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Assessing augmented reality in production: remote-assisted maintenance with HoloLens

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Abstract

Digitalisation provides many opportunities for process improvements by using smart devices such as Augmented-reality (AR) displays in production. Nevertheless, in-depth studies about the effects of these applications on key performance process indicators are sparse. The goal of this study is to evaluate AR-based remote maintenance processes supported by cutting edge optical head-mounted display technology. A total of 12 test runs conducted with real-world maintenance engineers in a real-world industry setting were analysed based on video recordings and semi-structured interviews. The study identified both case-specific and general issues, and the inherent potential of the technology.

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1. Introduction

The increasing digitalisation in industry leads to more agile and networked production resources. At the same time, machines and their interrelations are becoming increasingly complex. More expert knowledge is needed to solve problems and correct errors [1]. This knowledge is often not available on-site. Since experts are rare, and therefore not always available on the premises, knowledge must be transferred from remote places. To avoid expensive travelling costs and time delays, remote consultations between experts and maintenance workers currently take place using technologies that are available in production sites (often smart phones/ cordless DECT); these leads to suboptimal communication processes because complex situations need to be described verbally [2]. As suggested in [3], knowledge transfer based on direct verbal and visual synchronous communication may allow problems to be solved more quickly. Furthermore, cutting edge technologies are developed with increasingly shorter lifecycles, and the entry barrier for interested end users to tweak and program this technology is becoming steadily lower. The use of freely available System Development Kits (SDKs) and interfaces combined with increasing end-user expert knowledge has led to in-house innovation in many industries. This paper presents the results of an innovation project conducted in the automotive industry and provides an overview of an evaluation of a newly-available, head-mounted display in a real-world industry setting with automotive industry employees as testers. As part of this project, Microsoft's latest generation of Optical Head Mounted Displays (OHMD), Microsoft HoloLens, was evaluated for its suitability as a remote assistance tool during maintenance processes. OHMD allows the user to see both real and virtual objects augmented to this view. Various mixed reality devices have been introduced on the market in recent years (e.g., Google Glass). These devices have not yet been fully accepted by end users. HoloLens appears promising due to its technical possibilities, such as marker-less tracking, immersive human-system interaction and hands-free operation. It therefore may provide an instrument that can be used moving forwards to tackle the three main challenges (tracking, human-system interaction, and display device) of AR in maintenance scenarios as reported by Zhu et al. [4].

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In this study, HoloLens is used in a Virtual Interactive Presence and Augmented Reality (VIPAR) [5] setting. The maintenance worker wears the HoloLens and transfers an audio and a first-person live video to the expert. This expert watches this live-stream video on a laptop and provides advice orally or via 3D virtual annotations that are transferred back to the maintenance worker.

2. Related Work

Research in the area of Augmented Reality and near-eye display devices has a long history that reaches back to the work that Sutherland conducted during the 1960s [6] and the pioneering work of Steven Mann [7], which is being continued today [8] in many application areas. Research has shifted from basic technological research to more applied research with the aim of identifying and testing useful areas of application.

As mentioned in [3], the first wave of research and development in the area of remote maintenance started in the early 1990s with KARMAR [9] and continued as prototypes were developed by the Fraunhofer Institute [10] and Boeing in collaboration with the University of Southern California [11]. To create both prototypes, objects had to be prepared with markers to allow spatial orientation. Early work in this field by Kraut et al. [12] showed that performance dramatically increased when the remote expert helped compared to when the task was solved solo. Fiorentino et al. [1] refer to fundamental work, comparing paper-based guiding with AR-based guiding [13] [14], which showed the superiority of AR-based animated instructions over text and diagrams in paper manuals in the area of assembly tasks. Hou et al. [13] used a large monitor, AR animations and tag-based tracking in a lab setting to compare the use of paper-based manuals with AR supported guiding. They reported on "*shorter task completion times, less assembly errors, and lower total task load*" if the testers were supported by the AR-based system [13]. Furthermore, trainees significantly benefited from the AR system in that they showed an improved learning curve and a lower error rate [13]. Similar results were found by Webel et al. [15] who concluded that "*on average, technicians who trained with an AR-based training platform made less errors and achieved better performance times*". They also suggested that live expert feedback should be evaluated via an AR application if a situation occurred which was not pre-implemented in the training system. This suggestion precisely matches the experiment setup described in this study.

In the area of maintenance processes, Zhu et al. [4] proposed a context-aware, AR-based system that could provide the first steps into automatic information retrieval depending on the situation and individual needs of a maintenance worker. A similar idea was also followed by Espindola et al. [16] who proposed a system that combined maintenance data, Computer Aided engineering data and AR presentation technology in one application. A test of the system provided evidence for the superiority of the AR-based solutions over conventional desktop and Virtual Reality desktop applications. The tested AR-based application used an head mounted display (HMD) and tag-based tracking, which required pre-preparation of the application environment.

Several end devices, ranging from tablets, to large monitors and HMDs, can be used for AR applications. For example, Webel et al. [15] used tablets for an AR-based training application. Fiorentino et al. [1] tested AR-interactive maintenance instructions based on large screens. One of the reasons for this choice was the fact that existing head-mounted AR devices still needed improvement at that time (2013). Azpiazu et al. [17] proposed an AR application that could be used to provide remote support for maintenance operations in trains based on marker-based tracking and an HMD.

Basic research on camera positions in remote consultations has been conducted [2] [18], and the results show that settings which provide an overview of a scene are preferred over the first-person views that are typically generated by head-mounted displays [2]. Nevertheless, the contingency that scene-oriented cameras may not provide a high level of detail and, in some cases, may even be unable to show the area of interest, must be considered for each setup individually. The results on combining camera systems to provide details as well as an overview in separate streams are divergent. Whereas [2] states that both streams decrease performance, [18] concludes that both views are superior for complex tasks in terms of task completion time and perceived usefulness compared to systems that provide only one view.

Despite the long history of research and promising use cases (e.g., [19]), few 3D holographic applications have found their way from labs into everyday use in production environments. Recently, a few start-up companies have appeared that offer AR-based applications commercially (e.g., Oculavis [20]). As stated by Ong et al. [21]: "*VR technologies are relatively more mature, AR development is really only in its infancy*". The high technical demand for OHMD for AR has often limited studies, since the hardware was simply not available in the required maturity. Therefore, studies on interactive Augmented-Reality(AR)-based maintenance processes using OHMD that allow smooth operation in real-world industry settings are still rare. The development of the Microsoft HoloLens has sparked excitement about its potential to improve work processes. A first study in the area of teaching [22] investigated the 3D collaboration and annotation functionality of HoloLens.

In the current study, we focused on examining the practicability and suitability of 3D AR-supported remote consultations based on latest hardware developments. To get a baseline, a similar set of tests were conducted based on regular, audio-only communication between an expert and workers. Furthermore, a real-world industrial setting with real-world industrial staff was chosen to get insights into the practicality of the use of the latest 3D AR-based technology.

3. Methods

For the data collection a real-world industrial setting in the automotive industry and involving industrial staff was chosen to gain results with practical relevance. Data collection was structured around test scenarios that compared the use of the telephone and the Hololens. Errors that needed to be resolved by maintenance engineers were simulated on a processing machine. The engineers were supported remotely by an expert, either by conventional telephone or by HoloLens. The latter case provided live first-person video data for the expert and allowed expert feedback with audio communication and 3D annotations, which were projected in the line of sight of the maintenance engineer. This study was conducted using an exploratory qualitative research design. Data was gathered based on three pillars to facilitate triangulation: (1) *Interviews* - We gathered feedback from the maintenance workers who took part in both test scenarios (telephone and HoloLens) in a semi-structured interview. (2) *Video/audio analysis* - Video recordings of the tests were made from three (in the case of the telephone) or four (in the case of the HoloLens) different points of view, and audio was recorded (in the case of the telephone). (3) *Pre-study based on a literature review and stakeholder workshops* - During a preliminary project, possible areas of application for Smart Devices in production and possible use cases were analysed. This study [23] was based on the result of a literature review and end-user workshops. The use case "remote guidance in maintenance processes" analysed within this study was identified as promising and widely applicable in the participating company.

3.1. Technical details of experiment

As described in [24], HoloLens is equipped with "*four 'environment understanding cameras,' two on each side; a depth camera; an ambient light sensor; and a 2MP photo/HD video camera*". In combination with an Inertial Measurement Unit (IMU), this array of sensors enables the generation and processing of video data enriched with real-time spatial data. This data is the basis for the Augmented Reality features of the system. 3D-holograms can either be generated by the persons wearing the HoloLens or by other persons using a companion application. As described in [22], this companion app can be used by an expert who can see the live, first-person view taken by the HoloLens. Furthermore, a scene of this video can be frozen, and annotations and 3D holograms can be created and transferred to HoloLens. These annotations are then augmented to the real-world view of the person wearing the device. Annotations stay where they were initially placed, irrespective of head movements. In this study, Skype with an AR extension was used as a companion app. The combination of the HoloLens and the companion app enables the 'Picking, Outlining, Adding (POA)' interaction paradigm described in [25] [3], which is important for expert consultations.

3.2. Experimental setup

The experiments were conducted in real-world production facilities with six maintenance engineers and one engineer acting as the remote expert (see Figure 1).

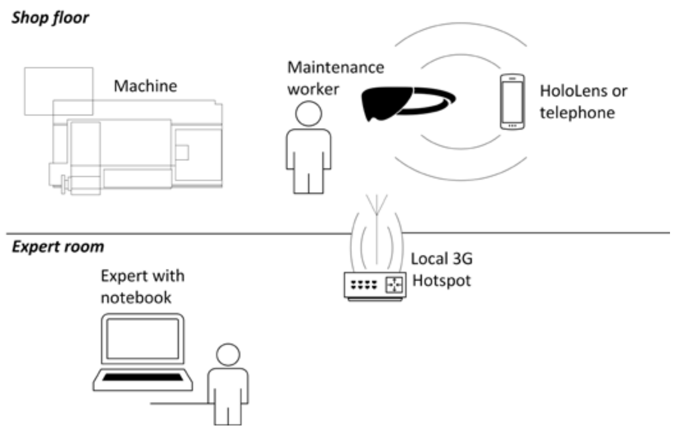

Fig. 1. Technical experiment setup.

Economic boundaries were set to restrict the number of test runs and participating workers. Nevertheless, this real-world setup was chosen in favour of a laboratory setting to improve our ability to gain practical expert insights and increase practical relevance. Errors were simulated using a 5-axis processing machine. Special parts of the machine were manipulated to trigger errors that indicated a bedraggled sensor. One case simulated a bedraggled sensor at a swarf transport unit, while the other case simulated a blocked filter. To allow a comparison to be made, both tasks had the same structure of steps that needed to be executed: (1) Diagnosis of error via control panel (2) Locate position of error at machine (3) Test sensor to verify error and fix error (4) Check if problem is solved.

To address possible learning effects that could happen, for example, during common control procedures, the sequence was switched, wearing each communication device, after half of the tests had been conducted. In general, the testers can be characterised as people who had previous experience working with the machine used for the tests. Only one maintenance engineer did not have any experience working with the machine. Regarding their general educational level, half of them could be categorised as 'engineers', with a higher educational level, and half of them as 'machine operators', with a lower educational level than engineers.

The goal of the experiment was to test if and to what degree the HoloLens could be used to facilitate the completion of remote-assisted maintenance tasks compared to telephone-supported maintenance. This setup was chosen because, at the time the tests were conducted, telephones were usually used as tools to provide remote assistance for maintenance tasks at the participating company.

4. Results

4.1. Results of post-test interviews and questionnaires

Overall, the maintenance workers as well as the remote maintenance expert could be characterised as being familiar with new technologies since, for example, 86% of them reported that they used smart phones at home. On a four-degree scale 43% of the participants fully agreed and 43% partially agreed that they use new technologies at work. Only 14% of the participants indicated that they did not use any new technology at work. The interviews were conducted to identify positive as well as negative effects, risks and possible potentials for improvement using the HoloLens during remote maintenance tasks.

In general, all the maintenance workers reported that they saw an improvement in the process by using the HoloLens. As indicated in Table 1, 67% of the testers agreed fully that they had saved time, 83% reported that efficiency was improved and 67% reported that risk was minimised.

In addition to improvements, all the maintenance workers also identified features that impeded the process. They reported that these impediments included risks of injuries, a narrowed range of vision, loss of spatial orientation and discomfort. When specifically asked about the risks due to distraction, 50% reported that there were absolutely no risks and 50% reported that there were few risks, according to the four-degree scale (Table 1). Regarding negative influences on normal motion, the responses were not clear-cut. Whereas 50% stated that their motion was occasionally negatively influenced, 33% responded that their motion was often negatively influenced. The responses regarding negative physical effects were also not clear-cut. Unlike this, however, the responses regarding negative social influences were quite clear. In addition, respondents noted poor audio and, in one instance, poor video quality; this was inherent to the test setup since the standard loudspeakers of HoloLens were used with no headphones, and network bandwidth variations may have occurred during the tests.

Table 1. Selected results of the post-test questionnaire.

Was there an apparent improvement in the following areas?					
	Fully agree	Partially agree	Partially disagree	Disagree	
Saving of time	67%	16%	17%	0%	
Increase in efficiency	83%	17%	0%	0%	
Risk minimisation	67%	33%	0%	0%	
Can risks be identified in the following areas?					
	Fully agree	Partially agree	Partially disagree	Disagree	
Distraction	0%	0%	50%	50%	
Negative influences on usual motion	0%	33%	50%	17%	
Negative physical effects	0%	17%	50%	33%	
Negative social effects	0%	0%	17%	83%	
How efficient did you think the description was of the situation based on the respective communication device?					
	Very good	Good	Sufficient	Poor	Very poor
Telephone	33%	17%	50%	0%	0%
HoloLens	67%	33%	0%	0%	0%
How safe did you feel taking the advice you received via the respective communication devices?					
	Safe	Rather safe	Sufficient	Rather unsafe	Unsafe
Telephone	*17%*	*50%*	*33%*	*0%*	*0%*
HoloLens	*67%*	*16%*	*17%*	*0%*	*0%*

4.2. Comparison of telephone and HoloLens

A crucial aspect of remote consultations is the need to describe the on-site scene to communication partners. A comparison of the two means of communication being tested revealed that describing situations with the HoloLens was rated as more efficient than with the telephone (Table 1). Participants reported that description "*was easier with the HoloLens*" and that the provision of a visual feedback-channel via the HoloLens was specifically helpful when interpreting complicated errors.

Another important aspect of remote consultations is how comfortable certain communication partners feel taking the advice offered. The participating maintenance engineers reported that they felt safer during the HoloLens test case (Table 1). They reported feeling more self-assured due to the positive feedback received and expert control enabled by the visual feedback-channel. Furthermore, one participant remarked favourably on the HoloLens feature that enables the creation of virtual 3D overlays to point at things in the real world.

When they were asked to grade the use of the HoloLens in the test scenario on a five-point scale, 67% of the participants gave it the highest grade; 16%, the second highest grade; and 17%, a sufficient (third highest) grade.

When asked to provide general remarks, the maintenance workers mentioned that smaller and lighter hardware would be more convenient, a larger field of vision would be desirable, headphones should be used in loud environments and an external lamp would help in dark situations, such as in areas with low light levels in large machines.

4.3. Feedback from the maintenance expert

The maintenance expert, who provided his expertise in the test cases via telephone and the HoloLens, can be categorised as a person with a high degree of technological affinity. He reported an improvement in the process while using the HoloLens. When specifically asked about the time saved, he responded with rather correct on a four-point scale. He clearly experienced an improvement in efficiency due to the use of the HoloLens, but did not conclude that its use minimised any risk. He did not note any impediments in the process caused by using the HoloLens, but expressed his concerns about IT-security. He added that an industry solution for remote consultation based on the HoloLens must ensure data security throughout the entire process chain. The efficiency of the description of the situation on-site was rated as sufficient (3) with use of the telephone and very good (1) with use of the HoloLens on a five-point scale. Interestingly, he also mentioned that the benefit of using the HoloLens over the telephone increases as the complexity of the maintenance operations increases. Furthermore, the use of the HoloLens may be more beneficial in cases in which non-experts or maintenance workers who are not trained on the machine at hand must solve a problem. Regarding the perceived safety of the advice given via each communication device, the expert reported a sufficient (3) level of perceived safety with the telephone and a high level of perceived safety (1) with the

HoloLens on a five-point scale. Due to its technical properties and for reasons described in [2], the stability of the first-person view and overview of scene was not rated with highest score. The expert was satisfied overall with the technical aspects of the virtual consultation supported by the HoloLens and rated almost all criteria with good. Only the 'picture quality' was rated with a score in between very good and good. All in all, the expert rated the use of the HoloLens for remote consultation with a good (2) score on a five-point scale.

4.4. Results of the video analysis

The video material was used to analyse task durations supported by the HoloLens and telephone. All four process steps lasted longer with the telephone. On average, telephone-supported tasks required approx. 20% more time. The following issues were identified while using the HoloLens during remote maintenance sessions in a real-world industry setting:
Safety issues: Analysis identified five instances in which maintenance workers had to move their heads very close to the machine. If the machine has rotating or hot elements, this could lead to accidents and injuries.
Ergonomic issues: In five instances, maintenance workers moved into and stayed in awkward and uncomfortable positions to allow the expert to see the areas of interest at the machine through the HoloLens.
Problems in dark conditions: Videos recorded via the HoloLens may be of bad quality under low light conditions. Furthermore, the tinted glass of the HoloLens impairs the view of maintenance workers working under low light conditions.
Problems in noisy surroundings: The tests were run in a real-world production facility. Consequently, the noise level was quite high. Tests were conducted without additional headphones and, therefore, comments about poor audio quality were made frequently. Two major problems with audio which heavily influenced operations were identified and consequently cut out in the timing calculations. Therefore, additional headphones are necessary in loud environments.
Various instances were identified in which a change in the method of communication was observed when a visual feedback-channel was used (see also [12]). This feedback-channel facilitated more spatial commands and questions. The following commentary in which the expert guides maintenance worker 6 during test run 1 has been selected as a representative example: "*You can see the chip's forwarder from the maintenance space's side. Go a little more and you'll see the switchboard, a little more and if you turn right, there's going to be the working space. That's it. I can see the sensor*".

Two issues were identified when using telephone as a communication device for remote maintenance sessions:
(1) Ergonomic issues - Maintenance workers clamped the phone between head and shoulders when they needed both hands. This uncomfortable position was observed five times during the experiment. Alternatively, maintenance workers put the phone on a nearby table (two times) or handed it over to colleagues (two times) to have both hands free. As observed for audio problems with the HoloLens, headphones may be one way to solve this problem. (2) Orientation issues - Without a visual feedback-channel, spatial tasks such as locating or finding areas of interest can be less efficient than with the HoloLens. This effect was specifically identified in the case of the unexperienced maintenance worker.
One goal of our research was to identify settings in which each mode of communication is especially useful. Regarding the question of whether the expert status is relevant for task performance based on different modes of communication, we identified four cases with experienced maintenance workers that showed that they could fulfil their tasks efficiently with the telephone and, therefore, without any visual feedback channels. On the other hand, we identified a case with an inexperienced worker in which the visual feedback channel significantly improved the efficiency of the guidance process and another case in which severe communication problems were not easily resolvable due to the lack of this channel. In the latter case, the maintenance worker 4 in test run 2 was at an incorrect location at the machine that looked like that described verbally by the expert. Therefore, more than seven minutes were needed to resolve the misunderstanding. The combination of feedback gathered during interviews and video analysis provides evidence that the HoloLens can be used to improve task performance, especially by inexperienced maintenance workers.

5. Discussion and Outlook

In this paper, we have presented the results of a study conducted using an AR-based and audio-only communication system for remote maintenance in a real-world industry setting. One aim of the experiment was to reveal if and to what degree the HoloLens could be used to improve the efficiency and efficacy of remote maintenance tasks compared to telephone-supported maintenance processes. In total, we made twelve test runs with six different maintenance workers and one expert. Due to this limited number, the statistical relevance of our results is limited. Due to the international setting of testers and researchers, transcripts, etc. had to be translated in different languages.

Our results clearly show that audio-only consultations resulted in longer task completion times as well as poorer individual assessments regarding the perceived efficiency while describing situations or safety while taking advice. This finding had been predicted by experts during the preliminary study and is supported by the results of the video analysis (approx. 20% slower than with the HoloLens) as well as in individual ratings. These results parallel those of Fussel et al. [2] who also concluded that "*pairs worked least well in the audio-only condition*". Taking a closer look at this effect, it became evident that VIPAR is especially useful when complex and difficult tasks must be performed by inexperienced staff. As described in a previous study [12], we were also able to identify scenes in which the method of communication took on a more context-sensitive character when a common shared view was available via the HoloLens. In addition to these findings, various practical areas of improvement and general recommendations were identified by the participating workers and during the analysis.

In general, special safety awareness training is needed to prevent the workers from moving too close to rotating/hot machine parts and to increase the safety of users in industrial settings. Furthermore, headphones may improve the audio quality of transmissions in noisy environments.

Areas of potential practical improvement in terms of the technology are:

- A longer battery lifetime would increase its practicability in industry settings.
- Hardware needs to be more rugged for daily use in production sites.
- Information security needs to be ensured throughout the entire process.
- Reducing the weight of the OHMD could improve user comfort.
- A remotely-controllable camera focus would enable the expert to directly focus on areas of interest.
- Especially under low light conditions, additional light to illuminate the field of view of the person wearing the OHMD would improve video quality and support hands-free operation.
- An additional camera mounted on a stick or another freely-movable and range-extending device would be helpful to reach hard-to-access areas at machines.

As an outlook, it will also be interesting to learn the results of studies being conducted in other application areas and disciplines that are developing and testing AR-based communication applications. Health care disciplines provide a wide range of use cases where these kinds of applications could generate benefits. The critical nature of processes and data security requirements in this area are equal or even greater than in the production field and, therefore, opportunities to learn from one another should be seized.

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