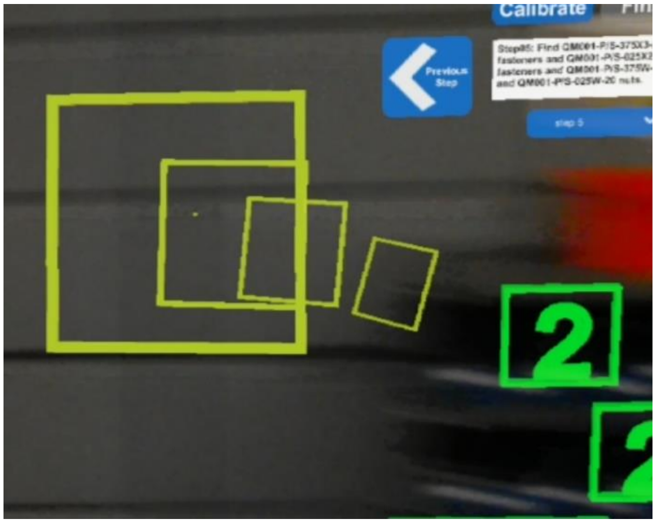

Figure 8. Yellow navigation gates.

Occlusion

Occlusion is crucial to an AR assembly application. The depth perception cues given by occlusion ensures the trainee sees the proper representation of the work instructions [20], [21]. Therefore, real world parts must be able to occlude the virtual parts shown in the work instructions. As previously discussed, the HoloLens can create a mesh of the real world but in very poor detail. This would not be ideal for occlusion as inaccuracies may misrepresent the instructions given. To overcome this limitation, the augmented tracking capabilities of Vuforia and knowledge that the stations are stationary are utilized. The solution implemented includes using the station positions and orientations received from the Vuforia image targets. From there, the position and orientation of each assembled part can be calculated from simple vector math. Finally, a virtual representation of each previously assembled part can be placed in the scene with the same position and orientation as its real counterpart. A shader is then used to write this virtual part to the z-buffer but not render anything. A separate shader is then used to render the work instructions a solid opaque color when in front of a real part but a yellow outline where it is occluded, see Figure 9. This custom solution allowed the trainee to see virtual work instructions properly occluded by real parts leading to the proper representation of the work instructions.

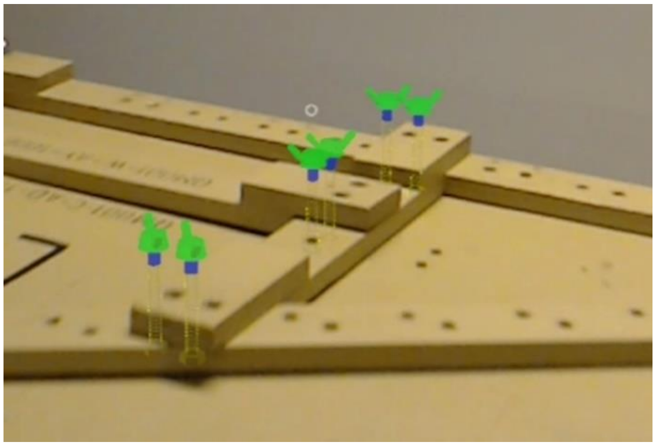

Figure 9. Virtual bolts occluded by real parts.

Data Collection

During the training session, data can be collected on the trainee's experience from the same sensors used to track the environment. This data includes position data, orientation data, when input actions are performed, and how long they spend on steps. The data can then be stored locally on the HoloLens as CSV files to be easily parsed for later analysis. In addition, data can be collected from various other sources such as wearable physiological sensors and post-processed assembly error data. This data can help lead to a greater understanding of the trainee's experience.

Data Visualization Tool

From a technological standpoint, the HoloLens is unable to validate that the work instructions were delivered accurately. The HoloLens is an emerging technology with various limitations previously discussed. It is necessary to ensure that these limitations were mitigated in a way that allowed for the accurate delivery of the work instructions. In addition, while the HoloLens can collect a wealth of information during the training session, it is unable to provide the means to analyze it with additional data sources. To address these problems, a data visualization tool was developed to virtually recreate the trainee's assembly session. From this recreation, an analyst, referring to anyone who would use this tool to review the data, may validate that the instructions and explore any potential trends that occurred during the session. This analysis

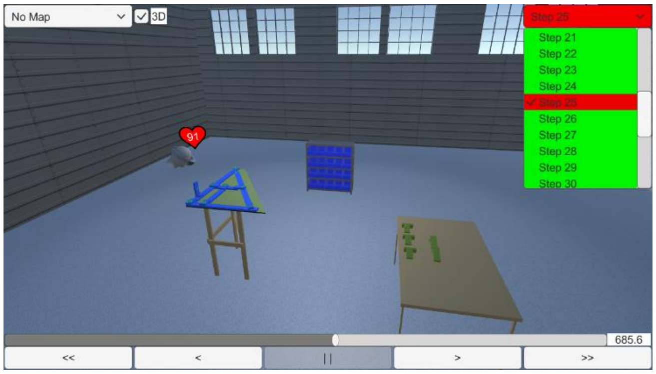

Figure 10. Visualization tool UI.

would be highly advantageous to identify if the trainee is prepared but also to pinpoint inefficiencies in the assembly process. The data visualization tool was developed using Unity3D for this purpose. Data from the HoloLens, Empatica E4 and post-processed assembly error data was parsed and synced within the application.

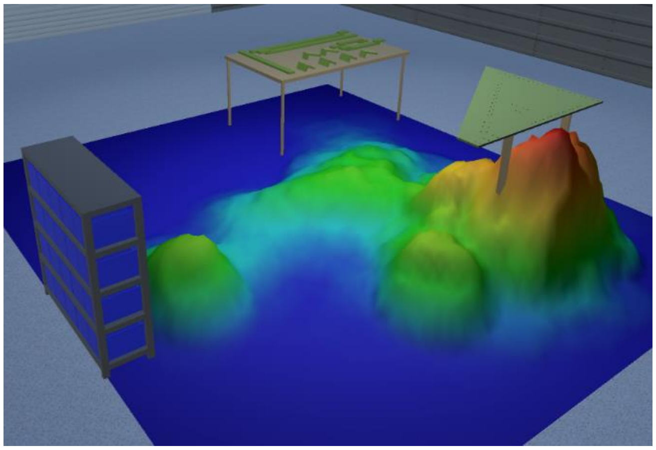

Figure 11. 3D positional heat map.

From the fusion of data within the application, there are various tools for analysis. A playback tool is available to scrub through the timeline of the training session, see Figure 10. A scrubber and timestamp show the current time location. The analyst can then use buttons to pause, play, play-2x, rewind, and rewind-2x to navigate along the time line. The analyst is also able to navigate around the environment to view the session from various vantage points. An avatar, representing the trainee, is displayed within the virtual recreation of the training environment. The avatar will follow the same path the trainee did during the training session. The avatar shows where the trainee was located but also which direction they were facing. In addition, the heart rate of the trainee is displayed over the avatar's head to show their physiological responses during the session. A dropdown menu displays the list of steps and shows the current step. From the post-processed assembly error data, steps that were completed correctly show up as green and steps that had errors show up as red. The navigational tools and data represented would allow the analyst to quickly assess if the instructions were delivered accurately and identify high-level trends during the session.

To further explore these trends within the training session, heat maps are generated from positional and heart rate data. For both map types, 2D and 3D heat maps are available. Color is used to show the variation from high to low, red representing high values and blue representing low values. The positional heart map, shown in Figure 11, displays the amount of time that was spent at each point in the training environment. This map is then overlaid on top of the virtual training environment for a clear representation of where the trainee spent the most time. The heart rate heat map takes the average heart rate within a given region. This map is also overlaid over the virtual training environment to show where the trainee had the highest physiological response, shown in Figure 12. Since both maps represent where the participant traveled, any unusual points may represent issues within the tracking system of the HoloLens during the training session.

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

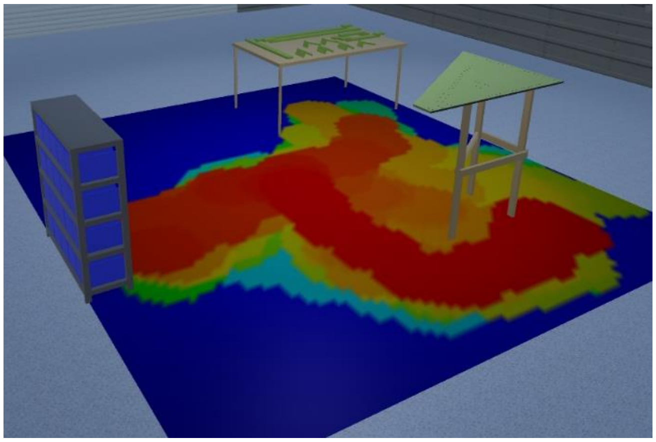

Figure 12. 2D average heart rate heat map.

The capabilities of this application present many unique opportunities regarding data analysis. It should be noted that this application does not provide statistical significance or give any conclusive explanations. The purpose of this application is to provide a high-level analysis to augment traditional statistical methods by helping to explain trends already found or generating new leads to explore further. In addition, time studies would also benefit greatly from a tool of this nature. Instead of the time-consuming process of overserving how a task is performed, the analyst could quickly scrub through the session to identify major trends paired along with the heat maps generated.

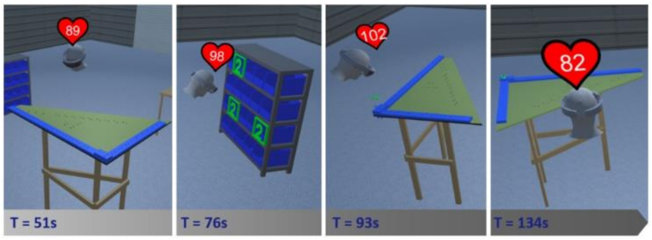

Figure 13. Analysis of heart rate data over time.

It was found in a prior study using the same training environment described in this paper found that participants had significantly higher average heart rates on picking and assembly steps compared to placing steps [30]. However, there was no explanation to why this had occurred. By combining positional, rotational, step time, and heart rate data into this data visualization tool, a hypothesis is formed. Figure 13 shows a timeline of a trainee who experiences a change in heart rate over the course of a picking and assembly step. The trainee moves from a placing step to a picking step requiring them to bend down to reach the fasteners required. Their heart rates spikes and it's possible see this physiological response continue into the assembly step following. After that assembly step is complete, we see that their heart rate returned to normal. From this high-level analysis, it is possible to hypothesize that the increased heart rate is caused by poor ergonomic conditions during the picking step. While the statistical analysis in Hoover et al. showed significantly higher heart rates for picking and assembly steps, this additional evidence shows that the elevated assembly step heart rate may just be due to the physiological response bleeding over from the picking step preceding it.

Conclusion

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

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

References

[1] S. Henderson and S. Feiner, "Exploring the benefits of augmented reality documentation for maintenance and repair," *IEEE Trans. Vis. Comput. Graph.*, vol. 17, no. 10, pp. 1355–1368, Oct. 2011.

[2] M. Hoover, J. Miller, S. Gilbert, E. Winer, and P. Davies, "Evaluating Augmented Reality Assembly Instructions Delivered via Microsoft HoloLens," 2018, pp. 1–14.

[3] R. T. A. Azuma, "Survey of Augmented Reality," *Presence: Teleoperators and Virtual Environments*, vol. 6, no. 4. pp. 355–385, 1997.

[4] D. W. F. Van Krevelen and R. Poelman, "A survey of augmented reality technologies, applications and limitations," *... J. Virtual Real.*, vol. 9, no. 2, pp. 1–20, 2010.

[5] R. Palmarini, J. A. Erkoyuncu, R. Roy, and H. Torabmostaedi, "A systematic review of augmented reality applications in maintenance," *Robot. Comput. Integr. Manuf.*, vol. 49, pp. 215–228, Feb. 2018.

[6] T. P. Caudell and D. W. Mizell, "Augmented reality: an application of heads-up display technology to manual manufacturing processes," in *Proceedings of the Twenty-Fifth Hawaii International Conference on System Sciences*, 1992, pp. 659–669 vol.2.

[7] K. M. Baird and W. Barfield, "Evaluating the effectiveness of augmented reality displays for a manual assembly task," *Virtual Real.*, vol. 4, no. 4, pp. 250–259, Dec. 1999.

[8] F. Loch, F. Quint, and I. Brishtel, "Comparing video and augmented reality assistance in manual assembly," in *Proceedings - 12th International Conference on Intelligent Environments, IE 2016*, 2016, pp. 147–150.

[9] D. Tatić and B. Tešić, "The application of augmented reality technologies for the improvement of occupational safety in an industrial environment," *Comput. Ind.*, vol. 85, pp. 1–10, Feb. 2017.

[10] F. De Crescenzio, M. Fantini, F. Persiani, L. Di Stefano, P. Azzari, and S. Salti, "Augmented reality for aircraft maintenance training and operations support," *IEEE Comput. Graph. Appl.*, vol. 31, no. 1, pp. 96–101, Jan. 2011.

[11] D. Wagner, T. Pintaric, F. Ledermann, and D. Schmalstieg, "Towards Massively Multi-user Augmented Reality on Handheld Devices," pp. 208–219, 2005.

[12] Microsoft, "Microsoft HoloLens | The leader in mixed reality technology," 2018. [Online]. Available: https://www.microsoft.com/en-ca/hololens. [Accessed: 03-Jun-2018].

[13] Daqri, "Smart Glasses^{TM} - DAQRI," 2018. [Online]. Available: https://daqri.com/products/smart-glasses/. [Accessed: 03-Jun-2018].

[14] Meta, "Meta | Augmented Reality," 2018. [Online]. Available: http://www.metavision.com/. [Accessed: 03-Jun-2018].

[15] G. Evans, J. Miller, M. Iglesias Pena, A. MacAllister, and E. Winer, "Evaluating the Microsoft HoloLens through an augmented reality assembly application," p. 101970V, 2017.

[16] A. Tang, C. Owen, F. Biocca, and W. Mou, "Comparative Effectiveness of Augmented Reality in Object Assembly," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 2003, no. 5, pp. 73–80.

[17] R. Azuma, Y. Baillot, R. Behringer, S. Feiner, S. Julier, and B. MacIntyre, "Recent advances in augmented reality," *IEEE Comput. Graph. Appl.*, vol. 21, no. 6, pp. 34–47, 2001.

[18] A. I. Comport, E. Marchand, M. Pressigout, and F. Chaumette, "Real-time markerless tracking for augmented reality: The virtual visual servoing framework," in *IEEE Transactions on Visualization and Computer Graphics*, 2006, vol. 12, no. 4, pp. 615–628.

[19] J. P. Rolland and H. Fuchs, "Optical Versus Video See-Through Head-Mounted Displays in Medical Visualization," *Presence Teleoperators Virtual Environ.*, vol. 9, no. 3, pp. 287–309, Jun. 2000.

[20] M. M. Shah, H. Arshad, and R. Sulaiman, "Occlusion in Augmented Reality," *8th Int. Conf. Inf. Sci. Digit. Content Technol. (ICIDT 2012)*, vol. 2, pp. 372–378, 2012.

[21] M. M. Wloka and B. G. Anderson, "Resolving occlusion in augmented reality," in *Proceedings of the 1995 symposium on Interactive 3D graphics - SI3D '95*, 1995, pp. 5–12.

[22] Microsoft, "HoloLens hardware details - Mixed Reality | Microsoft Docs," 2018. [Online]. Available: https://docs.microsoft.com/en-us/windows/mixed-reality/hololens-hardware-details. [Accessed: 22-May-2018].

[23] M. Garbarino, M. Lai, D. Bender, R. W. Picard, and S. Tognetti, "Empatica E3 - A wearable wireless multi-sensor device for real-time computerized biofeedback and data acquisition," in *Proceedings of the 2014 4th International Conference on Wireless Mobile Communication and Healthcare - "Transforming Healthcare Through Innovations in Mobile and Wireless Technologies", MOBIHEALTH 2014*, 2015, pp. 39–42.

[24] Unity Technologies, "Fast Facts," 2018. [Online]. Available: https://unity3d.com/public-relations. [Accessed: 10-May-2017].

[25] Microsoft, "Unity development overview - Mixed Reality | Microsoft Docs," 2018. [Online]. Available: https://docs.microsoft.com/en-us/windows/mixed-reality/unity-development-overview. [Accessed: 22-May-2018].

[26] L. Soussi, Z. Spijkerman, and S. Jansen, "A Case Study of the Health of an Augmented Reality Software Ecosystem: Vuforia," in *International Conference of Software Business*, 2016, pp. 145–152.

[27] Microsoft, "Using Vuforia with Unity - Mixed Reality | Microsoft Docs," 2018. [Online]. Available: https://docs.microsoft.com/en-us/windows/mixed-reality/vuforia-development-overview. [Accessed: 22-May-2018].

[28] Vuforia, "Optimizing Target Detection and Tracking Stability," 2018. [Online]. Available: https://library.vuforia.com/articles/Solution/Optimizing-Target-Detection-and-Tracking-Stability.html. [Accessed: 22-May-2018].

[29] A. MacAllister *et al.*, "Comparing Visual Assembly Aids for Augmented Reality Work Instructions," in *Comparing Visual Assembly Aids for Augmented Reality Work Instructions*, 2017.

[30] M. Hoover, A. MacAllister, J. Holub, S. Gilbert, and E. Winer, "Assembly Training Using Commodity Physiological Sensors," in *Assembly Training Using Commodity Physiological Sensors*, 2016.

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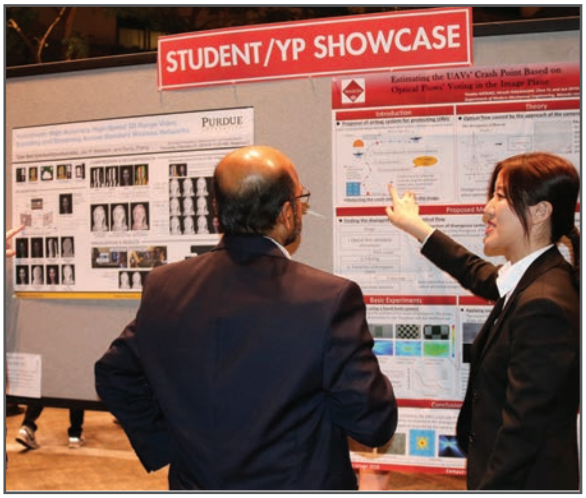

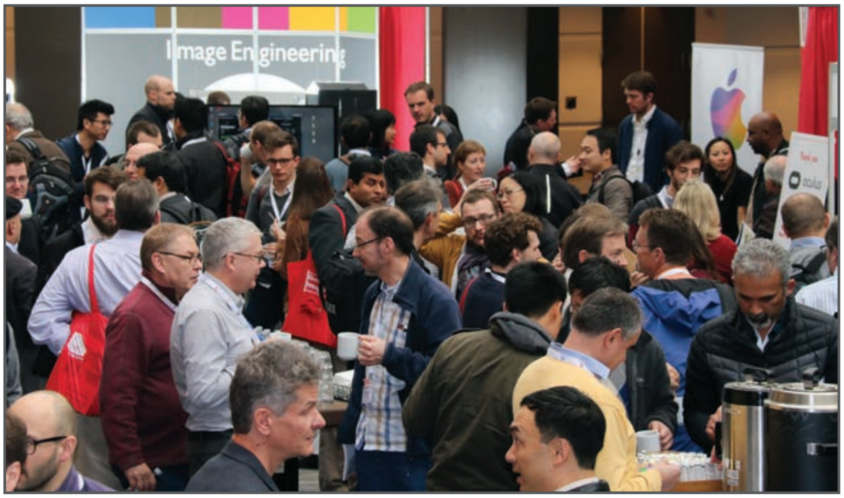

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