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Using Mixed Reality in Intralogistics - Are we ready yet?

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Abstract

The Industry 4.0 vision proposes a seamless integration of several modern concepts and technologies, such as the Internet of Things (IoT), artificial intelligence, or robotics, to capture and contextualize data to improve the manufacturing processes. In this respect, Industry 4.0 is all about information and connectivity. Mixed reality (MR) takes the data collected by IoT systems and helps workers by visualizing contextualized data in real time. Human-Computer Interaction research has shown that MR can be advantageous in various application scenarios. However, there is a gap between research and practice when it comes to real world scenarios. So the question arises whether MR is already suitable for efficiently supporting employees in their daily work in industrial settings. To answer this question, we examined two maintenance scenarios in the field of intralogistics: (i) the maintenance of roller conveyors and (ii) the alignments of containers in shuttle warehouses using the Microsoft HoloLens. This paper (i) describes the scenarios and the specific challenges they pose, (ii) presents the prototypes that have been developed, and (iii) discusses the results of user studies that have been conducted to evaluate the practical applicability by presenting inhibiting and facilitating factors. In summary, although MR technology itself seems to be very promising in the scenarios presented, further research on hardware ergonomics and intuitive interaction design is needed.

Keywords: Mixed Reality; Augmented Reality; Microsoft HoloLens; User Studies

1. Introduction

Industry 4.0 dramatically changes the production process from mass production to an ever-increasing number of product variants. The vision of Industry 4.0 proposes a seamless integration of various modern technologies, such as the Internet of Things, artificial intelligence, or robotics in order to collect data for the improvement of production processes and put them into context. However, this requires more flexibility and skills from the human production worker [16]. This kind of flexibility adds additional complexity to the production process, which can lead to higher cognitive load, stress and the risk of errors, which must be counteracted by supporting the human with appropriate tools [9].

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Furthermore, not only production workers are affected by these constant processes of change, but also maintenance workers. One area where immediate maintenance and service is of utmost importance is intralogistics [3]. Whereas in the past customers were prepared to wait several days for delivery, today one-day delivery is becoming the standard. Intralogistics is increasingly taking on value-adding tasks and is becoming an integral part of an optimal production process. Thus, intralogistics solutions need to provide tremendous performance with almost 100% availability.

In order to meet these requirements and specially to support service and maintenance personnel, Augmented Reality (AR) and Mixed Reality (MR) are used to provide employees with access to digital information and overlay this information with the physical world [1, 10]. This makes it even more important that necessary information is displayed where it is needed due to the work situation in order to direct the employee's attention and to reduce the cognitive load accordingly. This trend is supported by several factors: (i) MR hardware is becoming increasingly powerful and easy to wear, (ii) the necessary flexibility in smart production requires new tools for workers in industrial setting, (iii) more people have become familiar with natural user interfaces. The paper presents two projects from the field of intralogistics: (i) maintenance of roller conveyors and (ii) the alignment of containers in shuttle warehouses. We followed the human-centered design process defined in ISO-9241-210:2019[1] for the implementation of MR prototypes to support maintenance workers (cf. Figure 1) and tried to answer the question whether MR is already ready for use in industrial context, in specific in the domain of maintenance work in intralogistics. Based on an contextualization of the problem domain, we designed and built several prototypes based on the HoloLens I (since the HoloLens II was not yet available at the time of implementation) and finally evaluated these prototypes through user studies.

Structure of the paper. After discussing related work in Section 2, we outline our human-centered design approach in Section 3. Then we discuss the two use cases *maintenance for roller conveyor* in Section 4 and *container alignments in a shuttle warehouse* in Section 5, present the prototypes, and discuss the findings of the user studies. Finally, in Section 6, we discuss the applicability of MR in industrial settings and give an outlook on future work in Section 7.

2. Related Work

In their survey on AR, van Krevelen et al. [8] analyzed the field of AR, including a brief definition and history of development, enabling technologies, and sample applications to provide insight into limitations, e.g., limited field of view. However, technologies and user acceptance have improved significantly since 2010, when this survey was conducted. Rauchenschnabel and Yo [13] have investigated drivers and barriers of AR smart glasses like HoloLens I and Google Glasses by developing a model that explores what factors influence attitudes to using smart glasses and the intention to adopt them. However, instead of focusing on industrial use, they focused on general user acceptance and found that although smart glasses are worn similarly to fashion accessories and capture various personal information, self-presentation benefits and potential privacy concerns seem less likely to influence smart glasses adoption.

Korn et al. [7] describe in their work a context-aware assistive system for production environments. They use projection to augment work to build an assistive system for impaired workers in assembly. The underlying requirements for their approach were formulated to (i) provide scalability at the competency and process level, (ii) provide small chunks of information at the right time, and (iii) increase motivation and fun at work. Instead of head-mounted display, they built an experimental assembly table with motion detection and projection systems.

Funk et al. [2] have built a system called "Teach Me How!" in which in-situ projection was used for interactive assembly instructions. Although there is no head-mounted display in use, it shows how visual instructions can be used to support workers during the assembly of an engine starter. The system highlights the position where a part should be assembled and checks that it has been assembled correctly. Their work goes beyond projecting work instructions and it provides very helpful features like pick detection, assembly detection and detection of tool usage.

Wang et al. [15] have analyzed 36 cases of the application of AR technology in intralogistics. Their results were clustered in the following application perspectives: (i) AR application warehousing/storage, (ii) AR application in picking, (iii) AR application in shipping & handling, (iv) AR application in inventory and warehouse planning, (v) AR application in in-house logistics for other purposes. Following their classification, our work of maintenance would be classified as "AR application in in-house logistics for other purposes".

[1] https://www.iso.org/standard/77520.html

Mourtzis et al. [11] have used AR technology for warehouse design and operation in the paper industry, both for warehouse simulation and for inventory management. For example, they use QR codes on items, and when an operator needs to locate a particular item, handheld device assists her to warehouse location. This has some similarities to one of our use cases for aligning containers in a shuttle warehouse (cf. Section 5).

Čujan et al. [18] show how Virtual Reality (VR) and AR can be used in the automotive industry. They used video-mapping for the workplace of the parts that are assembled on the pallet. A beamer displays instructions on a specific part, on the part carrier, or on the hall floor. Text, figures and videos show the optimal fixing of the parts and components. From the studies carried out, they have found that video mapping for the parts assembly workstation brings remarkable time savings.

Although there are several prototypes and user studies, hardly any of them focused on the use of AR or MR systems in industrial settings where there may be specific requirements such as noisy environments, or areas with limited space that could affect the proper use of AR devices.

3. Approach

The use of MR applications in intralogistics contributes to greater visibility, training and problem solving. Improvements can be achieved in areas such as design, assembly, quality control, maintenance and safety [18]. In [5], central roles in intralogistics processes were identified, namely picker, operator, and service technician. In this paper we focus on maintenance and the role of service technicians who are primarily responsible for troubleshooting errors within a warehouse, e.g., from hardware maintenance to the replacement of certain (incorrectly stored) items. This is since both pickers and operators normally work at fixed workstations, while service technicians are mainly on site. During this on-site work, the provision of information for the work processes is of utmost importance .

Both projects presented in Sections 4 and 5 were conducted in cooperation with TGW Logistics Group. TGW is a worldwide leading general contractor for intralogistics solutions. It develops and manufactures logistics equipment for unit loads, from small conveyor systems to complex distribution centers and provides warehouse management systems. Both projects were conducted by master students of our university between 2017 and 2019. Thereby, a human-centered design approach was followed (cf. Figure 1).

Human-Centered Design. For the success of digitization, the human-centered design of intralogistics systems is becoming increasingly important in order to improve the efficiency and user acceptance of the planned system [4, 6, 12]. In the projects presented in the following, the human-centered design process is therefore followed, which runs through the phases (i) *understanding and specifying the context of use*, (ii) *specifying the user requirements*, (iii) *producing design solutions* and (iv) *evaluating the design*.

Understand and Specify the Context of Use. The first step is to analyze the tasks of service technicians. This includes, e.g., the worker's environment, frequently occurring problems and impairments during the work process. For this purpose, interviews and observations are conducted with future end users of the intended prototypes in order to place them as domain experts in the focus of the requirements elicitation, as can be seen in Figure 1(a).

Specify the User Requirements. The main findings of the interviews are clustered into requirements and main goals. We formulated requirements in terms of user stories and visualized them by drawing storyboards.

Produce Design Solutions. Based on the requirements of the previous phase, first concepts are developed, which are refined to a complete design. In a Design Thinking process [14] possible solutions are developed without consideration

(a) Observation (b) Prototyping (c) Testing

Fig. 1. Impressions of the conducted Human-Centered Design Process

of (e.g., technical) limiting factors. The focus is on generating first ideas that support employees and bring MR directly to the workplace. Finally, we construct a prototypical workstation using cardboard engineering (cf. Figure 1(b)).

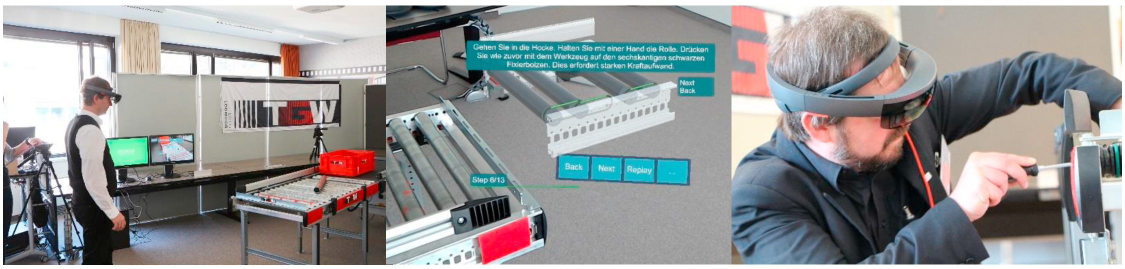
Evaluation of Design. In the final phase, the prototypes are repeatedly discussed and tested with users to ensure that their requirements are met. Our testing strategy can be divided into three categories. First, the developers themselves as well as dedicated people from TGW apply the HoloLens prototypes at the cardboard to check the maturity level. In a second step the HoloLens prototypes are evaluated by non-experts, i.e., prospective students who attended the open day at our university. Finally, the prototypes are tested by domain experts in a real environment. In the second and third scenario we applied heuristic evaluation methods and user tests in combination with observation and interviews. In addition, we measured e.g., the time needed to complete a task and the frequency of errors. The observations of the user tests are also used to record the spontaneous impressions of the participants in a Thinking Aloud protocol. Questionnaires and interviews are also used to obtain a reflected assessment of the users. The findings build the basis for improvement in recurring cycles of the process. The user studies were deployed on the Microsoft HoloLens I. Although some of the results may be device-specific (and may be different on the successor model), we also obtained device-independent findings to answer our research question whether MR is ready for industrial use. In particular, we present two prototypes for common scenarios in intralogistics, namely (i) maintenance for roller conveyors and (ii) fixing container alignments in shuttle warehouses. For each scenario a detailed description of the requirements, the implementation of the prototype and the results of the user studies are discussed in Sections 4 and 5.

4. Maintenance for Roller Conveyor

Conveyor systems are an essential part of intralogistics. Goods to be picked are delivered in a loading unit (e.g., pallet or container) to a fixed picking location (e.g., workstation or depot) by means of conveyor technology. The picker takes the required number of parts and the remaining load is returned to the warehouse. Maintaining the functionality of such systems is crucial for the operation of entire companies. Like most mechanical systems, conveyor systems become more error-prone over time and may eventually fail. A failure can bring sales and manufacturing processes to a standstill for a long time, and without replacement of the failed part, other systems could be affected. Sooner or later, mechanical parts will have to be replaced. A service technician performs basic diagnostics and repairs on such hardware. Traditionally, they often used paper-based service lists for instructions. Lately, paper-based instructions are increasingly being replaced by tablets or smartphones. However, during maintenance, technicians often need their hands free for their actual work. We want to support these maintenance work by using Microsoft HoloLens I to provide digital instructions with textual task descriptions and 3D models to enable hands-free interaction.

4.1. Prototype

The prototype is implemented in Unity and covers two typical repair tasks that occur in conveyor systems in daily operation: (i) replacement of a conveyor roller and (ii) replacement of a photosensor. These tasks are defined using a structured JSON document allowing easy extension of the prototype. Each task consists of individual steps. These steps can contain text instructions, actions (e.g. audio output and animations), models (e.g. 3D model of the object to be repaired), and decisions. With the help of these decision elements (e.g. ”Is the red LED light sensor lit?”) and response options to these decisions (e.g. ”Yes” and ”No”), a simple navigation structure with a non-linear sequence can be set up. In our maintenance and repair context, our users may need both hands to do their jobs and may prefer



(a) Study Setting (b) Visualization of concrete task (c) User exchanging light sensor

Fig. 2. Evaluation of the Prototype for Maintenance of Roller Conveyor

hands-free interaction modalities. Therefore, our prototype supports gaze and dwell interactions, and voice input and voice output of textual instructions and questions.

4.2. Evaluation

The evaluation served to get feedback on the interaction concept and user experience of our prototype to gain first insights into voice commands and output of the HoloLens, and the quality of task instructions. We recruited 49 participants (17f, 32m) aged between 15 and 57 years (M = 20). The evaluation was done in a lab environment at our university, using a real-world conveyor belt for the maintenance tasks (cf. Figure 2(a)) in 2017. During an observation phase the participants were asked to solve one of two prepared maintenance tasks: (T1) replacement of a conveyor roller or (T2) replacement of a photosensor. T1 consists of 13 and T2 of 14 steps, both tasks take about 10 minutes. Before starting the task, a short introduction to the HoloLens was given. During the tasks two observers took notes, the participants were recorded on video and a live capture of the HoloLens spectator view was recorded for later analysis. In the interview the participants were asked to describe their first impressions and experiences with the prototype. This was done by means of a semi-structured interview and a questionnaire to collect demographic data.

4.3. Findings

4.3.1. Tasks and instructions

Tasks. The maintenance task was deliberately chosen to be of limited complexity and easy to solve. Despite the simple task, we often observed errors in about 5 steps where the participants needed help. Some participants also showed signs of stress, and they tried to solve the task as quickly as possible. We found that 35% of the participants performed the steps without hesitation. 32% needed extra time to understand the instructions, think about them and then perform the actions correctly. 5% were not sure if their actions had been performed correctly and repeated a step they had already performed. 27% needed further help and support. Help was needed especially by those participants who were inexperienced in using the technique and were afraid of breaking something.

Instructions. Figure 2(b) shows a typical description of one task. Some attendees had difficulty performing such tasks described in the work instructions correctly. This was mainly due to the participants' increased nervousness and not reading and following the instructions closely enough. Half of the participant (50%) performed the action first and then used the `Next` command (voice command or click on the button) to proceed to the next instruction step. About a third (33%) of the participants read the instruction, went on to the next step immediately and only then did the actual work. Participants stated that it was easier for them to see the next step first, so that they knew more precisely how the work should be done. The remaining 17% of the participants used the `Next` command while doing their work. In general, text-based instructions were sufficient. A majority of the participants said that they did not need a virtual model of the machine to be repaired. It would be more helpful if overlay symbols would make navigation easier and point to the parts of interest.

4.3.2. Interaction with prototype

Acceptance of voice commands. The majority (77%) of the participants pronounced the voice commands clearly and without hesitation. Only 22% hesitated and 3% felt uncomfortable saying voice commands. We observed this behaviour especially in front of others. In almost ten cases there was no observable utterance of voice commands. These participants preferred to control the application via visual navigation (buttons). The participants also switched to this control option if the voice commands were not recognized.

Quality of voice recognition. During our evaluation 58% of the voice commands were understood correctly at first attempts, 15% had to repeat the command once and 27% even more than once. In addition, we had situations where a larger group of people were present during the evaluation run, which increased the noise level and made the HoloLens speech recognition temporarily unreliable. At the time of development, the HoloLens speech recognition service was only available in English. Some participants pronounced the English commands with a strong German accent, which also caused problems and resulted in a low recognition rate. Often this problem could be solved after the attention of the participant was directed to a more conscious pronunciation. Problems arose mainly with the `Start` command, which had to be repeated by several participants or activated by the visual navigation, apparently due to short length of the command, i.e., shorter commands led to a lower recognition rate.

4.3.3. Ergonomics

Wearing the HoloLens. The majority (62%) of the test persons did not re-adjust the HoloLens after placement, most likely due to the fact that the persons were first trained in the use of the HoloLens and that a team member adjusted the HoloLens before the actual test was performed. However, 13% had to re-adjust the HoloLens once and 26% even several times, often due to the length of the persons hair or the incorrect basic setting of the HoloLens. Additional behavioral patterns were observed in six other test subjects (n = 43): Test subjects held their glasses with their left hand, the glasses slipped down or caused headaches. Errors in the fit and wearing of the HoloLens led to the most application errors. However, it can be assumed that more comprehensive training will be provided in industrial use.

Using glasses with the HoloLens. 10 spectacle wearers participated in the evaluation (about 20%). Half of them took off their glasses, half wore them under the HoloLens. The tests showed that especially progressive glasses can cause major problems. The field of view of the HoloLens is very limited and is further reduced when progressive glasses are worn, which is why some test persons stated that they had difficulty using the HoloLens correctly.

5. Alignments of Containers in Shuttle Warehouses

In intralogistics, shuttle systems are used for the automatic operation of warehouses. They are typically used in goods-to-picker systems [17] and run individually in each row of storage racks to store and retrieve containers or pallets. During this process, the shuttles may not always be able to properly pick the containers and therefore fail to retrieve the goods. This may be because the containers are misaligned, in the wrong location or not available at all. In these cases, the errors have to be manually checked by maintenance personnel. A service technician looks over to the corresponding error location and tries to fix the cause of the error (e.g. by aligning the containers or detecting missing items). Therefore, in most cases the solution is to remove the container from the rack, take it to a picking station and have the system replace the container, which is quite inefficient and time consuming. Consequently, this process should be supported by the use of AR by indicating the correct assignments of the containers in the storage racks to enable immediate error correction on site.

5.1. Prototype

The prototypical implementation is divided into two parts: (i) a HoloLens application for maintenance instructions and visualization, and (ii) a backend for data storage, connected via a REST API. The HoloLens application is the frontend for the service technician to get maintenance instructions. It is implemented as a Unity application and deployed to MS HoloLens I. For the exact positioning of virtual objects (e.g. target position for misaligned containers) the prototype uses marker-based tracking by applying Vuforia[2]. The backend simulates a traditional warehouse management system and provides the current rack allocations, the positions of the load carriers, and the type of their contents. The service is implemented using .NET Core.

5.2. Evaluation

In addition to continuous tests on the cardboard prototypes, two user studies were carried out, one with prospective students and a second with service technicians from TGW. To analyze the interaction behaviour we chose in-depth observations paired with a Thinking Aloud approach. In the study with prospective students we additionally used a questionnaire to collect subjective impressions from the participants.

For the first evaluation, which was conducted in March 2019, we recruited 42 participants (16 f, 26 m) aged between 17 and 54 years (M = 26). The testbed for our study consisted of two mock-up storage racks with containers using cardboard prototypes (cf. Figure 3(a)). We started the evaluation with an introduction of the HoloLens (e.g., training of gestures for basic interaction) and the functionality of the prototype using a tutorial exercise. Next, the participants in the main evaluation task were asked to solve a total of four error tasks at two different stations. Both stations used the same types of errors (container misaligned and missing). However, the setup at the two stations varied depending on the placement of the containers and the visualization used (2D and 3D, cf. below) for the maintenance instructions. At least two observers were present and took notes during all evaluation runs. Afterwards a second evalu-

[2] https://developer.vuforia.com/

ation was conducted at the TGW training center within a “real” shuttle storage with five participants. The suggestions for improvement found in the first study were already included into the prototype.

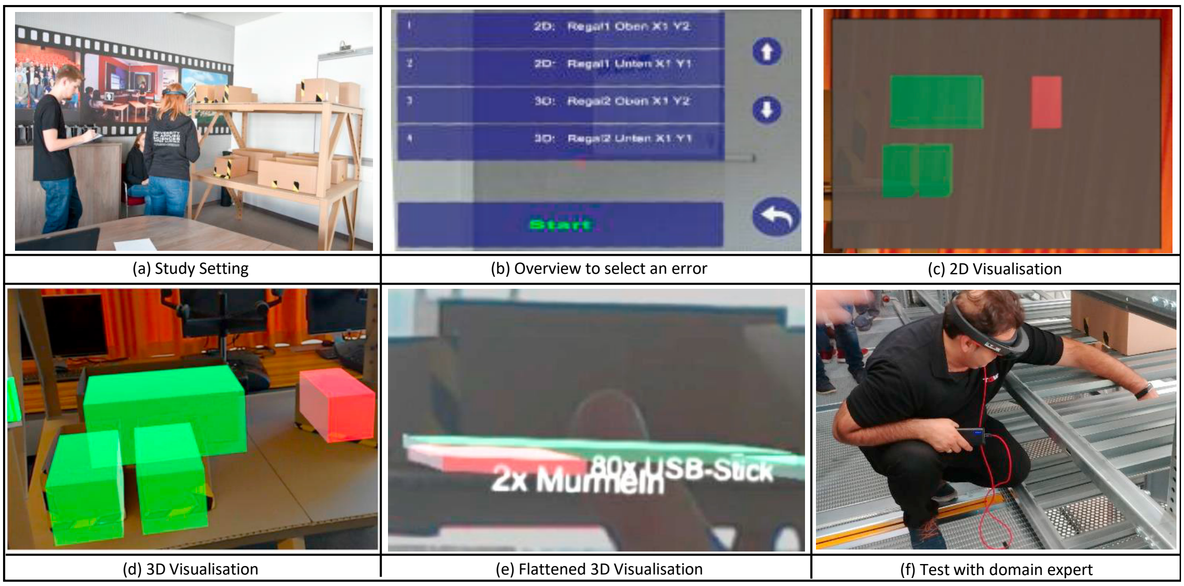
5.3. Findings

5.3.1. Tasks and instructions

Small fonts. Participants found it difficult to read the texts correctly because of the small font (cf. Figure 3(b)). The contrast between text and background also felt to be too low, especially in poor lighting conditions. Thus, the text should always be placed on a suitable background, otherwise the text could be invisible depending on which element the text is augmented onto. However, the background should not completely overlay reality, i.e., the degree of opacity is important.

2D vs. 3D instructions. With the 2D instructions (cf. Figure 3(c)), users often had problems finding the correct shelves and positions of the containers. Participants struggled with whether the displayed error was in the top or bottom shelf and in fixing the error, many were unable to position the containers according to the displayed instructions. Using the 3D instructions as shown in Figure 3(d), problems were caused by the restricted field of view. For example, the error to be corrected was already projected on the shelf, but outside the participant’s field of view. She did not know what to do, and this caused confusion. The short distance to the shelves was also a challenge for the users. They argued the projected containers were difficult to distinguish at short distances. Some had difficulty even detecting the error. The color codes for errors states (red boxes for misaligned or missing containers) and correct states (green boxes for correctly aligned containers) were correctly interpreted by all participants. Even a person who reported a red-green deficiency was able to solve the tasks without any problems.

When comparing the two variants, the participants found it easier to locate the error with 2D instructions, as this variant shows a top-down view. They stated that they could see the entire shelf at a glance, which was an advantage for better orientation. However, when fixing the error (aligning the containers), the participants found it easier to use the 3D instructions. The main advantage of the 3D instruction is to compare the actual and target positions of the bins through their field of view. Both variants therefore show advantages in certain steps of the process. Nevertheless, the results of the questionnaire clearly show that users are in favour of the 3D instructions (81% prefer 3D over 2D instructions). Others stated that a combination of both variants would be useful. The 2D instructions with its top down view as an overview for locating the containers and the 3D instruction for displaying the target positions of the missing or incorrectly aligned containers. Therefore the prototype was evolved combining both views, resulting in a flattened 3D visualisation (cf. Figure 3(e)). This visualisation was tested with TGW’s domain experts, who were all



(a) Study Setting | (b) Overview to select an error | (c) 2D Visualisation

(d) 3D Visualisation | (e) Flattened 3D Visualisation | (f) Test with domain expert

Fig. 3. Evaluation of the Prototype for the Alignments of Bins in Shuttle Storages

able to correctly align wrong containers. However, they would have appreciated feedback when bins had been aligned correctly, which would require precise object recognition.

5.3.2. Interaction with prototype

Navigation and gestures. Eight participants out of 42 of the first evaluation think that the navigation in the HoloLens app is not intuitive and tedious to use due to the many tap gestures required. The reason for this could be that many steps in the navigational structure need confirmations (by tap gesture). Several times, different participants had difficulties performing the tap gesture (gesture was not recognized and had to be executed several times). This is also covered by the questionnaire: 33% (2% strongly, 31% somewhat) disagreed with the statement “I found it easy to interact with the HoloLens using the gesture control”. To counteract this, our users suggested using a flatter navigation structure, the HoloLens clicker, or a compatible smart glove, which allows new forms the interaction with the app. The situation was also confirmed during the test with the domain experts who also sometimes struggled with the tap gesture. However, using voice input and audio output as alternative seemed inappropriate due to the typically loud background noise in shuttle warehouses.

5.3.3. Ergonomics

Wearing the HoloLens (with glasses). Many participants found the device uncomfortable to wear due to it’s weight (579 g), even for the short period of the evaluation task. We even saw in the observations that seven participants supported the device with their hands to reduce the strain on their necks. Although the HoloLens is generally designed large enough that users can wear glasses, our participants struggled seeing the projections clearly. Especially participants with farsightedness reported that they had seen diplopic images. One of the people wearing glasses also had a built-in filter for the upper end of the blue light. This person could not see any projections in the HoloLens because the entire spectrum was filtered. Without the glasses, however, it was difficult for her to read and interpret the icons and projections. In general, our participants with glasses feel uncomfortable wearing the HoloLens.

Field of view. More than half of our participants already had experience with AR/VR devices. It was therefore somewhat surprising that difficulties arose at the beginning of the evaluation runs. One of the main problems was the limited field of view, which required the HoloLens to be placed precisely and tightened on the wearer’s head. When performing manual tasks, it is almost inevitable that the HoloLens will slip (which happened for 40 participants) and require correction and fixation the field of view. For example, tests in the early development showed that parts of the field of view were cut off without the user even noticing. To counteract this, we introduced a red frame for user orientation that covers the entire field of view. This frame is only visible in the main view and can be removed with a tap gesture. However, the evaluation also revealed problems with this approach. Repeated clicking away the frame is tedious or was completely forgotten during the evaluation tasks. This in turn meant that the red frame obscured display elements (and possibly concealed relevant information). Nevertheless, we observed situations where projections or parts of the application were not in the participants’ field of view.

6. Discussion

Based on the results of the prototypes and the user studies, *inhibiting* and *facilitating* factors are discussed that should be considered when using MR in industry.

6.1. Inhibiting Factors

Ergonomics. A major inhibiting factor for the use of HoloLens I in industry is the poor ergonomics observed in both scenarios. To make the best possible use of the restricted field of vision, it is firstly necessary to place the device precisely on the wearer’s head and to tighten it. Secondly, during manual activities it is almost inevitable that the HoloLens will slip, which will require corrections from time to time. However, while writing this paper we were able to test the HoloLens II, which is currently being used in a follow-up project. All students and professors involved (11 persons in total) mentioned that (i) the HoloLens II is now much more comfortable and can be worn longer and (ii) the larger field of view (52° diagonal for the HoloLens II vs. 34° diagonal for the HoloLens I) makes holographic objects appear much more immersive than before. However, it is still significantly narrower than a typical VR headset. In addition, the possibility of folding the visor upwards to end the MR was also mentioned positively. When using the HoloLens I with glasses, problems such as dizziness or blurred vision occurred for a group of users, including those with progressive glasses. Some have taken off their glasses for it to work, especially users with myopia. As for HoloLens II, only three out of 11 people wore glasses. However, these people did not mention any restrictions.

After all, both versions of the HoloLens consume quite a lot of battery power. Depending on the holograms used in the app, the battery lasts about 2 to 3 hours. To extend battery lifetime in our user studies, we used external USB power supplies, which allow a significant improvement in battery life.

In summary, it can be said that the ergonomic limitations of HoloLens I hindered an application in the scenarios investigated, while HoloLens II seems to be a big step in this direction. However, more and longer lasting studies must be carried out to confirm these impressions.

Imprecise Positioning and Object Recognition. Use cases that require precise augmentation are still challenging to implement and must be extensively tested under real conditions. This is not least due to the permanent changes in the HoloLens SDK, Vuforia and Unity which often lead to inconsistencies, i.e., it remains unclear if it is better to use exclusively the API contained in the HoloLens SDK, to rely exclusively on external APIs or to implement a combination of them for a more precise positioning of virtual objects. Therefore, in the first prototype we did not precisely position the parts to be exchanged on the physical roller conveyor system, which was evaluated negatively by several participants of the study. Similarly, a major point of criticism in the second study was that virtual and physical containers did sometimes not overlap perfectly. The positioning of high-resolution 3D elements exacerbates these factors and pushes both versions of the HoloLens to their limits. Finally, if the scenario requires the detection of real-world objects, e.g., to detect that containers are correctly placed after repositioning in our second scenario, the HoloLens built-in support is still in its infancy which limits it's applicability in certain use cases.

Complex Development. In general, the development of MR applications is complex, requiring the use of multiple tools, APIs and programming languages. Concerning the HoloLens, a tighter integration into e.g., Visual Studio would be desirable, as this would probably streamline the development process and could be advantageous to deal with version dependencies between tools. Furthermore, the important factor of maintenance and evolution of HoloLens applications over a longer period of time is neglected, which hinders it's industrial use.

6.2. Facilitating Factors.

Usefulness of the HoloLens for the given use cases. It was very interesting to observe that in both use cases, both the test persons and the domain experts found the HoloLens useful and helpful in performing certain maintenance tasks. In general, the augmentations of the maintenance tasks were understandable for the majority of our participants and were considered as helpful for both, domain experts as well as non-experts. Thus, we conclude that MR applications are useful in maintenance, teaching and training scenarios were the augmentations on real-world objects (thus excluding VR solutions) can guide the user in fulfilling the actual task.

Interaction integrated into Workflow. In general, users felt comfortable interacting with the HoloLens while they were still able to perform their actual task. Most problems of misunderstanding were due to the interaction design or since it was unclear for certain users that they could move around to get a better overview of things. Therefore, extensive user testing is essential for the successful deployment of MR applications. Especially during the interaction with our prototypical applications, it became apparent that some users had problems with predefined gestures of HoloLens I, e.g., air tap. Voice commands are often not recognized correctly, either due to background noise, as is the case in industrial settings, or due to improper pronunciation of commands, which are currently only available in English. External devices like the HoloLens clicker could obstruct the worker during the execution of a task. However, in certain use cases, it might be useful to integrate external devices that are placed on physical objects, e.g., external Bluetooth buttons that are placed on the workstation to navigate through the application.

The HoloLens II offers new gestures. Our first tests have shown that especially the new click gesture is more intuitive than the air tap of the HoloLens I. The actual interaction with the virtual objects, e.g., their scaling, seems to be promising to allow a more detailed view on certain details, but has not yet been evaluated in dedicated user studies.

Interactive Augmentations. Since MR is still new to most people, interactive and animated augmentations attract the attention of users, which in turn is an advantage in training and maintenance tasks. 3D animations in particular are considered useful for digging into details while, simpler 2D visualizations are preferred for getting an overview. It has to be noted, however, that the UI should not be overloaded with augmentations, on the one hand to still allow sufficient visibility of the "real world objects" and on the other hand to ensure comfortable interaction, which becomes cumbersome if elements are too small. Our user studies have shown that especially longer texts should be omitted, which can be replaced by meaningful icons.

7. Conclusion and Future Work

Based on the findings of our user studies, the question whether MR can be used in industrial settings allows two different answers. On the one hand the MR technology itself seems to be very promising and useful in the scenarios presented. This can be concluded from the mainly positive reactions on the MR applications themselves. However, there are also limiting factors such as poor hardware ergonomics and challenging interaction design on the other hand. With regard to ergonomics, it should be noted that at the time the studies were conducted (2017 to 2019) only the first version of the Microsoft HoloLens was available. First tests with the second version showed tremendous improvements, so this will not be such a big issue any more, especially since we have identified some use cases where the device is worn less than 20 - 30 minutes. The additional gestures could also enable a more intuitive interaction design to further increase acceptance in the industry.

We are currently building another prototype in an industrial setting where we plan to conduct a user study with the HoloLens II. We focus on the interaction design and the new possibilities of the new version of the device. In summary, while with the HoloLens I an important first step has been taken to bring MR into industrial settings, the HoloLens II seems to bring the idea of MR an important step further towards practical applicability. To answer our research question, we would like to say that with HoloLens II we are close to finish, but that appropriate user studies and evaluations still need to be carried out to substantiate this impression.

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