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Remote maintenance assistance using real-time augmented reality authoring

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Remote maintenance assistance using real-time augmented reality authoring

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The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this thesis. The Graduate College will ensure this thesis is globally accessible and will not permit alterations after a degree is conferred.

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ABSTRACT

Maintenance operations and lifecycle engineering have largely been considered one of the most expensive and time-consuming components for industrial equipment. Numerous organizations continually devote large quantities of resources towards maintaining equipment. As such, any optimizations that would reduce maintenance errors and expenses could lead to substantial time and cost savings. Unfortunately, there are often not enough specialists to meet the demand, forcing localized technicians to perform on-site maintenance on equipment outside their area of expertise. Augmented reality (AR) is one technology that has already been shown to improve the maintenance process. While powerful, AR has its own set of challenges, from content authoring to spatial perception. This work details a system that puts both the power of AR and the knowledge of a specialist directly into the hands of an on-site technician.

An application was developed that enables a specialist to deliver AR instructions in real-time to assist a technician performing on-site maintenance. Using a novel and simplified authoring interface, specialists can create AR content in real-time, with little to no prior knowledge of augmented reality or the system itself. There has been ample research on different AR-supported processes, such as real-time authoring, video monitoring, and off-site assistance. However, much less work has been done to integrate them and leverage existing personnel knowledge to both author and deliver real-time AR instructions. This work details the development and implementation of such a system. A technical evaluation was also performed to ensure real-time connectivity in geographically distributed environments. Three network configurations were evaluated. A high-latency high-bandwidth network was used to represent a typical modern maintenance facility. A

low-bandwidth network was evaluated to mimic older or more isolated maintenance environments. Lastly, a 4G LTE network was tested, showing the potential for the system to be used across global locations. Under all network configurations, the system effectively facilitated the complete disassembly of a hydraulic pump assembly.

CHAPTER 1. INTRODUCTION

Purpose of Work

The primary goal of this work is to allow maintenance specialists to convey their unique systems knowledge in real-time using augmented reality without the need to learn an intricate interface or use expensive hardware. The developed system was evaluated for feasibility, and to identify any issues with the approach.

Motivation

Maintenance has always been an essential component across a wide range of industries. The maintenance sector has seen substantial growth as far back as the 1990s and earlier [1]. In addition, maintenance spending is often the largest part of an operational budget, second only to the equipment's raw energy costs [2]. In 2008, the aeronautic industry estimated that the cost of maintenance would grow by more than USD $54 billion [3]. As a generalization, any organization that is heavily invested in machinery and equipment will also have a significant portion of their operations budget dedicated to maintenance tasks [4]. This is not only true for private corporations, but for all organizations. As an example, the U.S. Military allocated almost USD $200 billion for operations and maintenance in 2016, which is almost half of the entire U.S. Defense budget [5]. In fact, it was found that the cost of equipment maintenance often comprises almost 60-70% of a product's total cost during its entire lifetime [6]. Not only are maintenance operations expensive, but they are also often poorly optimized. One study found that maintenance data is vastly underutilized simply due to poor accessibility and reliability [7]. With such a significant investment in the support and maintenance sectors, any improvements to the maintenance process would not only lead to lower operating costs, but also to a reduction in required technician hours and shorter equipment downtime.

Table 1.1: Current maintenance methods

	Repair Facility	Skilled Specialist	Novice Technician	Novice with Support
Low Cost			X	X
Short Delay			X	X
Available	X		X	X
Effective	X	X		X

Today, most maintenance tasks are performed in one of four ways, involving shipment to a repair facility, or employing a skilled specialist, a novice technician, or a combination of the two. A basic summary analysis of these methods is seen in Table 1.1. For smaller equipment, it is often shipped to a repair facility, serviced, and shipped back to the work area. While effective, this method involves significant shipping times and costs, and may be greatly delayed due to the schedule of the repair facility. Additionally, little communication occurs between the repair facility and the worksite, leaving significant room for ineffective repairs.

The second method, utilizing a skilled specialist, would no doubt facilitate faster and higher-quality maintenance than a novice technician. However, there may not be a specialist on location, ultimately leading to longer equipment downtime and higher travel expenses. Furthermore, if the maintenance issue is not properly reported before the specialist arrives, additional transportation may be needed to allow the specialist to both diagnose and receive the proper tools and replacement parts. One study found that the proper identification of critical components and determining the root cause of malfunctions are two of the main components to improving the overall reliability of a mechanical system [8].

A third method used for maintenance would be to utilize a novice technician assisted by an operations manual or additional instructional material such as videos. While personnel would be widely available, the support material takes a significant amount of time to produce, and quickly becomes outdated when modifications are made to equipment. Specific to the aviation industry, it was found that almost 45% of an Aircraft Maintenance Technician's (AMTs) time is spend finding and reading instructional material for their current maintenance task [9]. An additional study found that Aircraft Maintenance Manuals (AMMs) only focus on a limited number of procedures, and do not clearly define many terms, ultimately leading to higher error rates [10]. One study found that over 60% of errors in an aircraft maintenance operation occurred due to the technician misunderstanding the manual [11]. A subsequent evaluation expressed that in order to increase air-transportation safety, the error rate of aviation maintenance employees must be drastically reduced [12]. Given this information, it would not make sense to equip a novice technician with extensive, error-prone material and expect a positive result. Problem diagnosis also requires extensive knowledge of underlying mechanical systems which can be difficult to portray pictorially or textually [13], leaving further potential for errors to occur. Lastly, Paz and Leigh found that the complexity of maintenance operations has been steadily increasing [14]. Given the greater complexity in machinery found today, this has made illustrating maintenance operations even more challenging, and increases the cost and time required to train skilled maintenance specialists, making their time an increasingly valuable resource [15].

A fourth option to perform maintenance is to allow an off-site skilled specialist to guide an on-site novice technician through maintenance tasks using an audiovisual call. Even though this is the standard support mode for many commercial industries today, real-time audiovisual calls suffer their own set of problems. Due to a high reliance on technical vocabulary, it may be difficult to effectively communicate tasks when both the specialist and the novice technician are not familiar with the same terminology. Additionally, no spatial alignment information is shared, making small, intricate systems even more challenging. While each of these methods have been used to facilitate the completion of maintenance tasks, they each have significant room for improvement. As such, finding more effective ways to train and guide technicians is essential to the continued maintenance of globally-distributed equipment [16].

Augmented reality (AR) is an emerging technology that has already shown great promise for improving maintenance performance. AR essentially allows a user to see the real world, except that this view is augmented with computer-generated graphics overlaid alongside real objects [17]. This augmented view is displayed to the user through an electronic device such as a camera-equipped tablet or a head-mounted transparent display.

An exhaustive evaluation found that AR could be a highly beneficial technology with a huge potential to improve manufacturing and maintenance operations [18]. One study found that a user's cognitive knowledge can be improved by adding real-time digital information to their view, helping them to better perceive their environment [19]. A more recent study found that by using AR, the time needed to identify suitable maintenance steps was reduced by more than 50% [20]. More than simply reducing the amount of time required for maintenance, AR has also been shown to reduce the number of errors during assembly tasks. One study from 2014 found that by using augmented reality to show step-by-step instructions for an assembly procedure, the number of errors was reduced by up to 85% when compared to only using standard paper-based instructions [21]. Since the cost and effectiveness of maintenance largely depends on efficiency and accuracy, AR certainly has the potential to significantly improve the maintenance process. However, as with many emerging technologies, AR is not without its own set of challenges.

One such challenge is the time and difficulty involved with authoring the content for AR systems. As found by Quint et al., creating content for AR-based systems cannot easily be done by shop-floor employees, and is a primary reason why AR has not yet been more widely adopted [22]. Without significant improvements to AR authoring tools, each simple AR instruction or overlay must be modelled, animated, and scripted by skilled engineers. Given the numerous configurations of maintainable systems distributed across the world, it would prove almost impossible to create an exhaustive collection of animated 3D maintenance instructions for each assembly and subassembly in production. Attempting this without efficient authoring tools would take a dedicated team of skilled personnel weeks or months to produce a full AR maintenance instruction set for a single reasonably multipart assembly. Additionally, significant rework would be required if the equipment undergoes any physical modifications. An ideal maintenance system would combine the easily interpreted visual overlay of augmented reality with the years of accumulated knowledge obtained by a specialist, without the need to waste countless hours authoring AR instructions manually.

To that end, this work explores how simplified visual-based AR content generation can enable a remote specialist to create detailed AR content in real-time, and immediately deliver customized instructions to an on-site technician. By focusing on a simplistic user interface, trained specialists would not be required to learn cumbersome controls to generate content, and can instead focus on transferring their knowledge to a technician using the visual capabilities provided by AR. The challenges, benefits, and shortcomings of this approach are discussed.

Thesis Organization

Chapter 2 discusses the evolution, benefits, and shortcomings of AR, and how it is being used in the maintenance industry. The effectiveness of multiple AR content generation systems is also evaluated. The unique work presented in this thesis is comprised primarily of a paper submitted to *Computers in Industry*. Chapter 3 is the paper as it appeared in the journal. It focuses on the process and techniques used to create a visual-based real-time authoring and delivery system, as well as a subsequent evaluation of its performance. Following this, Chapter 4 discusses some general conclusions of the work, and Chapter 5 highlights future efforts that may improve the overall effectiveness of the work.

CHAPTER 2. BACKGROUND

Prior research relating to the work described in this paper is spread across five areas, including: 1) the evolution of technologies used to enable AR, 2) the benefits of augmented reality, 3) research that uses AR to facilitate maintenance, 4) research that analyzes or improves the authoring process for AR, and 5) spatially registering AR with the real world. Work presented in each of these areas had an influence on the AR authoring and delivery methods developed in this thesis.

Evolution of Augmented Reality Technology

Augmented reality became a popular research topic in the 1990s. Many of these first AR systems were custom head-mounted displays (HMDs) with transparent screens and crude tracking mechanics that did little more than display information to the wearer. Despite their simplicity, they were integrated into many industries with success. Caudell and Mizell from The Boeing Company created a prototype system that used a transparent HMD to deliver wiring instructions to manufacturing personnel [23]. Even with this early implementation of AR, the researchers envisioned that the system could one day be used to reduce costs and improve the efficiency of human-involved manufacturing operation. Additionally, this paper essentially coined the term "augmented reality" as we know it today. More than just the private sector, the U.S. military was also key to exploring the early uses of AR [24].

Through developments in tracking capabilities and the continued miniaturization of electronics, AR continued to improve its ability to comprehend the real world through the user of better cameras and sensors. While computer vision is still the primary method used by AR to build an understanding of the physical environment, data from additional sensors also improves the overall effectiveness of AR. A system developed by You, Neumann and Azuma explored the benefits of supplementing vision-based AR with inertial sensors [25]. Their work showed the limitations of visual-only AR and highlighted the need to integrate multiple data sources together to improve the overall effectiveness of AR displays.

Today, tablets and smartphones have largely replaced the first generation of AR's bulky custom HMDs. While they are abundantly availability and relatively low cost, these portable devices limit the mobility of the user's hands. This downside could lead to problems in many areas where AR could otherwise prove beneficial, such as in manufacturing or maintenance. Largely due to this reason, transparent HMDs were still found to be one of the best display configurations for AR maintenance [26]. Recently, a new class of commercially-available self-contained transparent HMDs emerged, capable of spatially mapping the environment in real-time. They were quickly adapted to a number of disciplines including collaborative design review [27], surgical operations [28], and manufacturing [29]. While they effectively combined several capabilities together such as real-time depth sensing, voice commands, and hand gestures, they also have significant drawbacks. Not only are they more expensive than most modern tablets and smartphones, but they have a very limited field of view and display resolution, making detailed maintenance operations even more challenging. These new HMDs represents a positive step toward the future of AR, but there are still significant barriers to overcome before mass adoption. For these reasons, the work presented in this thesis focuses on delivering AR through modern inexpensive mobile devices such as tablets and smartphones. However, should the need arise, a new display platform can easily be supported through a few simple rendering modifications.

The technology behind augmented reality is no doubt rapidly improving. Through the last two decades, both the hardware and software has evolved from expensive prototypes to sophisticated and accessible commercial systems that can truly make a significant impact on many fields.

Benefits of Augmented Reality

Early augmented reality research looked at how it could lead to improvements in several industries, including medical visualization, maintenance, annotation, path planning and identification, entertainment, and the military [17]. What makes AR so attractive in both academia and industry is its continually proven ability to reduce cognitive load, decrease task time, reduce errors, and even facilitate more effective training over most current practices.

Cognitive Load

With the increasing complexity of maintenance and assembly tasks, the mental load on technicians also increases. A major benefit of augmented reality is its ability to minimize cognitive load and improve cognitive knowledge at the same time. One study from Tang et al. found that by using AR to show assembly instructions, the mental effort of users was decreased [30]. The study had users build a LEGO assembly using either traditional or AR-based instructions, and the researchers measured mental workload using the NASA Task Load Index. It was found that by using AR-based instructions, participant's perceived workload was significantly decreased, and was offloaded to the AR system.

Another study from Kim and Dey was developed to test how AR could improve driver navigation performance [31]. Twenty-four participants of varying ages were split into two groups, using either a standard GPS navigation system or a novel AR system that overlaid navigation instructions directly on the windshield. It was found that participants who used the AR-based system experienced significantly fewer issues related to divided attention than those using a standard GPS navigation system. This highlights how AR can be used to reduce the cognitive load required to translate between informational and real-world spaces.

A third study by Bujak et al. evaluated how AR improves the learning of increasingly challenging mathematical concepts in a classroom setting [32]. By evaluating numerous publications where AR was used to present mathematical concepts to students, the researchers found that AR is an invaluable tool that improves the understanding of abstract concepts through the spatiotemporal alignment of information.

The growing complexity of maintenance has been the main limitation holding back any substantial improvements to the maintenance sector [33]. As the difficulty of maintenance operations increases, new methods for simplifying operations for human operators must also be introduced. Using AR has been shown to not only reduce the mental strain required for involved tasks, but also enable the accelerated understanding of the entire system. Both characteristics are essential to allowing maintenance technicians to service more intricate systems.

Task Duration

Simply understanding an engineered product is not enough. To truly improve the efficiency of maintenance operations, the time required to service equipment must also be reduced. To that end, augmented reality has been shown to reduce the time required for numerous tasks across several industries. One study from Hou et al. evaluated 50 participants who were directed to build a composite LEGO assembly [34]. Half of the participants were given standard paper-based instructions, and the other half were equipped with an AR system that showed a spatial overlay to display the next step in the assembly process. It was found that participants using the AR instructions completed the assembly almost 40% faster on average than those using standard instructions.

More specifically, AR has also been shown to significantly reduce the time to perform maintenance operations. A system developed by Henderson and Feiner explored how AR could improve the delivery of maintenance instructions to a technician [35]. The technician was given 18 tasks to perform on an armored personnel carrier, and each task was displayed in one of three ways, using either an LCD panel, a head-mounted static heads-up display (HUD), or a head-mounted AR overlay. It was found that the tasks performed using the AR display were completed 23% faster on average than those completed using the standard LCD panel. Even more importantly, using the AR display, the technician was able to locate the appropriate maintenance tasks 47% faster than the LCD panel, and 56% faster than the HUD. Not only does this translate into significantly shorter maintenance operations, but it also suggests that AR greatly improves spatial cognition.

Error Rate

Speed and efficiency are no doubt an important aspect to performing any maintenance task. However, if done improperly, further time and rework would be required and may result in dire consequences such as expensive broken equipment in the case of manufacturing and maintenance, or even death in the case of surgical operations. As such, the accuracy with which any task is performed is paramount to its effective resolution. Augmented reality has already shown significant effects on reducing errors for many disparate tasks. One system developed by Sanna et al. compared AR instructions and standard paper-based instructions for performing maintenance on a netbook laptop computer [36]. The researchers found that maintenance errors were reduced by more than 60% for participants who used the AR instructions instead of paper-based instructions. Additionally, they discovered that participants who were less experienced with laptop repair procedures improved more from using AR than did those with prior experience. This suggests that AR has a greater benefit to novice technicians than it does to skilled specialists.

A recent study in 2017 evaluated how different AR displays perform against standard paper-based instructions for delivering LEGO assembly instructions [37]. The evaluation compared a Microsoft HoloLens, an Epson Moverio BT-200 used to statically display instructions, an AR-driven smartphone, and paper instructions. The researchers found that the modern HoloLens display reduced the errors made in locating the proper LEGO brick by more than 80% compared to standard paper instructions. However, errors made while placing the LEGO brick were higher for the HoloLens than for paper instructions. This disparity is likely caused by a slight misalignment in the HoloLens' tracking, as we as occlusion issues that make the AR overlay completely block out any landmark information on the real LEGO grid board. An earlier study by Tang et al. involving a LEGO assembly, described above in the cognitive load section, found that the error rate was overall reduced by 82% [30].

Another study from 2014 focused on comparing AR instructions with paper-based instructions to perform maintenance on a full engine assembly [38]. Each participant was given access to a large tool bench and an engine assembly. After being given a period to become familiar with the setup, the participant completed four maintenance tasks, individually completed using both the AR system and the paper instructions. A subsequent analysis revealed that the AR system created a staggering 92.4% reduction in errors when compared to the paper maintenance instructions. By reducing the error rate of maintenance operations, significant cost savings could be realized both through minimizing equipment downtime and reducing potential rework.

Training

There is no doubt that augmented reality can be an effective tool for improving the efficiency and accuracy of maintenance tasks. However, if the skills and actions depicted by AR are not retained, the benefits it provides may be diminished. To this end, several researchers have examined the effects that AR can have on training personnel and knowledge retention.

One evaluation from Gavish et al. compared traditional video-based training methods with AR-based training in the area of industrial assembly and maintenance [16]. Forty expert technicians were given the task of assembling and servicing an electronic actuator. The technicians were split into four groups, assisted by AR, VR, or a corresponding video-based control group. Once complete, the performance of each participant was once again measured on the final task. The researchers found that while the AR group took slightly longer to train than the video-based control group, they also performed fewer errors. Ultimately, they found that the use of an AR platform to facilitate training for industrial maintenance and assembly tasks would prove highly beneficial.

The medical domain has also seen significant research on AR learning. A study by Yeo et al. analyzed how AR images overlaid on a spinal facet joint might affect the final performance [39]. Forty participants were split into two groups, given either AR and laser-guided needle insertion training, or traditional training given by a professional. Each participant had six practice sessions with their respective training method. For a final test, each participant then conducted two unassisted needle insertions to assess how effective the training had been. It was found that the group using AR had a success rate 20% higher than those using the traditional training methods. Additionally, the amount of needle movement was reduced by almost half for participants trained using AR, meaning less tissue damage would occur during a real operation. This shows that AR training could be implemented to improve current training practices. In the maintenance industry, this could mean that AR may prove to be a viable method for reducing dependence on maintenance manuals and still improve the overall effectiveness of training.

Through previous work highlighted above, using AR has the potential to significantly improve traditional maintenance practices in measures such as cognitive load, task duration, error rates, and training. Due to these promising results, AR was chosen as the delivery medium for the work presented in this thesis.

Augmented Reality Maintenance

Given the benefits that AR can provide to the field of maintenance, many industries continue to adapt the technology to be used in their own sector. Palmarini et al. recently conducted an exhaustive review that examined 723 publications that involved augmented reality and maintenance [40]. Those with the highest potential impact were selected, ultimately narrowing the list to 30 unique AR maintenance systems. The resulting publications belonged to six distinct maintenance areas including mechanical (29%), plant (21%), aviation (17%), consumer technology (17%), nuclear (8%), and remote applications (8%). Several of the most relevant AR systems are highlighted, along with the conclusions and shortcomings of the research. These systems can be roughly categorized into two groups including self-guided and expert-guided systems.

Self-Guided Systems

Self-guided systems are by far the most popular method of delivering AR maintenance instructions. These systems are comprised of a self-contained unit, often a mobile tablet or HMD, capable of delivering AR instructions. An on-site technician controls the AR device to advance through maintenance steps and performs the repairs illustrated by the AR overlay. Systems from multiple maintenance fields are highlighted.

Repairs in nuclear power plants have some of the highest risks in the maintenance industry. Yim and Seong highlighted that 45% of all human-related accidents in Korean nuclear power plants were caused by improper maintenance [41]. The researchers decided that the use of AR could significantly reduce these maintenance failures, and built a prototype maintenance application to test the strengths and limitations of AR. Using 15 participants with a background in nuclear and quantum engineering, each was required to perform maintenance operations on a Wilo 801 industrial pump. They found that the overall learning efficiency improved. Additionally, they found that novice technicians learned best when no more than 4-5 pieces of information were displayed at any given time.

One system developed by Benbelkacem et al. evaluated how AR could be used to perform maintenance on critical equipment in remote environments without the need for a skilled specialist [42]. The system was tested on a photovoltaic water pumping system that is often found in isolated environments. They found that by using AR, paper-based maintenance manuals were not required, which led to greater flexibility and reductions in repair times. Additionally, they highlighted that the use of AR in remote regions such as deserts enables technicians to increase their experiences while significantly reducing the risk of serious accidents.

General facility maintenance is one of the most commonly studied areas of AR maintenance [40]. This is no surprise, given that up to 85% of total lifecycle costs come from their operation and maintenance [43]. To reduce costs and repair times, Koch et al. built a prototype AR system that guides technicians through aa facility using natural markers already present in the facility, and then provides on-site AR guidance during the maintenance operation itself. Using an iPad to deliver AR instructions, researchers evaluated the system's ability to both guide the technician to the problem area, as well as its effectiveness in issuing AR maintenance instructions to repair a damaged smoke detector. They found that the use of natural markers present in the environment could successfully guide technicians through an unfamiliar environment and perform effective maintenance.

Self-guided AR systems have been shown to facilitate safe, effective, and accurate maintenance operations across a range of different industries. However, maintenance is an increasingly unpredictable discipline, and most self-guided AR maintenance systems would be rendered ineffective when presented with an imperfect scenario, such as heavily damaged equipment or missing equipment or tools. Since all possible edge cases cannot be realized in a single self-contained AR system, the guidance of a human specialist would prove invaluable to performing successful maintenance. As realized by Quint et al., AR cannot yet completely replace the skills and experience of knowledgeable employees [22].

Expert-Guided Systems

In many situations, the technician performing maintenance has not had enough prior experience with the equipment to perform successful repairs. Even today, it can take up to 2000 hours for an aviation inspector to be fully trained [44]. Because of this, skilled specialists are in short supply, and bringing one on-site may not be a viable option. To resolve this issue, several AR systems were developed that allow an off-site expert to remotely control AR maintenance instructions seen by the on-site technician.

A system developed by Wang et al. explored how augmented reality could be used for remote collaborative maintenance operations [45]. A remote expert is provided with an interface capable of both monitoring the on-site technician and creating AR instructions consisting of text, simple adjustments, and 3D models. The system was tested on a gasoline engine and was found to successfully facilitate effective communication between a technician and off-site expert. However, the expert's interface was largely text-based, making content generation somewhat challenging to visualize.

The TeleAdvisor system developed by Gurevich et al. was another system that employed basic AR techniques to assist a novice technician under the guidance of a remote expert [46]. Using a video camera and projector on the end of an adjustable arm, a remote expert can both monitor the technician's view as well as project basic instructions to it. The expert is provided with a live video from the technician's workspace and can mark up the video using simple drawing tools and symbols. These annotations are then sent back to the novice technician and projected directly onto the work environment. The system was tested using wiring procedures on the back of a consumer television. A major strength of the TeleAdvisor system is that it does not rely on absolute positioning. Instead, all augmentation is shown just as it is drawn on the screen by the expert. Additionally, all participants indicated that the system was intuitive to understand.

Moving beyond academia, several systems are being commercially developed that connect a remote expert with a novice technician. Scope AR is one company that is creating a suite of products that may significantly standardize the remote support industry [47].

Additionally, PTC is exploring how consumers can be used in a widespread network of product assistance through the use of their popular AR software development kit Vuforia [48]. However, in an attempt to become more widely adopted, these systems do not focus on using spatially-aligned 3D models and animations, but rather simple annotations like those used in the TeleAdvisor system described above. Due to this shortcoming, the work presented in this thesis attempts to improve remote support guidance through real-time 3D model manipulations.

Whether self-guided or led by an expert, AR maintenance systems have been shown to replace current maintenance practices with great success, as detailed above. However, most of the AR systems described thus far have not discussed one of the most essential components to the development of a successful AR system: content creation.

Authoring Augmented Reality

While AR maintenance itself has seen significant interest in the past several years, much less attention has been given to the time-consuming effort of creating the content and animations that drives an AR application, a process known as authoring. The process includes three key components, including creating the static mesh models, planning and creating animated motions in 3D space, and then aligning these motions with the real world. This content can include several things such as 3D mesh models, animated components, or even spatially-registered symbols and text. In 2008, less than 4% of work published on AR described or focused on authoring AR instructions [49]. Despite this, Bae et al. describe AR authoring as one of the two key components of AR, next to pose estimation [50]. Without specialized authoring systems, content generation is done manually with the use of CAD software, and is done by skilled engineers familiar with programming, AR, and modeling. To combat the issue of AR content creation, researchers have developed AR authoring systems that can be roughly classified into three separate categories, including pre-generated, automated, and expert-driven authoring. There are two different foundations these methods use, including generic and model-based AR. Generic AR is the process of using basic symbols to represent instructions, such as an arrow. It is the simplest to implement, as it is agnostic to the maintenance environment, and doesn't require 3D CAD models to function. However, it also suffers from ambiguity, where the technician isn't sure which part is being identified, or the action to perform. Therefore, many systems use model-based AR, which uses 3D mesh models to directly show relevant parts of the model, spatially overlaid on real-world counterparts. This significantly improves a technician's spatial cognition and removes ambiguity but relies on a specialized team of digital artists to generate these models through CAD software and then convert to another package (sometimes two) to create the proper animations and placements. However, many industrial fields already create these CAD models as part of the design process, which minimizes any rework required to support future maintenance operations. The authoring systems presented below assume the static content (basic symbols or CAD model) is readily available. Instead, they focus on how this static content can be manipulated and segmented into a relevant sequence of steps that guide a technician through maintenance operations.

Pre-authoring

The process of pre-authoring AR content involves the creation of assets before a technician needs it. This is often done during the development of the AR system itself, and the content is not normally modified once the system is deployed. While unassisted creation of AR content technically falls in this category, this analysis will instead explore specialized tools that have been optimized to create AR content significantly faster than the manual process.

A system developed by Engelke et al. created a unique JSON-based authoring system that reduced the authoring time for custom maintenance instructions to only 17 hours for a 10-task assembly [51]. The authoring process focused on an expert technician generating AR instructions for the landing gear of an airplane and an industrial pump. Through the use of an HTML interface, experts would specify the maintenance steps required, and the content to be included, such as images, text, and 3D models. While this showed significant improvement over manual authoring, it is still a substantial time requirement that must be performed for each maintainable system. The researchers also discovered that the expertise level of the technician did not have any impact on the speed of generating AR instructions.

To author quality AR content, a skilled expert who understands the system is usually required to create the content. However, Jee et al. attempted to change this by developing an AR content authoring process that would allow non-experts to author content, potentially lessening the strain on highly-trained specialists [52]. While non-experts were able to successfully produce AR content, the researchers pointed out that a skilled engineer would still be required to focus on the technical aspects, such as geometries and model relationships.

One system developed by Bhaskar Bhattacharya took a very different approach to authoring AR instructions [53]. By using a commercially-available depth sensor, an expert was recorded performing an assembly or disassembly procedure. Using the generated point clouds, parts of the model were matched to their virtual counterparts, and their motion was tracked. This enabled an expert technician to easily showcase his practiced ability, without the need to utilize another interface or authoring tool. However, this system also showed significant variability under different lighting conditions. Also, due to the nature of point clouds, the system may not lend itself well to assemblies with small parts.

Specialized AR content creation tools such as these significantly decrease the time and expertise required to produce quality AR content. However, these tools still rely on generating content prior to being needed. As such, they still suffer from the issues seen in self-guided AR systems, where not all possible maintenance operations can be realized and generated before the system is in use. The time lag to create new AR instructions also causes significant risk for time-sensitive maintenance situations. To bypass the manual AR content generation process altogether, several researchers developed automated AR authoring tools that can produce content in real-time.

Automated Real-Time Authoring

Automated real-time authoring is another method that can be used to eliminate the cumbersome process of AR content generation. Instead of having to make content before the technician requires AR guidance, automated authoring techniques use computer vision and specialized algorithms to perceive a maintenance assembly in real-time. By utilizing a simplified set of input parameters, AR maintenance steps can be automatically generated and presented to the technician, even during the maintenance operation itself.

Hong and Wenhua developed an automatic AR content generation platform to explore these techniques for facilitating civil aircraft maintenance [54]. By exploiting relational links between the existing aircraft maintenance manual, the bill of materials, and the illustrated parts catalog, specialized AR instructions were generated automatically that would guide a technician through disassembly. Using specialized sensors in combination with a video feed, natural features were extracted that allowed the AR content to be overlaid accurately.

In a 2015 study from Neges, Wolf and Abramovici, an automated AR system was developed that provided maintenance assistance to plumbing technicians [55]. By exploiting the grid-like nature of plumbing, computer vision was used to translate the actual pipe assembly into a graph data structure, which was then solved using Dijkstra's algorithm. In this use case, automated AR authoring was extremely effective. However, plumbing is not usually fully exposed, as it was in this study. Additionally, the algorithms are tailored specifically to pipe maintenance, and would have no benefit to other areas of maintenance.

Automated AR authoring techniques are significant due to their ability to generate instructions in real-time with little to no input from the technician or off-site specialists. This leads to a significant time savings, especially in organizations with significant investments in disparate maintainable systems. However, many AR systems using this technique are precisely tuned to a specific maintenance operation. Given the dynamic nature of maintenance, it would take significant efforts to retrain these AR systems to operate effectively for different environments or equipment configurations. As computer vision algorithms improve, this method will become increasingly effective and reliable. Until then, skilled specialists are still the best source of real-time information when it comes to operating in unknown maintenance environments where the state of disrepair may not be known beforehand.

Expert-Driven Real-Time Authoring

Expert-driven real-time authoring allows a remote specialist to create and send AR content to the on-site technician in real-time with little to no effort. Because of the ability to adapt in real-time, it is the most generalizable AR authoring solution of the three techniques presented here.

Masoni et al. developed a system that utilizes off-the-shelf mobile technology to allow an expert to create content in real-time, and share knowledge with an on-site technician [56]. By augmenting still frames received from the technician, the remote expert could add symbols, text, and sketches and then send these annotated frames back to the technician. While effective in drawing interest to areas of concern, the system was limited in its effectiveness since no 3D models were used. As such, intricate maintenance steps could not be authored well, and led to further confusion.

A different approach to solving the problem of AR authoring would be to abandon spatially-registered symbols and models, and instead simply use hands to intuitively communicate information. Such a system, developed by Zenati-Henda et al. allowed the assisting expert to use an interactive table to communicate maintenance instructions. The expert's hand motions were captured and displayed back to the on-site technician. A system like this is beneficial since the interface does not require special training to use – there is no more intuitive interface than physical interaction. However, since no 3D models are used, spatial awareness may not be well communicated, and hand animations may actually hinder performance.

Some researchers have even attempted to combine both automated and expert-driven real-time methods. In these systems, most of the authoring is done automatically, and is reviewed by the remote expert prior to being sent to the on-site technician. Erkoyunca et al. created an application that would automatically generate AR maintenance steps for a motor assembly, using simple input parameters specified by a remote specialist [57].

The ability for a skilled specialist to issue AR instructions in real-time leads to a highly adaptable maintenance delivery system that combines the benefits of AR with the years of experience from trained personnel. One problem with many expert-driven AR authoring systems is the confusing and overloaded interface the specialist must use to create new AR content. Due to this complexity, additional training may even be required to allow the specialist to effectively use the AR authoring system. The work presented in this thesis was largely inspired by the success of these expert-driven systems. However, as described later in the methodology, a novel authoring interface was created to improve the usability of real-time content creation.

Each AR authoring technique has its own benefits and drawbacks that must be considered. For example, while expert-driven authoring may produce the most adaptable result, it takes the resources of two technicians instead of just one. As technology continues to advance, automation will likely replace many manual maintenance operations, ultimately removing the human operator entirely. Automated robots have already been tested for power line maintenance [58] and even orbital facility maintenance [59]. However, due to current limitations in hardware and computer vision, this kind of full automation cannot yet provide the same reliability as human technicians.

The numerous studies and publications above highlight the success of integrating augmented reality into different maintenance industries. However, the underlying methods of how augmented reality works must be explored to fully understand the design decisions made by the work detailed in this thesis.

Spatial Registration for Augmented Reality

In the words of Siltanen, tracking is the “heart” of AR [60]. For augmented reality to truly be effective, accurate tracking is critical [61]. Even a slight misalignment could make any AR augmentations unusable, especially with intricate assemblies. To create accurate spatially-aligned visuals, AR must comprehend its 3D environment in some way. Through video-based tracking techniques, AR systems can establish a relationship, or mapping, between the virtual and real worlds. There are two primary methods for accomplishing this mapping, known as marker-based registration and markerless registration.

Marker-Based Registration

Marker-based registration is generally regarded as the most accurate method to establish this coordinate system mapping, using what is known as an image target. Using this technique, a high-contrast, high-detail image is used as an anchor point for any AR augmentation. Using computer vision algorithms, the device's RGB webcam is used to detect the position and orientation of a predefined image target. As seen in Figure 2.1, computer-generated visuals are then displayed at an offset from the detected image. There are several important benefits and drawbacks to this image-based approach.

Figure 2.1: Marker-based AR

One primary benefit of image-based tracking is that the augmented content is independent of the tracking method. Because of this, a single image target could be used to augment the workspace of different maintainable systems without having to change the tracking algorithm. A second benefit to the image-based tracking method is its simplicity. It only requires a live video feed and does not depend on expensive external hardware to function effectively. Because of this, the adoption of AR systems would not be hindered by cost or availability, as most organizations already have a significant inventory of mobile AR-capable devices.

Image-based tracking also has substantial drawbacks that must be considered. If the image target leaves the camera's field of view, no AR augmentation can be seen since the coordinate mapping no longer exists. To mitigate this issue, additional sensors, such as an inertial measurement unit (IMU) can be used to approximate the device's orientation after image tracking is lost. Yang et al. showed that this synthesis provides significantly improved tracking performance when implemented on vision-based handheld AR devices [62]. Another drawback of marker-based tracking is its potential for failure in harsh industrial environments where an image target may become damaged or dirty [63]. However, this is not an issue unique to image targets, and the same problems would be seen using markerless registration techniques in unforgiving environments.

Markerless Registration

Markerless registration is another method for enabling an AR system to understand its environment. In place of a marker, this registration technique uses custom algorithms to detect unique features present on a given real-world object. The AR system then attempts to align any augmentation with these extracted features. To test this method, Platonov et al. built a custom AR system that used an HMD rigged with a camera to provide maintenance instructions to a technician repairing an automotive engine [64]. They found that their system was able to successfully perform under numerous lighting conditions. However, they also noted a significant flaw with model-based recognition by noting that variability in CAD models would cause problems with tracking accuracy.

Another popular technique used for generalized markerless tracking is known as simultaneous localization and mapping (SLAM). By dynamically finding natural features in the environment, SLAM can create a mesh of coordinates in real-time. While slightly more resource intensive than marker-based tracking algorithms, SLAM has been shown to maintain a surprisingly high level of accuracy, with misalignment less than 5mm [65]. However, one problem with SLAM tracking today is the inherent uncertainty with choosing a coordinate origin. Seen in Figure 2.2, there are hundreds of tracked feature points that represent natural points of interest in the real world, but there is no perceived depth, and no sense of cohesion. Ways of determining an absolute position anchor are being evaluated [66], but no consensus has been reached on how to solve the absolute position issue inherent to SLAM. Additional research proposed using primitive shapes such as lines, circles, and spheres to fit a SLAM feature point cloud onto real-world objects [67]. However, approximation methods like this are not robust or accurate enough to fully rely on for small-scale maintenance operations. In general, object recognition is very challenging to perform accurately, even when real-time depth information is provided alongside video data. Additionally, this method would suffer from circumstances where the real-world object is altered, such as in disassembly during a maintenance procedure.

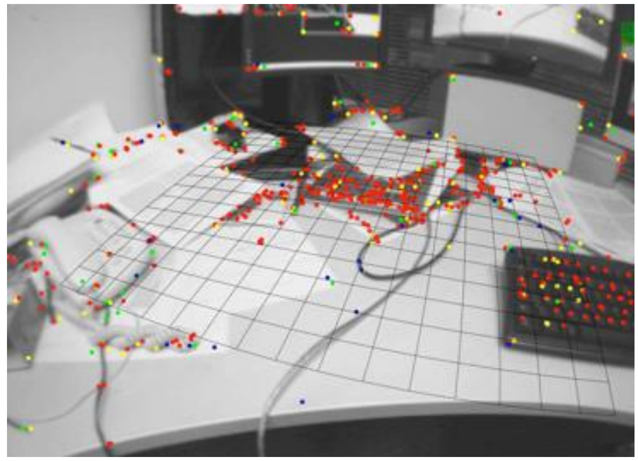

Figure 2.2: Markerless AR using SLAM [68]

Marker-based and markerless tracking each have their benefits and drawbacks. On the one hand, markerless SLAM recognition would represent a very streamlined approach to delivering AR maintenance instructions, since a technician would not have to worry about preparing the workspace ahead of time by placing image targets. However, since model-based tracking has not yet been proven to be robust enough to handle disparate maintenance environments without significant rework, a marker-based system was used for the AR maintenance system described in this thesis.

Research Questions

Based on the literature review and the problems outlined, the following research questions were developed to guide the research in this thesis.

1. What components are needed to create an AR system that allows a remote expert to provide real-time assistance, and can they be integrated on modern commodity hardware?

   To effectively design a system, the necessary components of it must be identified. In addition, implementation on commodity HMDs or other appropriate AR hardware must be possible.

2. Can a real-time visual-based AR authoring method enable users with no modeling or animation experience to generate complex AR instructions?

   If the designed system requires significant training or expertise, then it will only be useful to a limited number of experts. For broad applicability, the software interface for both the expert and remote technician must be simple to use.

CHAPTER 3. EXPERT-ASSISTED REMOTE MAINTENANCE USING REAL-TIME AUGMENTED REALITY AUTHORING

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Abstract

Maintenance operations and lifecycle engineering have largely been considered one of the most expensive and time-consuming components for industrial equipment. Numerous organizations continually devote large quantities of resources towards maintaining equipment. For example, the US military budgeted almost USD $200 billion in 2016 on operations and maintenance alone, the largest appropriation category by far [1]. As such, any optimizations that would reduce maintenance errors and expenses could lead to substantial time and cost savings. Unfortunately, there are often not enough specialists to meet the demand, forcing localized technicians to perform on-site maintenance on equipment outside their area of expertise. Augmented reality (AR) is one technology that has already been shown to improve the maintenance process. While powerful, AR has its own set of challenges, from content authoring to spatial perception. This work details a system that puts both the power of AR and the knowledge of a specialist directly into the hands of an on-site technician. An application was developed that enables a specialist to deliver AR instructions in real-time to assist a technician performing on-site maintenance. Using a novel and simplified authoring interface, specialists can create AR content in real-time, with little to no prior knowledge of augmented reality or the system itself. There has been ample research on different AR-supported processes, such as real-time authoring, video monitoring, and off-site assistance. However,

much less work has been done to integrate them and leverage existing personnel knowledge to both author and deliver real-time AR instructions. This work details the development and implementation of such a system. A technical evaluation was also performed to ensure real-time connectivity in geographically distributed environments. Three network configurations were evaluated, including a high-bandwidth network, a low-bandwidth network, and a 4G LTE network. Under all configurations, the system effectively facilitated the complete disassembly of a hydraulic pump assembly.

Introduction

Any organization invested in machinery and equipment will have a significant maintenance budget [2], second only to raw energy costs [3]. In 2016, the U.S. Military allocated USD $200 billion for operations and maintenance, almost half the entire defense budget [1]. Often, maintenance costs can comprise 60-70% of a product's total cost during its lifetime [4]. As such, any improvements that reduce resource requirements and increase equipment up-time would have substantial benefits.

Today, most maintenance tasks are performed in two ways. For smaller equipment, it is often shipped to a repair facility, serviced, and returned. While effective, this involves significant shipping times and costs. The second method utilizes trained specialists. However, a specialist may not be available on location, leading to transportation costs and long equipment downtime. One solution would be to provide an operation manual to on-site personnel unfamiliar with the equipment. Unfortunately, manuals quickly become difficult to comprehend, and require significant time to create. One analysis found Aircraft Maintenance Manuals (AMMs) only focus on a limited number of procedures, and do not clearly define terms, leading to higher errors [5]. In fact, over 60% of errors in aircraft maintenance occurred due to misunderstanding the manual [6], where 45% of an aircraft technician's time is spent simply reading instructional material [7]. In general, maintenance data is vastly underutilized simply due to poor accessibility and reliability [8]. Another solution involves an on-site technician leveraging a specialist's knowledge through audiovisual calls. While standard in many industries, communication can be challenging due to the reliance on technical vocabulary that on-site technicians may not possess. Finding more effective ways to train and guide technicians is essential to the continued maintenance of globally-distributed equipment [9]. Some emerging technologies have shown promise for greatly improving these practices.

Augmented reality (AR) is one such technology that can guide technicians through complex maintenance procedures using spatially-aligned 3D visual information. AR systems use computer-generated graphics overlaid onto a view of the real world to provide real-time instructions. Numerous studies have found AR can improve human cognition and reduce errors [10], both of which are integral to maintenance. One study found that AR significantly reduced the time needed to identify maintenance steps by 50% [11]. Another study found that AR reduced errors by 85% for complex assembly procedures [12]. AR has the potential to improve maintenance practices, but for this technology to be adopted, the issues surrounding authoring AR content must be addressed. Currently, each AR overlay must be modeled and animated by skilled artists. This strategy of creating prebuilt 3D instructions for every part is impractical for widespread systems. An ideal method would combine the visual overlay of AR with the accumulated knowledge from a specialist, without the need to pre-author any instructions. This paper details a visual-based AR authoring method that enables a specialist to create and deliver real-time complex animation instructions without having knowledge of modeling or animation. The evolution of AR and how it is currently being used in maintenance greatly influenced this work.

Background

Evolution of Augmented Reality

Many initial 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 including manufacturing [13] and the U.S. Military [14]. The next evolution of AR enabled the technology to comprehend the real world using cameras, sensors, and computer vision algorithms. This allowed 3D augmentations to be displayed in relation to real-world objects.

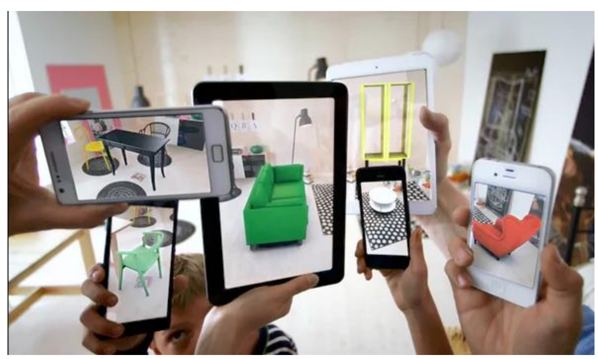

Figure 3.1 IKEA augmented reality app [41]

Today, most AR uses tablets and smartphones due to availability and cost. Figure 3.1 shows an IKEA application that displays virtual furniture as it would appear in a room. However, mobile devices limit hand mobility, which could be an issue for manual processes like maintenance. In 2016, Microsoft released a commercially available transparent HMD capable of spatially mapping its environment in real-time. These types of devices are being evaluated for potential benefits [15]–[17], but are still expensive and have a limited field of view that detracts from the overall experience.

State of Maintenance using Augmented Reality

Using augmented reality to deliver maintenance instructions is integrated into numerous industries. A recent review examined 723 publications involving augmented reality and maintenance [18]. Six maintenance areas were identified, including mechanical (29%), plant (21%), aviation (17%), consumer (17%), nuclear (8%), and remote (8%). One publication explored the benefits of AR on the repair procedure of an armored personnel carrier [11]. They found that AR not only reduced the time required to locate maintenance tasks, but also reduced head and neck movements. AR has also been used to reduce maintenance errors by a staggering 92.4% during engine repair [19].

Large-scale commercial AR applications are also being implemented to facilitate expert-guided assistance [20], [21]. While they show great promise, few have focused on allowing a specialist to use spatially-aligned 3D models and animations to manipulate an on-site technician's view in real-time. To that end, an intuitive AR authoring interface was combined with a collection of 3D models to facilitate the creation and delivery of spatially-aligned AR instructions in real-time.

Augmented Reality Spatial Registration

For AR 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 to establish a mapping between virtual and real-world coordinates. Two main methods for accomplishing this are used, known as marker-based and markerless tracking.

Currently, the most accurate registration method is marker-based tracking. Using this technique, a high-contrast image provides a real-world anchor for overlaid 3D content. This is seen in Figure 3.2, where the picture of pebbles acts as a reference for the position and orientation of the chinook helicopter on the tablet's display.

Figure 3.2. Marker-based AR

The other method of registration is through markerless tracking. This dynamically determines natural features in the environment and creates its own coordinate points in real-time, such as those seen in Figure 3.3. The major problem with current markerless tracking is its inability to determine a coordinate origin. There are numerous features points in the environment, but it is unclear where any augmentation should be. Some researchers have attempted to use the feature points of the object itself [22]. However, this is not robust or accurate enough yet to rely on for complex or small-scale maintenance tasks.

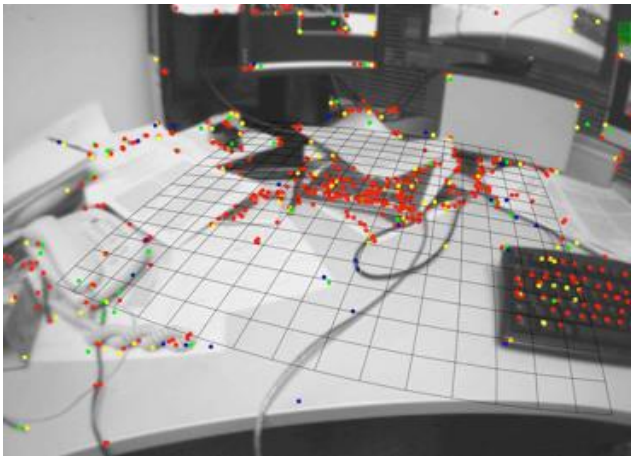

Figure 3.3. Markerless AR [42]

Each tracking method has benefits and drawbacks. Markerless recognition represents a streamlined approach since a technician would not have to prepare the work area ahead of time. However, a marker-based solution would prove more reliable since the physical state of the machinery cannot be relied upon. For this reason, a marker-based method was used for the AR maintenance system described in this paper.

Authoring Augmented Reality Instructions

Not only does AR need to understand the environment, there must also be content to display. This involves creating static symbols or models, producing animations, and overlaying them in the real world. This manual animation process is slow and involved. Since the feasibility of AR relies on the quality of this content, several approaches to authoring AR have been researched, including pre-authoring, automated real-time authoring, and expert-driven real-time authoring. This work assumes a basic hierarchical mesh model of an assembly exists and does not discuss the static modeling process.

Pre-authoring relies on creating content before an on-site technician needs it. This is commonly done using CAD and animation packages to create defined steps. This not only takes a long time, but also requires digital artists intimately familiar with maintenance procedures. A second method for pre-authoring content relies on specialized programs optimized for AR content creation. One system reduced the authoring time for custom maintenance instructions to 17 hours for 10 tasks [23]. This showed improvement over manual authoring, but still takes considerable time. The main issue with pre-authoring is it’s impossible to create instructions for every outcome.

Automated authoring is another promising method of reducing the burden of creating AR content. Using computer vision, instructions are generated immediately. A system from Hong and Wenhua generated AR instructions for aircraft maintenance using relational links in existing documentation [24]. In a 2015 study, a system automatically provided AR maintenance assistance to plumbing technicians [25]. Automated authoring eliminates authoring times, but requires significant setup to recognize real-world assemblies. To support additional variations, entirely new algorithms are needed. As computer vision improves, this method will become increasingly reliable, but it is still far from universal.

Expert-driven real-time authoring is another method for authoring AR. This relies on an off-site specialist helping an on-site technician perform maintenance in real-time. As found by Quint et al., "[AR] cannot replace skills and know-how of experienced employees" [26]. Masoni et al. connected a skilled technician in a control room with an unskilled technician on-site [27]. The remote technician analyzed the workspace in real-time and sent spatially-registered symbols to the on-site technician. While this method does not depend on 3D models for content generation, the use of basic symbols diminishes spatial understanding and leads to ambiguous instructions. The main issue with many expert-driven authoring systems is the complexity of the interface itself. Without specialized training, the authoring software is difficult to understand for maintenance personnel. Additionally, there is little spatial cognition between the model overlay and the values entered in the interface, leading to authoring ambiguity and creating a slow trial-and-error approach.

Each AR authoring technique has shortcomings. Pre-authoring is time-consuming and unadaptable. Automated authoring is environment-specific. Expert-driven authoring relies on overly complicated interfaces for content creation. In the future, full automation may replace maintenance technicians [28], [29], but it cannot yet provide the same reliability as specialized technicians. Thus, to minimize current shortcomings, this paper details an AR authoring system capable of leveraging expert knowledge to adapt to any situation. Using a simplistic spatial authoring interface, specialists can create animation sequences to deliver model-based AR maintenance instructions to a technician in real-time.

Methodology

To research the components and methods involved with creating a visual-based authoring system, a prototype system was developed. The Augmented Reality Customer Collaborator (ARCC) was created to optimize costly maintenance procedures and improve content authoring systems. It consists of two applications: a mobile application for on-site technicians, and a workstation application for off-site specialists. These form a communication system where an off-site specialist uses visual authoring techniques to guide an on-site technician through maintenance procedures using 3D models and animations, truly harnessing the power of AR.

The mobile application is used for visualization, allowing a technician to see spatially-aligned 3D models overlaid onto real-world objects, enabled by tracking an image target present in the scene. When launched, no augmented content is shown. Instead, commands are received from an off-site specialist that control what is shown to the technician. These commands direct the mobile application to fetch the corresponding 3D model(s) from a remote model repository and display them at a specified offset from the image target. The technician's mobile application sends live video to the off-site specialist, enabling remote monitoring. This communication system, seen in Figure 3.4, allows a truly expert-driven system that allows the specialist to directly transfer systems knowledge to an on-site technician.

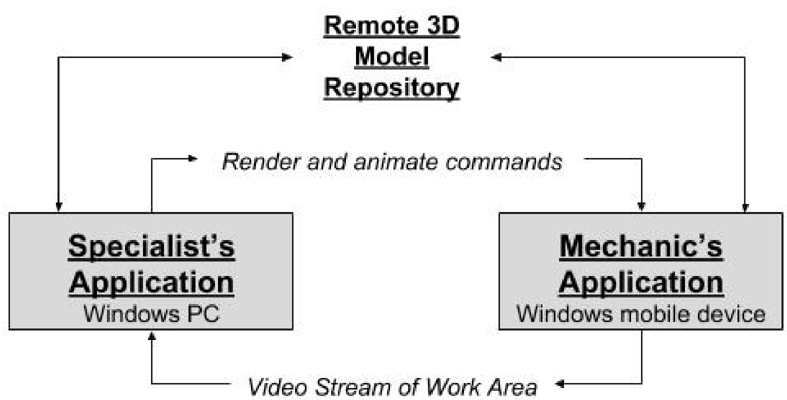

Figure 3.4. System diagram

The specialist uses the workstation to remotely observe the technician's situation and manipulate their view. By receiving a live webcam stream, a specialist 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 specialist can select parts of interest, choose a pre-made animation, or create a new one in real-time. Once the authoring process is done, a command is sent to the technician's mobile application that details the parts and animation that should appear. By allowing the specialist to fully control the content shown, the on-site technician will not be overwhelmed with information, and can quickly execute the instructions presented.

To implement the features described, several components were required. A scripting and rendering engine was needed to control the content displayed and provide networking capabilities such as video streaming. Computer vision algorithms allow the mobile application to comprehend its environment, and a real-time model importer provides real-time access to a model repository. Additionally, a custom visually-based AR content generation system was developed within the rendering engine that facilitates the simple creation of complex AR instructions.

Development Environment

To support the numerous capabilities of the proposed AR system, a robust scripting and rendering environment was needed. The Unity3D [30] game engine was selected for its inclusion of a number of essential features. With a large collection of plugins and reference material, features like video streaming and dynamic model loading could be implemented in a short time. Additionally, the engine's interface enabled the creation of the visual authoring system central to this work. As discovered by Kim et al., Unity3D can substantially improve application quality and reduce development time compared to standard graphical programming [31]. Despite this, only 10% of published AR maintenance systems use game engines like Unity3D to create applications [18].

AR Registration

To spatially register AR on the technician's mobile application, an image target-based approach was used for its environment-agnostic capabilities and lack of dependence on model-specific information. Vuforia [32] was chosen due to its feature-rich Unity3D plugin. The library is specialized to track image targets in real-time, allowing technicians to change perspective to see augmentation from any angle.

Vuforia's algorithms trivialize many problems with marker tracking, such as camera blur and occlusion. Thus, a technician can see AR instructions without needing to stabilize the mobile device, or fully clear the image of debris. Technicians can benefit from being able to work in more diverse environments.

Dynamic Model Loading

The authoring system developed for this work relies on the expert's ability to select a CAD model at runtime. The AssetBundle plugin was chosen for its simplistic workflow and integration into Unity3D. By enabling fast creation and retrieval of CAD models from a remote repository, the plugin allows the expert to adapt to any situation, while minimizing model preparation. Three steps are needed to integrate new CAD models. First, the desired model is imported into Unity3D. Then, the model is labeled with a unique name. Lastly, the asset(s) are compiled with a click, and the resulting archive is placed on a remote location for immediate retrieval. Overall, the creation process takes a couple minutes for a full assembly. This represents significant improvements over other methods that require each 3D model to be specifically adapted for a single AR program. Thus, existing models, such as those available from a product's design phase, can be immediately integrated into the system. To facilitate simple retrieval, original models should not exceed a couple gigabytes in size.

Real-Time Visual-Based Authoring System

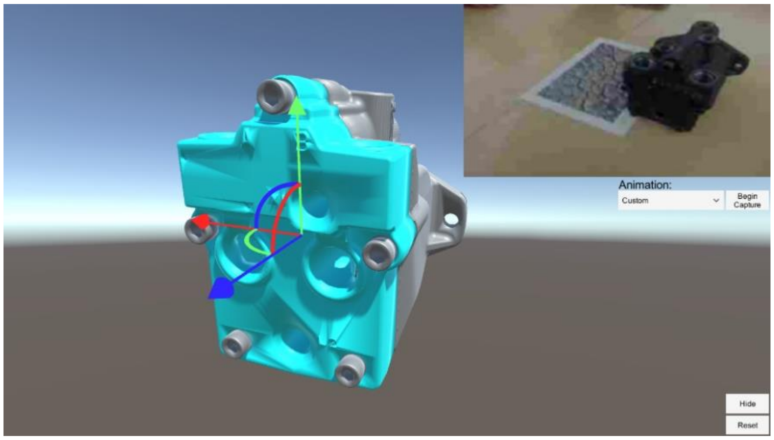

Figure 3.5: Real-time authoring system

The essential component of this system is the novel real-time authoring technique presented to the specialist when creating new AR instructions. Through intuitive on-screen controls, the specialist can create a sequence of animations of any length, without prior knowledge of the application. This enables the specialist to focus on transferring maintenance knowledge instead of dealing with the application itself. Seen in Figure 3.5, when the specialist enters custom animation mode, XYZ coordinate axes appear. These graphical elements enable both translation movements (arrows) and rotation movements (arcs). For each animation segment, the specialist clicks on an arrow or arc, and pulls the selected part(s) in the desired direction. On release, that step of the animation is stored and appended to previous segments. Strung together, the part animates from a beginning to end position.

The specialist uses these draggers to offset selected part(s) before capturing the animation sequence by moving the selected components before selecting “begin capture”. This is useful during reassembly, such as when bolts are removed and must be put back in a specific order. This offset can also correct the position of the virtual model if it becomes misaligned. Once the sequence is complete, a preview mode shows the sequence of animation segments, resulting in one smooth animation. When the specialist sends the final animation, all segments are concatenated, along with the selected model and part(s) and sent to the technician.

Instead of relying on complex menu-based controls to create animations, as many previous real-time authoring systems [27], [33]–[39], this visual-based approach enables specialists to create limitless animations capable of adapting to any maintenance situation, without being encumbered by a complex 2D interface. They simply must pick start and end positions for the various steps and the animation is automatically generated. The features described above were integrated to form a full real-time AR maintenance guidance system. The development of both the workstation and mobile application are detailed below.

Workstation

Combining the components above, the workstation application allows off-site specialists to assist technicians with maintenance tasks. When launched, the application sets up two network sockets. A TCP socket listens for incoming connections and provides a reliable transfer method for custom animation commands. A UDP socket receives the video stream from the technician, allowing fast video transfer with as little overhead as possible.

By receiving live video from the on-site technician, the specialist can identify equipment needing maintenance. Using a dropdown menu dynamically populated with possible CAD models, the specialist chooses the corresponding 3D model from a remote asset repository. The model is loaded and displayed locally in the specialist's main viewing area. Using a standard mouse to rotate, translate, and zoom, the specialist can easily view the loaded model from any angle, and can choose which components need maintenance based on the live video. Once selected, there are four primary actions the specialist can take:

1. *Hide the selected part(s)*

    a. Many maintainable systems are complex, and the ability to visualize internal components is paramount to giving the specialist a view of the entire system to assist with diagnosis.

    b. Since the on-site technician's AR overlay relies on the specialist's input, excess information may hinder progress. Parts can be hidden from the specialist's 3D model, which can be kept at a similar state of disassembly as the real object.

2. *Send the selected part(s) as a static overlay*

    a. This can be used to highlight specific parts or areas of concern. This mode is a more direct approach similar to many AR maintenance applications that use basic symbols to convey information [27], [33]. However, without animation data, the required action is ambiguous to the technician.

3. *Select and send a pre-built animation*

    a. If a specific maintenance step is difficult to create in real-time, pre-built animations may be more efficient than trying to recreate complex procedures using basic movements. Many AR maintenance systems use pre-built animations for all instructions. While effective, manual authoring is time-consuming if many steps have to be created [23].

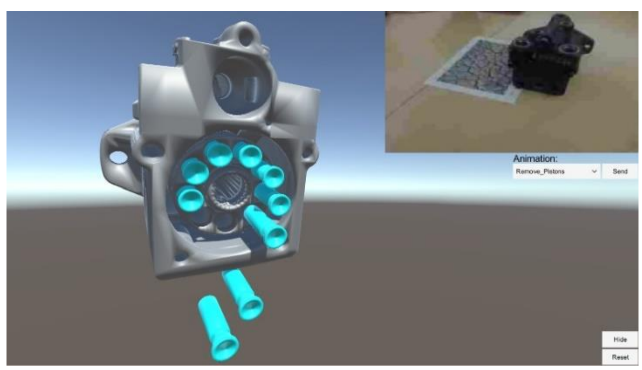

Figure 3.6: Pre-built animation

The system also allows for pre-built sequences of common animations to be stored and recalled. Figure 3.6 shows a piston removal process that was pre-built during model creation.

4. *Generate and send a custom animation sequence, created in real-time*

   a. A simple controller is attached to the selected parts, which can be translated or rotated. Each movement is recorded and concatenated to form one multi-step animation sequence. Thus, a specialist can create a unique animation sequence for any subset of components, adapting to any maintenance scenario.

   b. The captured sequence can be previewed locally before being sent to the technician, providing local validation before being sent. The model can be moved and rotated while being previewed, allowing further spatial cognition.

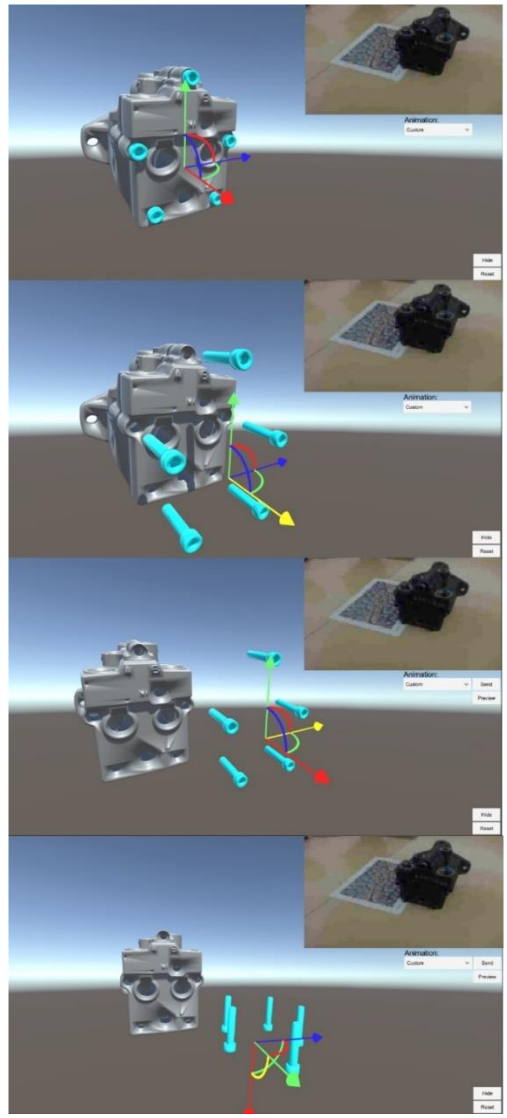

Figure 3.7: Custom animation sequence

When parts and any animations are sent, a command string is automatically generated and passed to the technician's application. This command includes the name of the asset, selected parts, and the animation name (for pre-built animations), or animation sequence (for custom animations). Figure 3.7 shows the creation of a custom animation showing the removal of five bolts from a hydraulic pump. Using basic dragging and rotation motions, the specialist can create an extensible sequence of animations, with little knowledge of the system itself. This allows maintenance specialists with no modeling expertise to create complex animations, potentially leading to shorter authoring times and improvements in the technical quality of the instructions.

The workstation application can be run on any modern 64-bit Windows computer. Testing was done on a 2012 Windows laptop running Windows 10 with a 1.9GHz Intel Core i7 processor, 10GB of RAM, and an Nvidia GeForce GT 620M graphics card.

Mobile Application

The mobile application is the viewer for the on-site technician. Using image target tracking, the mobile application overlays 3D content created by the specialist on real-world equipment. When launched, it requires the IP address of the specialist's workstation, but can be modified to connect to a server if one is available. The technician is not given controls, allowing the specialist to have full control over the content shown, minimizing confusion for the novice technician.

The mobile application sends compressed JPEG video to the specialist. A dynamic compression method is used, depending on network conditions. Compression is partly automated, where if frames fail to send, quality is reduced. It is also left to the user to decide how much of the bandwidth should be utilized. The stream does not contain augmentation since Vuforia has primary control of the camera and frames retrieved are straight from the webcam, but direct screen-capture would substantially increase computational strain. Once the

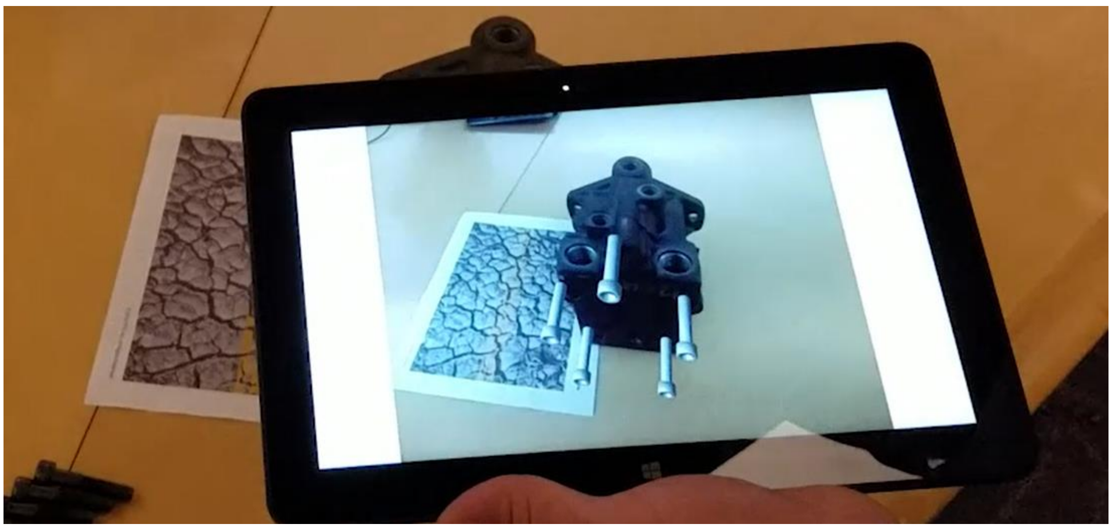

Figure 3.8: Technician's mobile application

specialist reviews the technician's outgoing video feed and selects the 3D model, part(s), and animation(s), the technician's mobile app receives a command denoting the asset to load, the part(s) to overlay, and the animation to play. The corresponding model is automatically retrieved from the remote repository then animated. Vuforia then locates the image target and places the specified parts at the proper location. Seen in Figure 3.8, the technician is shown how to remove five bolts on a hydraulic pump.

The technician's mobile application can run on any modern 64-bit Windows computer with an RGB webcam. Testing was done on a 2013 Windows tablet with a 1.6GHz Intel Core i5 processor, 8GB of RAM, and Intel HD Graphics 4200 graphics. This is a computationally demanding process for a mobile device. The application must grab video frames from the camera, compress them, send them, all while running computer vision for image target detection.

Evaluation

To evaluate the performance of the ARCC system, a hydraulic pump assembly was used, shown in Figure 3.9. An evaluation was performed that guided a user through all disassembly steps, including the removal of the front bolts, plate, gasket, spring, and pistons. Given the numerous components and relationship between them, this assembly was indicative of many real-world maintenance situations. Three evaluations were conducted, each using a different network configuration. The first utilized a high-bandwidth network representing the most common type of internet configuration. The second evaluation was performed on a low-bandwidth network with a maximum transfer rate of 1Mbps, representing limited networks found in older facilities. The third evaluation was conducted over 4G LTE, which tests how the system functions under a truly distributed network. Each

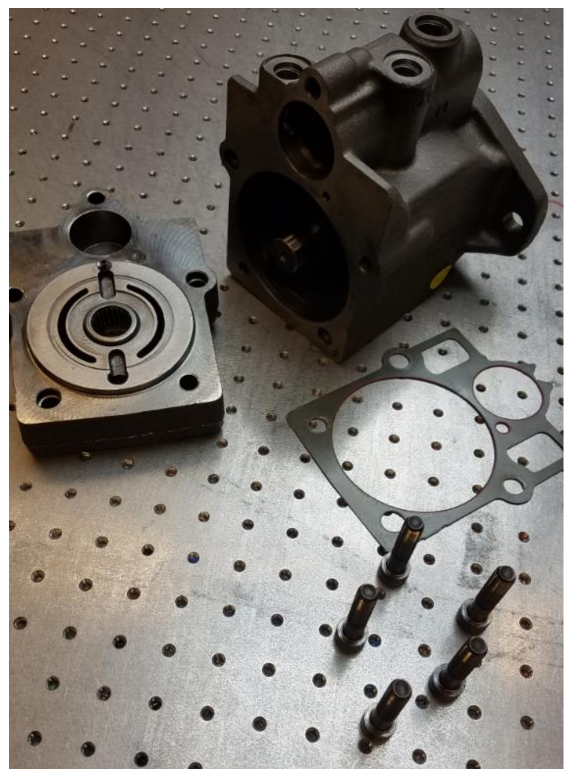

Figure 3.9: Maintenance assembly for evaluation

evaluation took approximately fifteen minutes. The specialist and technician used the laptop and tablet described above, respectively. The metrics collected during the evaluations were bandwidth usage, video latency, video framerate, video compression ratio, workstation framerate, and mobile framerate. The averages for all trials are shown in Table 3.1.

Table 3.1. Averaged network evaluation results

Network Type	High-Bandwidth (80Mbps)	Low-Bandwidth (1Mbps)	4G LTE (25Mbps)
Bandwidth Usage	2.6Mbps	0.6Mbps	1.8Mbps
Video Latency	0.7s	0.4s	0.6s
Video Framerate	11 fps	15 fps	13 fps
Video Compression Ratio	11%	86%	42%
Workstation Framerate	75 fps	83 fps	78 fps
Mobile Framerate	14 fps	19 fps	16 fps

On a high-bandwidth network, the system consumed 2.6Mbps to stream a standard-definition video at 14 frames per second (fps). The tablet webcam used an 8-megapixel camera, which saw an average compression ratio was 11% on the high-bandwidth network, meaning the stream was very close to the quality seen by the technician. The average video latency was 0.7 seconds. If the network became saturated, frames were dropped to maintain the lowest possible latency. Since the augmented overlay does not change until the specialist provides additional instructions, this small delay is not detrimental to providing AR instructions. The specialist's application achieved an average of 75 fps, allowing smooth content creation. The mobile application, given its modest specifications, achieved an average of 14 fps. In general, a framerate at or above 15 fps is adequate for displaying virtual information [40]. The only substantial delay to receiving and displaying AR content occurred when the technician's application received the first command, which directs the application to download a new CAD model from the remote repository.

With a low-bandwidth (1Mbps) network, the system used only 0.6Mbps for a standard-definition video at 15 fps. Given the constraints of a lower bandwidth, a compression ratio of 86% was needed to allow uninterrupted video. The workstation and mobile framerates were 83 and 19, respectively, suggesting that a lower quality stream reduces the computational strain on the system by a small margin. The average video latency was 0.4 seconds, suggesting that a compressed video stream results in less latency.

Lastly, using a 4G LTE network, the average bandwidth usage was 1.8Mbps for a 16 fps stream, with a compression ratio of 42% and a latency of 0.6 seconds. Similar to previous network configurations, the workstation and mobile framerates were 78 and 16 fps, respectively. This network provides the highest portability of all modes, given the globally-distributed cellular network. However, to fully deploy the system, a dedicated server would need to be established to facilitate communication, rather than a peer-to-peer approach.

Generally, the more network bandwidth available, the higher quality video can be streamed with less compression. Different networks will have a different balance between quality and bandwidth usage. For these evaluations, video quality was preferred over framerate, maximizing bandwidth usage and computational stress, thus lowering the video framerate to between 11 and 15 fps. Despite this, it was more than capable of real-time monitoring. The lower mobile framerate highlights the computational limitations of combining computer vision, video capture, live streaming, and animated model rendering on a single mobile device.

Creating a network-agnostic AR assistance system is vital in the globally-distributed maintenance environments of today. While the interactivity was adequate, this type of testing was hardly exhaustive. These tests show promise for the system, but multiple models and environments in a formal evaluation will need to be performed to further prove the validity of this approach. These feasibility tests did reveal issues that need to be considered as this system evolves.

Considerations

One consideration when using image targets for displaying AR content is the scaling between an image target and the size of the overlay. If a standard size ratio between an image target and a real-world object is not established, AR content will not match the object, leading to misaligned visuals that ultimately confuse the technician. For lab tests of the ARCC system, an 8.5”x11” target was used, and all models were scaled to the same size as the real-world object. Ideally, no image target would be required. However, markerless tracking and object recognition are not yet robust enough to rely on. Until model-based recognition becomes universal, a ratio must be established that relates the size of an image target with the size of a real-world object, so augmentation is accurately overlaid.

Under limited bandwidth conditions, the video framerate can be reduced with limited impact. Since the technician’s mobile application handles marker detection and AR content locally, a lower video framerate will not affect the experience for the technician. The only concern with a lower video framerate is the ability for the off-site specialist to recognize equipment properly when viewing a low framerate feed. Under extreme conditions, single frames can be used. As studied by Masoni et al., this snapshot method can prove effective, and could even be ideal in situations where no stable internet connection is available [27].

Conclusion

Using augmented reality to facilitate expert-assisted field maintenance can significantly reduce maintenance costs and errors across numerous industries. Within the last several years, the maintenance industry has seen a rise in the use of augmented reality for product support. As computational perception improves, AR guidance will become even more powerful, allowing anyone to perform complex tasks without specialist guidance. Until then, there is a significant gap between current maintenance practices and what modern technology affords. This research focuses on how AR can improve maintenance practices without increasing the burden of content generation or losing the expertise of trained personnel.

This research explores how real-time visual-based authoring can generate AR content with no prior knowledge of modeling or animation practices. Using simple 3D manipulation controls, maintenance specialists produce and deliver fully customizable AR animations in real-time without any understanding of animation practices or authoring programs. A configurable remote model repository also improves the portability of real-time AR authoring, as it allows for the dynamic selection of relevant assemblies for any maintenance environment. The Augmented Reality Customer Collaborator (ARCC) system was developed on these principles to evaluate if expert-driven real-time visual-based AR authoring is effective. The system was tested using a hydraulic pump assembly, and showed that real-time video monitoring, model retrieval, and complex AR authoring and delivery is possible using commodity hardware. A visual-based AR authoring system shows great promise for eliminating content generation time while not requiring training to use effectively. Further testing is needed to prove its benefits over manual techniques or other authoring solutions.

Future work would investigate hands-free platforms for the on-site technician's display. Additional testing would gauge the platform's efficiency compared to standard mobile devices. The integration of voice communication could also be evaluated, allowing the technician and specialist to communicate important information not visible through the video stream or augmented overlay. Lastly, a user study would be beneficial for assessing the effectiveness of the system compared to a standard audiovisual call. As augmented reality technology advances, so too will its effect across the maintenance industry and beyond.

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CHAPTER 4. CONCLUSIONS

Using augmented reality to facilitate expert-assisted field maintenance has the potential to significantly reduce maintenance costs and errors across industries such as railways, aviation, power plants, the military, and more. Within the last several years, the maintenance industry has seen a large rise in the use of augmented reality for product support. As technology and computational perception improves, AR guidance will become even more powerful, allowing almost anyone to perform complex tasks without specialist guidance. Until then, there is still a significant gap between current maintenance practices and what modern technology can afford. This research focuses on how AR can be used to improve maintenance practices in use today without increasing the burden of content generation or losing the expertise of trained personnel.

This research explores how real-time visual-based authoring can be used to generate AR content with no prior knowledge of modeling or animation practices. By utilizing simple 3D manipulation controls, maintenance specialists can produce and deliver fully customizable AR animations in real-time without any understanding of model animation practices or specific authoring programs. An easily configurable remote model repository also improves the portability of real-time AR authoring, as it allows for the dynamic selection of relevant assemblies for any given maintenance environment without changes to existing software. The Augmented Reality Customer Collaborator (ARCC) system was developed on these principles to evaluate if an expert-driven real-time visual-based AR authoring system is effective. The system was tested using a hydraulic pump assembly, and showed that real-time video monitoring, model retrieval, and complex AR authoring and delivery is possible using commonly available hardware. A visual-based AR authoring system like this shows great promise for eliminating content generation time while not requiring extra training to use effectively. However, further testing is needed to fully prove its benefits over current techniques or other AR authoring solutions.

CHAPTER 5. FUTURE WORK

Future work on this application could investigate additional display platforms for the on-site technician's mobile application. The Microsoft HoloLens is of particular interest, due to its commercial availability and extensive list of features. This will require reworking current network protocols to support the new Universal Windows Platform (UWP) build target and accommodate its hardware limitations. Additional testing would then gauge the HoloLens' efficiency compared to a standard mobile device, analyzing framerates and any improvements in maintenance instruction delivery. The integration of voice calling directly into the application will also be evaluated. This would allow the technician and specialist to communicate important information that may not be visible through the video stream or augmented overlay, such as serial numbers or tools.

Lastly, a user study would also be beneficial to assessing the effectiveness of the ARCC system compared to a standard audiovisual call. Feedback from the study would be used to improve the functionality and ease of use of the existing system. In such a study, users would be evaluated on their ability to diagnose and repair a mock assembly under the guidance of a skilled technician, using either AR assistance or an audiovisual call. Measures such as completion time and error rates would be collected, as well as qualitative measures such as enjoyment level.

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