

Expert-Assisted Field Maintenance using Augmented Reality

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ABSTRACT

In 2016, the US military had an operation and maintenance budget of almost USD \$200 billion, the largest budget of any appropriation category. As such, it is imperative to minimize errors and costs when performing maintenance tasks. Unfortunately, the military may not always have enough skilled technicians on hand to send to all maintenance sites. Because of this, warfighters must often perform maintenance on systems outside their area of expertise. Augmented reality (AR) has been shown to effectively deliver context-aware instructions, reducing the time needed to identify suitable maintenance steps by more than 50%. However, even with the use of AR, it would be impractical to create maintenance instructions for each unique piece of machinery. By connecting a remote warfighter to a skilled technician, a plethora of maintenance knowledge can be quickly transferred in a targeted manner.

This paper details a mobile application that puts both the power of AR and the knowledge of a technician directly into the hands of a warfighter in the field. A mobile application was developed using the Unity3D game engine that enables technicians to use AR to visually share maintenance knowledge with a remote warfighter. A live camera feed of the warfighter's immediate area is streamed to the technician. Observing this feed, the technician sends back real-time maintenance guidance in the form of augmented 3D models and animations, selected from a list or created dynamically. Once received by the remote warfighter, the augmentations are overlaid onto the physical object, and the technician-recommended maintenance step is visible to the warfighter. While there has been ample research regarding AR-assisted processes, little focus has been given to leveraging the detailed knowledge of existing personnel. This paper discusses the application development and technical evaluation to ensure real-time connectivity in geographically distributed locations.

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INTRODUCTION

The U.S. Military defense budget allocated roughly USD \$200 billion for Operations and Maintenance in 2016, comprising almost half of the entire U.S. Defense budget (*Office of the Under Secretary of Defense (Comptroller) / Chief Financial Officer, 2016*). A subsequent report by the Congressional Budget Office revealed that nearly half of this budget was allocated for services such as maintenance, technology services, and transportation. More specifically, maintenance accounted for over \$32 billion (*Congressional Budget Office, 2016*). With so much money invested in the support and maintenance sector, enhancing this process would not only lead to lower costs, but also to a reduction in technician errors and required hours.

Today, most maintenance tasks are performed by skilled, on-site technicians, leveraging their own amassed knowledge and assisted by an operations manual. While this often delivers quality maintenance, a major flaw in this approach is that there may not be a skilled technician on location. As such, a uniquely qualified technician must be sent to the problem site, often accruing significant transportation costs. To add to this, if the original maintenance issue is not properly reported, this may require additional transportation for the technician to both diagnose the issue and receive the correct parts and tools. All of this leads to longer downtime for the equipment requiring maintenance and higher overall costs.

One possible solution would be to provide a highly-detailed operation manual to on-site warfighters who may not be familiar with the equipment. Unfortunately, for more complex equipment, these manuals become very difficult to interpret and understand, as well as requiring significant time to create. Additionally, problem diagnosis and maintenance often requires experience with and knowledge of underlying systems that is difficult to deliver pictorially or textually in a short time, leaving significant potential for errors.

Another solution would be to have an on-site warfighter leverage existing knowledge by using audio/visual calls with an off-site technician. Though this is the standard in most support industries today, real-time audio/visual calls make it difficult to effectively communicate specific tasks due to the high reliance on technical vocabulary that on-site warfighters may not possess.

Augmented reality (AR) is an emerging technology that could guide warfighters through a complex maintenance process using spatially-aligned 3D visual information. At its core, AR is when computer-generated visuals are overlaid onto a view of the real world in real-time, delivered through an electronic device such as a tablet or head-worn transparent display. An exhaustive evaluation by Neumann and Majoros found that AR would be an extremely attractive technology to deliver manufacturing and maintenance information (*Neumann, Majoros, 1998*). Additionally, a more recent study found that AR significantly reduced the time needed to identify suitable maintenance steps by more than 50% (*Henderson, Feiner, 2011*). In addition to reducing time requirements, AR has also been shown to reduce the potential for errors. A study in 2014 by the authors found that using augmented reality reduced the number of errors by up to 85% for a complex assembly procedure (*Richardson et al, 2014*).

While AR has the potential to provide many improvements to the maintenance process, there is still a major issue that needs to be addressed. It is highly impractical to create animated 3D maintenance instructions for every part on each system that is currently in use. Doing so would take a dedicated team weeks to months to accomplish for each mechanical system, and the instructions would be rendered obsolete once parts are changed. An ideal system would combine the easily understood visual overlay of augmented reality with the knowledge base and prowess of a skilled technician.

This paper details a workstation and mobile application known as the Augmented Reality Customer Collaborator (ARCC). This system allows a skilled technician to use their pre-existing knowledge to step a remote warfighter in the field through maintenance tasks, using augmented reality as a visual guide. The challenges, benefits, and shortcomings of this application will be discussed in detail.

BACKGROUND

Augmented reality (AR) technology has been around in some form since the 1990s. Many of the first AR systems were head-mounted displays (HMDs) with transparent screens that were little more than a heads-up display. Despite their simplicity, they were integrated into many industries with much success, including manufacturing (Caudell, Mizell, 1992) and the U.S. Military (Ferrin, 1999). The next evolution of AR was enabling it to understand its 3D environment. This type of AR relies on computer vision and inertial sensors to build an understanding of the physical environment. Using this information, 3D augmentations can be displayed in relation to real-world objects and locations. This paper will focus solely on this “spatial” type of AR.

Spatially-aware AR systems improved upon the benefits offered by the original heads-up style displays. One study conducted in 2003 found that using spatial AR for an assembly process reduced the number of errors by over 80% when compared to both traditional printed media and a basic AR heads-up display (Tang *et al.*, 2003). A more recent study used AR for LEGO assembly training, and found that the group using AR completed the assembly up to 30% faster than the group using the manual method (Hou *et al.*, 2013).

Today, most mobile commercial AR is done using tablets and smartphones. Figure 1 below shows an application released by IKEA that can display virtual furniture in a real room. Due to hardware constraints, these types of mobile devices can contain more computing power than most current standalone transparent HMDs. However, these handheld devices obviously do not allow the user to be hands-free, which may lead to problems in many industries where AR could prove useful, such as in manufacturing or maintenance. In 2016, Microsoft released one of the first commercially available transparent AR HMDs capable of spatially mapping its entire environment. As researched by Henderson and Feiner, stereoscopic transparent HMDs are one of the best display configurations for AR maintenance (Henderson, Feiner, 2007). Unfortunately, these types of displays are very expensive and fragile, and often have a very limited field of view that detracts from the overall AR experience. Despite these early adopter issues, it is already being studied for its usefulness in delivering AR instructions for assembly tasks (Evans *et al.*, 2017).

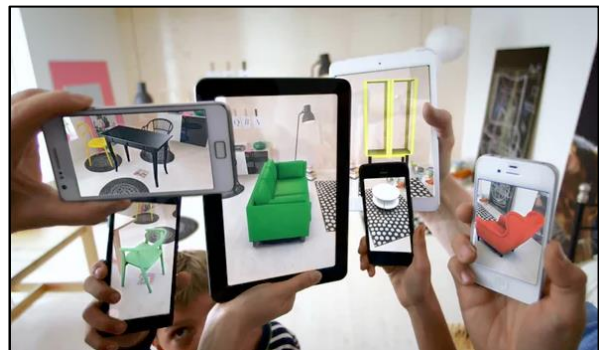


Figure 1. IKEA augmented reality app (IKEA, 2014)

AR Registration Techniques

Augmented reality has the potential to become an integral tool in numerous industries, but for it to be effective, the visual 3D augmentations need to be accurately overlaid onto the real world. To create these spatially-aligned visuals, the AR application needs to understand its 3D environment in some way, and establish a mapping between the virtual and real-world coordinate systems. There are currently two primary ways of accomplishing this, known as marker-based, and markerless tracking.

Currently, the most accurate method to create this coordinate system mapping is through marker-based tracking, using an “image target” (see Figure 2). Using this technique, a detailed, high-contrast image is used to provide

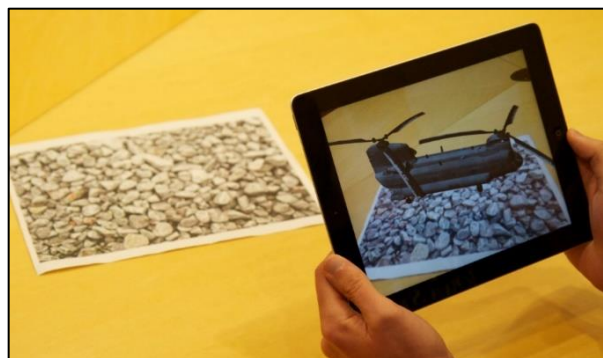


Figure 2. Marker-based AR

a real-world “anchor” point for overlaid 3D augmentations. AR applications use computer vision on a device’s RGB camera to detect the position and orientation of this image target, and all computer-generated visuals are placed at an offset from this image. However, one major drawback of using image targets is that when the image goes out of the camera’s view, any augmentation is lost. Fortunately, most modern mobile devices contain an inertial measuring unit (IMU) used to determine the device’s orientation. By utilizing this IMU to approximate device motion, AR applications can keep the 3D overlay active even when the image target goes out of view of the camera to a certain degree. This technique has been shown to provide superior tracking performance on vision-based smartphone AR applications (Yang *et al.*, 2015).

The other method of establishing a virtual and real-world coordinate system mapping is through markerless tracking. This technique often uses what is known as simultaneous localization and mapping (SLAM), which dynamically determines natural features in the environment and create its own coordinate points in real-time, such as in Figure 3. SLAM can be powerful for maintaining an accurate overlay, often with any misalignment of less than 5mm (Mahmoud *et al.*, 2017). The major problem with current markerless tracking is its inability to determine a coordinate origin. As seen in Figure 3, there are many tracked features points that represent the environment, but it is unclear to the application where any augmentation should be shown. However, ways to create an absolute positioning anchor dynamically are already being studied (Martin *et al.*, 2014). One popular method is to attempt to recognize an object and use that as the coordinate origin (Comport *et al.*, 2006), but this is not robust or accurate enough for use in the field. Due to the lack of consistency involved in maintenance tasks, object recognition accuracy may suffer with deformed objects or low-light conditions.

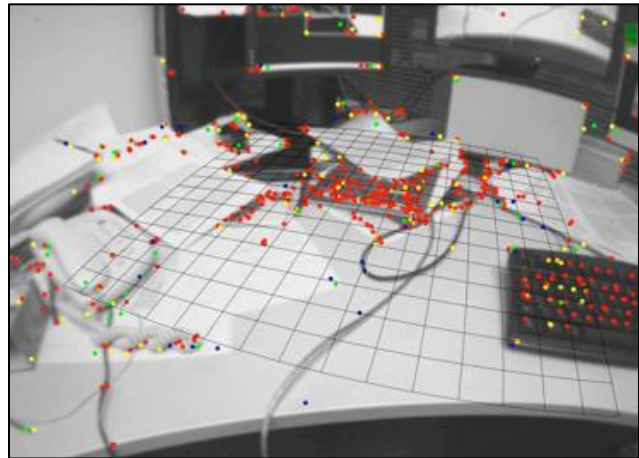


Figure 3. Markerless AR using SLAM (Kudan AR)

AR Software Toolkits

As described above, creating a spatially-aware AR application can prove challenging. Not only must the application scan the environment in real-time, but it must also load, manipulate, and render 3D models at the correct location on a device’s screen. Fortunately, due to AR’s rising popularity, there are several powerful AR software development kits (SDKs) capable of real-time computer vision. Some of the most popular toolkits are Vuforia, Wikitude, ARToolKit, and Kudan. Features of these popular SDKs are presented in Table 1. However, none of these SDKs provide rendering capabilities on their own. To that end, they all offer packages for popular rendering and programming environments, such as the Unity3D game engine, Android Studio, and XCode.

Table 1. AR SDK Feature Comparison

	Vuforia	Kudan	Wikitude	ARToolKit
2D Image Target Support	X	X	X	X
3D Object Recognition Support	X	X	X	-
Cloud Target Recognition	X	-	X	-
SLAM	-	X	X	-
Open-source	-	-	-	X

State of AR Maintenance

Using augmented reality to deliver maintenance instructions is already being studied for its potential benefits. In 2007, a team of researchers developed an application to explore the benefits of AR on the repair procedure of an armored

personnel carrier Military (Henderson, Feiner, 2011). They found that not only did AR reduce the time required to locate maintenance tasks, but it also significantly reduced head and neck movements.

Additionally, AR has made its way into even more maintenance sectors. Car manufacturers such as Hyundai and BMW have created smartphone AR applications that act as a digital owner's manual. By showing the user how to repair and replace common components using a 3D AR overlay, complex tasks can be easily conveyed. As early as 2017, the VTT Technical Research Center of Finland even developed an AR application for the European Space Agency, which has the potential to assist with repairs on the International Space Station (VTT Technical Research Center of Finland, 2017).

In addition to local augmented reality maintenance instructions, companies like Scope AR are beginning to develop commercial AR applications that connect an on-site customer to an off-site technician (Scope AR, 2016). While these connected applications show great promise, none of them have focused specifically on allowing an off-site technician to use spatially-aligned 3D models and animations to manipulate the warfighter's augmented view in real-time. To that end, the Augmented Reality Customer Collaborator (ARCC) system provides an opportunity to improve remote support guidance.

METHODOLOGY

The Augmented Reality Customer Collaborator (ARCC) was created to optimize costly maintenance procedures. It consists of two applications: a mobile Windows OS application, for on-site warfighters, and a Windows OS workstation application for the off-site technician lending assistance. Together, these two applications enable a communication system where an off-site technician can guide an on-site warfighter through maintenance procedures using AR.

The mobile application is primarily used for visualization, allowing a warfighter to see spatially-aligned animated 3D models overlaid onto real-world objects. The application detects and tracks an image target to enable this 3D overlay. When launched, no augmented content is initially shown. Instead, commands are received by an off-site technician that controls what is shown on the mobile device. These commands direct the mobile application to fetch the correct 3D model(s) from a remote repository, and display these 3D models at a specified offset and orientation from the image target. The warfighter's mobile application sends a webcam stream to the off-site technician, enabling simple remote monitoring capabilities.

The workstation application is used by the technician to remotely observe the warfighter's situation and manipulate their view. By receiving a live webcam stream, a skilled technician can diagnose the equipment needing maintenance, and select the corresponding 3D model from a remote server. This model is then loaded and displayed locally. The technician can then select parts of interest, chooses a pre-made animation, or creates a new one on-the-fly to represent a maintenance step. Once the selection process is done, a unique command is sent to the warfighter's mobile application that details the parts selected, and the animation to play. The basic communication architecture of the system is shown in Figure 4 to the right.

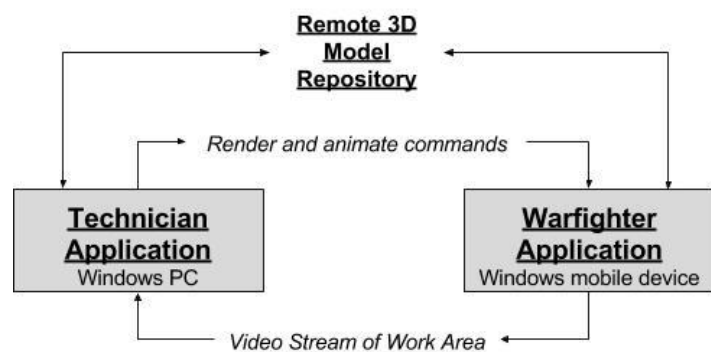


Figure 4. ARCC communication diagram

To implement the features described, a software development environment was required, which was comprised of several components. These components were a scripting and rendering engine to control what is displayed, computer vision algorithms to implement a spatial augmented reality overlay, and a way to load 3D models at runtime based on the situation.

Unity3D

The Unity3D game engine is a powerful cross-platform development and rendering environment that is quickly becoming one of the most used platforms in 3D application development (*Unity Technologies, 2017*). Not only does it support numerous mobile and workstation platforms, but the engine is built around a graphical user interface that exposes intuitive rendering and scripting capabilities to the developer. Additionally, it has already been proven to facilitate effective software development for augmented reality applications (*Kim et al, 2014*).

The Unity3D game engine was used to power both the mobile and workstation applications. It was chosen based on its intuitive interface, and for its large collection of compatible plugins. Due to this, features such as networking and dynamic model loading were possible to implement in a relatively short time. Additionally, using Unity3D's OS build support, only minor changes would be required to support additional mobile operating systems such as Android or iOS in the future.

Vuforia

Vuforia, from PTC, is one of the most popular AR SDKs currently in use (*Soussi, Spijkerman, Jansen, 2016*). Using proprietary computer vision algorithms, Vuforia can recognize the position and orientation of image targets, which can then be used to create 3D augmentations and place them in relation to these targets. By tracking image targets in real-time, warfighters can change their perspective and the virtual 3D overlay would be modified to match. Vuforia is also capable of utilizing onboard sensors like inertial measuring units (IMUs) to achieve extended tracking for when the image target goes out of view of the camera, creating a more seamless experience.

Since Vuforia cannot be used on its own to render a 3D overlay, it provides numerous application programming interfaces (APIs) that allow it to be used in many situations, with support for Android, iOS, Universal Windows Platform, and Unity3D. Vuforia was chosen for the mobile ARCC application due to its feature-rich and stable Unity3D plugin, and large development support forums and resources.

AssetBundle Manager

The AssetBundle Manager is a Unity3D plugin that facilitates loading assets, such as 3D models, at runtime. These assets can be either stored locally, or in the case of ARCC, on a remote repository. To create a valid asset package that can be imported later, three primary steps are involved. First, the desired 3D model should be imported into Unity3D. Second, the model must be marked and labeled with a unique name. Lastly, the asset bundle(s) are compiled with the click of a button, and the resulting archive files can be placed at any local or remote location for future use. This same asset bundle manager plugin can be used to load these asset bundles later.

The AssetBundle Manager was used to load 3D models dynamically for both the workstation and mobile application. It was chosen because it is currently the only well-documented way of loading assets into Unity3D from a remote location. When new assets are imported into Unity3D, they must go through a pre-processing step that allows the engine to recognize what has been imported. Since Unity3D is proprietary, this pre-processing step cannot be replicated by third parties. Since the AssetBundle Manager plugin was created directly by Unity Technologies, this pre-processing step could be used when creating asset bundles.

Workstation Implementation

The Windows-based workstation application enables the off-site technician to assist the warfighter with maintenance tasks. It uses the Unity3D game engine with the AssetBundle Manager plugin, and the accompanying C# scripting environment. When launched, the application sets up a new TCP socket using Unity3D's included C# networking libraries, and listens for incoming connections on a configurable port number. When a new on-site warfighter connects, the session data is saved, and another network socket (UDP) is opened to receive webcam data from the warfighter's mobile application. The original TCP socket is used to reliably transfer formatted text commands from the technician to the warfighter.

Once the technician begins receiving the video stream from the warfighter, the technician can identify the equipment needing maintenance. Using a dropdown menu, the technician can choose the corresponding 3D model from the remote asset repository. The model is then loaded and displayed locally in the main viewing area. Using a standard

mouse to rotate, translate, and zoom in, the technician can select one or more parts on the model. Once selected, there are four primary actions that can be taken:

1. Hide the selected parts, allowing the technician to view internal components, or to keep the 3D model at a similar state of disassembly as the object at the warfighter's location.
2. Send the selected parts to the warfighter as a static overlay with no animation. This can be used to highlight a specific area of concern.
3. Create and send a custom animation sequence on-the-fly for the selected parts by dragging and rotating coordinate axes. The resulting sequence can be previewed locally before being sent to the warfighter.
4. Select and send a pre-built animation that has been baked into the 3D model. If a particular maintenance step is highly complex and difficult to create on-the-fly, an animation can be generated beforehand.

When the parts and any potential animation are sent, a formatted command string is generated and delivered to the warfighter's application. This string includes the name of the loaded asset, the selected part names, and the animation name (for a pre-built animation), or animation sequence (for a custom animation). The workstation interface is shown below in Figure 5, where the technician is creating a custom animation sequence to show the removal of the front screws on a hydraulic pump.

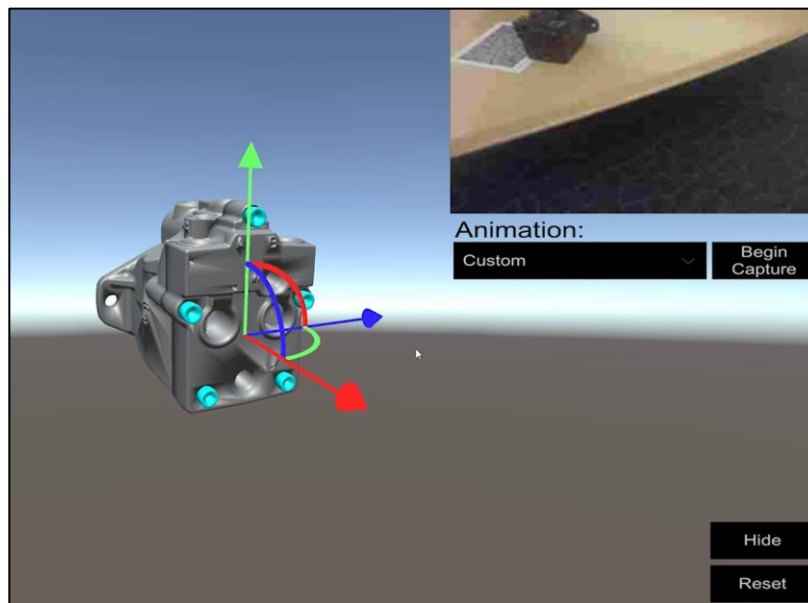


Figure 5. Technician's workstation ARCC application

The workstation application can be run on any modern 64-bit Windows computer. Testing was done on a 2012 Asus laptop running Windows 10 with a 2.4GHz Intel Core i7 processor, 10GB of RAM, and an Nvidia GeForce GT 620M graphics card. The workstation application can also be used offline to generate new asset bundles for future equipment that may require maintenance.

Mobile Implementation

The Windows-based mobile application is the augmented reality viewer for the on-site warfighter, who is performing maintenance. It is built using the Unity3D game engine with the Vuforia and AssetBundle plugins, using the C# scripting environment provided by Unity3D. When launched, the mobile application requires an IP address representing the technician's workstation computer. This is currently user-specified, which is not ideal for most support situations. When a dedicated support team is created, this can be easily modified to connect directly to the static public machine or to a server that can connect clients to hosts on-the-fly.

Once connected to the technician, the mobile application opens a UDP network socket using Unity3D's C# networking libraries, and begins sending compressed JPEG video frames to the technician's workstation app. A secondary TCP network socket is also opened to receive formatted text commands from the technician. Once the technician reviews

the outgoing video feed and selects the proper 3D model, parts, and animation, the mobile app then receives a text string denoting the asset to load, the parts to overlay, and the animation to play, if any. Using this information, the AssetBundle Manager plugin automatically retrieves the corresponding asset from the remote repository, and enables the specified parts and animation. At this point, control is given to the Vuforia plugin to use computer vision to locate the image target, and place the specified parts at the proper location to provide the warfighter an effective 3D overlay. Seen below in Figure 6, the warfighter is shown how to remove the front five screws on a hydraulic pump assembly.



Figure 6. Warfighter's mobile ARCC application

The warfighter's mobile application can be run on any modern 64-bit Windows computer with a standard RGB webcam. Testing was done on a 2013 Dell Venue Pro tablet running Windows 8.1 with a 1.6GHz Intel Core i5 processor, 8GB of RAM, and an Intel HD Graphics 4200 integrated graphics chip. Note that this is a very computationally expensive process for a mobile device. The application must grab video frames from the camera, compress them, send them over the network, all while actively running computer vision algorithms for image target detection.

Prototype Testing and Evaluation

The ARCC prototype had to be tested and evaluated for feasibility before tweaks to performance and reliability could be made. The hydraulic pump, shown earlier, was used for this testing. The main metrics were data throughput, based on the Internet connection available, the resulting video framerate to the technician, and the framerate of the mobile application in use by the warfighter. The system was tested on: 1) a low-latency, high bandwidth network, 2) a typical high-latency, high-bandwidth network, and 3) over a cellular LTE internet connection. The technician was able to achieve greater than 25 fps of video from the mobile application in all testing environments. The mobile application, given the modest hardware specifications listed above, also achieved an average of 25 frames per second (fps) for all tests. Sending of augmented content almost always happened in real-time. In a few cases, the mobile application took a few seconds to receive and show it. While the interactivity and framerates were good, this type of testing was hardly exhaustive. These tests show promise of the system, but multiple models and environments in a formal evaluation need to be performed in the future. These feasibility tests did reveal issues that need to be addressed or considered as this system evolves.

One such issue is the scaling between an image target and the size of the corresponding overlay. If a standard size ratio between a virtual image target and a real-world object is not established, the 3D augmented overlay will not match up with the real-world object, leading to incorrect visuals that ultimately confuse the warfighter. For lab tests of the ARCC system, a standard 8.5"x11" image target was used, and all 3D models were scaled to accurately reflect this baseline size. Ideally, no image target would be required at all. However, as described in the background section, markerless tracking and object recognition algorithms are not robust enough yet to rely on in the field.

Finding the correct balance between the video framerate and the quality of the webcam stream is also critical to producing the best possible experience. In its current form, the ARCC system requires about a 1Mbps bandwidth for uninterrupted standard-definition streaming at a framerate of 25fps. In contrast, a high-definition stream requires a bandwidth of between 5-8Mbps for a similar framerate.

Under limited bandwidth, the video framerate can be reduced with limited impact. Since the warfighter's mobile application handles marker detection and the 3D visual overlay locally, a lower video framerate will not affect the experience for the warfighter. The only major concern with a lower video framerate is on the ability for the off-site technician to recognize equipment properly with a low framerate video feed. Under extreme conditions, single video frames can be used in place of a video stream. This can still prove effective, and could even be ideal in situations where no stable internet connection is available.

With the ARCC's current standard-definition video stream, the maximum latency on a stable internet connection is, on average, 1.5 seconds. Beyond this, video frames are dropped to maintain a real-time feed from the warfighter. The average latency is less than 0.5 seconds. Since the augmented overlay won't be changed until the technician provides another animation sequence, this small amount of video delay will not likely be detrimental to providing adequate augmentation instructions.

An ideal ARCC system would use a hands-free head-worn device with a transparent display for the mobile application, rather than a tablet or phone. The newly released Microsoft HoloLens is one such device, but it comes with its own set of considerations. Firstly, the field of view of the headset is extremely limited, making it difficult to see the 3D overlay for a maintenance step in its entirety, especially when working in close proximity to equipment. Additionally, relying on uncommon or expensive hardware rather than existing mobile technology would require a large initial buy-in cost to facilitate effective use. Despite this, the HoloLens and similar emerging HMDs represent a solid step in the right direction of creating ubiquitous augmented reality.

CONCLUSION

This research presented the ARCC system, a maintenance assistance application that can effectively transfer existing personnel knowledge from an off-site technician to an on-site warfighter in a targeted manner. By leveraging augmented reality, a 3D overlay can be created that does not suffer from the communication misinterpretation present in current support techniques, such as operations manuals or voice calls. The ARCC system consists of a mobile application used by the on-site warfighter, and a workstation application, used by the off-site technician. The system relies on commonly available Windows-based computers, leading to very little, if any, initial buy-in costs.

Using augmented reality to facilitate expert-assisted field maintenance has the potential to significantly reduce the U.S. Military's current \$200 billion budget for Operations and Maintenance (*Office of the Under Secretary of Defense (Comptroller) / Chief Financial Officer, 2016*). Within the last several years, the maintenance industry has seen a large rise in the use of augmented reality for product support. However, the majority of current applications do not focus on delivering a real-time expert-driven spatial 3D overlay to a warfighter in the field. The ARCC system is designed to be an accessible maintenance assistance application that replaces the standard audio/visual calls of today's support industry.

In addition to maintenance circumstances, systems like the ARCC have the potential to improve many situations where expert direction is needed by on-site personnel. Areas such as remotely-assisted surgery or manufacturing could see benefits from using an expert-driven, remotely-controlled spatial overlay.

Future work on this application will look into implementing the warfighter's mobile application on the Microsoft HoloLens transparent HMD. This will require a rework of the current network architecture to support the new build platform dependencies, and will be tested to gauge its efficiency compared to a standard mobile device. An additional item would be to integrate voice calling directly into the application. This would allow the warfighter and technician to communicate important information that may not be visible through the video stream or augmented overlay. Due to Unity3D's plugin accessibility, this will be a relatively trivial process. As augmented reality hardware and software advances, so too will its effect on the maintenance industry. Lastly, extensive testing needs to be done to truly understand the data requirements the system needs.

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