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Evaluating an Augmented Reality Prototype for Enhanced User Guidance in an Industrial Production Context

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Abstract. This study evaluates an augmented reality (AR) prototype aimed at enhancing user guidance in industrial procedures, focusing on tool change tasks. The variability in experience and skills among operators and maintenance technicians in handling machine-related requirements poses challenges to smooth operations. To address this, an AR guidance system was developed for a head-mounted display device, utilizing image, object, and gesture recognition to minimize user interaction and enhance system adaptiveness, ultimately reducing cognitive load. A user study employing video observations and questionnaires was conducted to evaluate the AR system's impact on usability and cognitive load. Results indicate that the prototype effectively facilitated tool change tasks, providing a user-friendly experience with reduced cognitive load. The integration of image, object, and gesture recognition contributed to streamlined user guidance, minimizing the need for constant user interventions. Notably, participants experienced a fluid user experience with high usability and a moderate cognitive load, emphasizing the system's potential in managing complex tasks. The study also highlighted the applicability of AR technology in fields beyond tool changes, such as troubleshooting, and identified a preference for an apprenticeship-style training approach among participants.

Keywords. Augmented Reality, User Experience, Operator Guidance

1. Introduction

Despite a significant increase in the degree of digitalization of industrial manufacturing processes over the past two to three decades, certain production tasks still involve a blend of automated and semi-automated machinery overseen and managed by human operators [1]. Augmented Reality (AR) technology has the potential to serve as a platform for assisting the operators in their responsibilities, as it allows essential data to be overlaid directly within the physical workspace where they perform their tasks [2]. Furthermore, by employing a head-mounted display (HMD) rather than, for example, handheld devices, operators can take advantage of having unoccupied hands, thus enabling them to simultaneously follow the system's guidance and perform their work [3].

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Operators' work procedures in everyday practice are varying and tool change tasks are core duties that need to be accomplished to avoid machine stops and to continue a good workflow. However, there is a large variation of work experience and skills among operators and maintenance technicians to accomplish machine and system-related requirements [4]. Also, it takes time and resources to train new personnel, especially utilizing apprenticeship type of learning when two persons are allocated on the same job for an extended amount of time. This work aims to evaluate an augmented reality (AR) prototype designed for enhanced user guidance during industrial tool change procedures.

1.1. The case: Tool change procedure

In our case, we have employed AR tool to facilitate the procedural task of calibrating tool measurements. Once a tool is selected for measurement, it requires a fixture to be able to fit into a Zoller measuring machine. There are 4 fixtures available, each designed to accommodate different tool holders for drill bits and lathe bits.

Once the correct fixture for the selected tool is identified, it is inserted into the measuring machine, and the tool is then placed into the fixture. Subsequently, the user operates specialized software that controls measuring machine, initiating the measuring process. The user needs to verify whether the tool is correctly calibrated. Drill bits require the height to be adjusted, while lathe bits use the measuring machine's camera to pinpoint the lathe bit's edge in the software. Following these steps, the machine automatically records the measurement data, allowing the user to remove the calibrated tool. This calibration procedure is not a routine task and occurs sporadically. Unfortunately, errors often arise due to overlooked steps or a misunderstanding of the distinct requirements for different tools by the user.

1.2. AR tool to assist in changing tools

In this work, an AR assistance tool was designed, developed, and evaluated for its usability and perceived workload put on the user in the task of calibrating tool measurements for handling tool change operations directly on the shop floor production.

The rest of the paper is structured as follows. The second chapter addresses related literature. Chapter 3 goes through the design and development process of AR prototype for tool change. The fourth chapter describes the user study conducted to evaluate the prototype in production context and finally, chapter 5 presents the results. The paper ends with a discussion presented in chapter 6.

2. Related Work: Augmented Reality Guidance in Industry

2.1. Benefits of Augmented Reality in Industrial Contexts

The evolution of Augmented Reality (AR) systems has been marked by significant benefits over the years. Bottani and Vignali's survey [5] underscores the growing importance of AR in industry, emphasizing its potential to avoid delays and prevent mistakes. Existing AR applications have shown potential benefits in enhancing the speed and accuracy of manual tasks [6], reducing errors [7], and improving training effectiveness [8]. Manufacturing and training emerge as key application areas within the industrial context, signaling a broader acceptance and utilization of AR in the industry. The survey by Palmarini et. al [9] emphasized the potential of Head-Mounted Displays (HMDs) to enhance concentration on the task at hand due to the reduced need for users to consult paper manuals during maintenance tasks; reduced eye and head movements, leading to improved spatial perception and increased productivity; and therefore reduced time because of shifting attention between objects and instructions being time-consuming. However, HMDs come with their technical challenges, such as system latency, resolution, field of view (FOV), scene distortion, eye-point matching, ergonomics, and costs, as identified by various studies. Despite these challenges, the portability and enhanced user experience offered by HMDs make them a popular choice for AR implementations. Several studies evaluated the usage of augmented reality in the production environment [10-13].

2.2. Specific AR applications

A study involving six maintenance engineers assessed remote maintenance using Microsoft HoloLens [13]. The HoloLens scenario was deemed more efficient than a smartphone, with participants feeling safer and requiring about 20% less time. Another field study [12] compared HoloLens 2 with a tablet computer for machine setup tasks. Despite similar task completion times, participants found HoloLens 2 more comfortable, resulting in fewer distractions from the task compared to the tablet.

2.3. Augmented Reality Training for Cognitive Skills

Webel et al. [14] shed light on the importance of AR in training the underlying skills, both sensorimotor and cognitive, necessary for efficient acquisition and performance of new maintenance operations. Their research suggests that AR training can significantly reduce the number of unsolved errors compared to traditional training methods, which may be due to overconfidence among trainees. According to [9] training must be streamlined and efficient. The goal of AR is to minimize or eliminate training needs, directly impacting maintenance operations. AR can empower maintainers with immediate task execution capabilities, as reported by multiple sources, with HMDs playing a central role. AR can also help in daily work routines in a natural manner [15].

2.4. Need for adaptive AR systems

Several studies have highlighted the increasing importance of adaptive AR systems, capable of systematically capturing user intentions during maintenance operations and gathering data related to those procedures. Challenges lie in the high fragmentation among hardware, software, and AR solutions [9]. This fragmentation results in a complex landscape for selecting and developing AR systems, leading to the pressing need for adaptability of the AR systems. AR systems should be able to systematically capture the user's intentions in performing an operation and collect the data of a maintenance procedure [9]. Adaptivity based on level of experience of the operator [16, 17]. Adaptive work instructions, specifically collaborative authoring and dynamic content based on operator's preference and performance [18]. Adaptivity to different contexts, but same content for all operators such as Microsoft 365 Guides [19]. However, a self-developed system compared to, Guides suggested that authoring with a self-developed system was easier, much faster, required less mental and physical effort [20].

2.5. AR guidance for tool change

A separate study by Röhm et al. [21] explores the implementation of an AR guidance system for tool changes in CNC machines. This study emphasizes the use of Niels and Norman usability heuristics, image targets, visual features like buttons and highlights, and auditory instructions. However, it should be noted that this system has not been validated in an industrial environment by experienced users, nor has it been compared to other guidance approaches for tool changes.

3. Iterative Design and Development Process of an AR Prototype

The chosen method was action design research (ADR), combining system prototyping with action and design oriented user and learning activities [22]. Sein et al.´s [22] method consists of four steps; 1) problem formulation; 2) building, intervention and evaluation (BIE); 3) reflection and learning; and 4) formalization of learning. *Step 1* aimed to understand the workplace complexity, and practitioners' cognitive skills, information was therefore gathered by conducting interviews and focus groups with practitioners as well as video recording of the work procedures. This study was conducted in earlier research [4], building on the Situation awareness (SA) model [23]. In *step 2* an artifact in the form of an AR prototype was designed and developed using an iterative design process (BIE) together with the industry by doing interventions, formative evaluations, and tests. The prototype creation was based on previous theory consisting of design guidelines about human perception (for types of cues). *Step 4* consisted of finalizing the usability tests by evaluating practitioners (4 operators and 3 maintenance employees) perceived workload of the AR prototype including capturing their learning experiences. *Step 4* was performed directly on the shop floor aiming to bring an innovative artifact to the organization allowing them to influence the design and gain expertise from the research team. The whole process flow is depicted in Fig. 1.

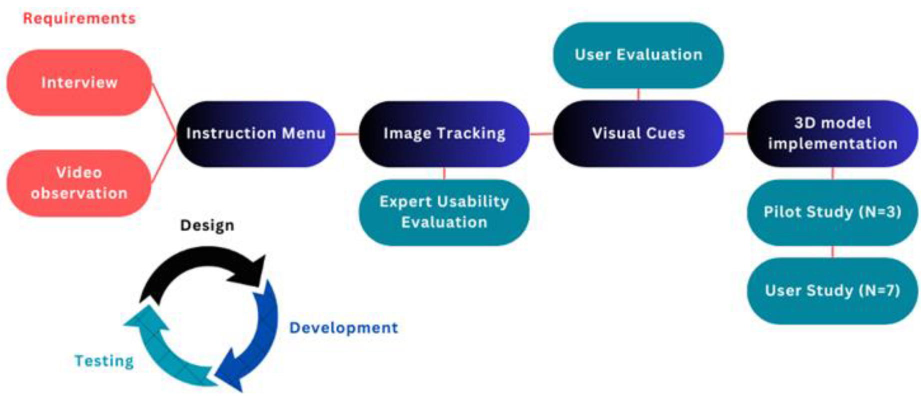

Figure 1. Iterative design process used for design and development, including three formative evaluations and one user study (green).

3.1. Work procedure of tool change

To understand the context AR tool will be used for, an interview with an experienced machine operator was held and the whole work procedure was video recorded for future reference. The tool change process begins by selecting a tool for measurement, which necessitates the use of a fixture to fit it into a measuring machine. After identifying the appropriate fixture for the specific tool, it is inserted into the measuring device, followed by placing the tool into the fixture. Subsequently, the user engages with software to operate the measuring machine and initiate the measurement process. The user's responsibility includes verifying the correct calibration of the tool. The machine automatically records the measurement data, allowing the user to remove the tool. This procedure occurs sporadically, and errors often occur due to overlooked steps or user misunderstanding of the distinct requirements for various tools.

3.2. Iterative design process

Prior to prototype development, a set of instructions was created. An interview with an experienced operator of the selected machine was held at the company's premises to create a comprehensive list of instructions and to obtain a video capturing the full process. No formal manual to operate the machinery was provided and therefore, a paper instruction set was made to serve as a basis for instructions in the AR prototype.

These instructions follow available design guidelines from related literature. The principles *what, where, how* defined by [24] aim to formalize manual assembly information and are simplified to where each action only takes place at a single location with a single action. To correctly localize instructions in the workspace and to help the system to be aware of in what instruction step the user is currently in, Image Tracking was used. After this step, an expert usability evaluation was performed by two participants to identify potential drawbacks.

In the subsequent design phase, visual cues were incorporated based on guidelines by Jeffri and Rambli [25]. These guidelines advocate for AR assistance in manual assembly, employing visual cues like highlighted part locations and overlaying 3D models to guide correct assembly location and orientation. The guidelines specify the use of exogenous cues or bottom-up processing for automatic processes, prompting users to react subconsciously to visual changes [25]. User attention to exogenous cues, like flashing or color changes, is reflexive and aims to minimize mental workload during tasks such as manual assembly. Both exogenous and endogenous cues, which require conscious user intention and mental effort, were incorporated into the prototype. Endogenous cues (Fig. 2) explicitly inform users of correctly performed actions, while exogenous cues shift attention without obstructing the view.

An experienced machine operator evaluated this prototype on the shop floor using the Think-Aloud Protocol [26], providing insights during testing. To ensure accurate virtual placement without image recognition, a 3D model of the environment was integrated. The final implementation underwent evaluation by three employees with varying AR and tool change procedure experience, followed by a user study involving seven participants. Detailed information on the final user study is available in Chapter 4.

Figure 2. AR prototype: after a user performs a step correctly, a green checkmark appears, and the system moves to the next step.

3.2.1. Software and hardware

HoloLens 2 [27] is used as the hardware platform for the AR HMD software developed. The AR application was developed in the game engine Unity and utilized Mixed Reality Toolkit (MRTK) [28] and Vuforia [29] packages in Unity as additional development tools. MRTK was utilized to convert the project settings for deployment onto HoloLens 2 and provided materials, menus, and prefab objects that are designed for AR applications. Image and object recognition is handled by Vuforia, which allows pre-configured image targets to be recognized by the HoloLens 2's camera. A HoloLens 2 emulator is used to initially test the software. An iPad Pro 11 with a Light Detection and Ranging (LIDAR) sensor was used to scan tools, fixtures, and the working environment using apps Polycam [30] and Vuforia's Area Target Creator (Fig.3).

Figure 3. AR prototype: a 3D scan of the working environment using Vuforia's Area Target Creator with instructions attached to different places of the scan.

For AR system adaptability, instructions are categorized based on the recognition status of physical elements. If the HMD recognizes a component, visual cues guide the user, and correct interactions can trigger automatic progression. If not recognized, additional imagery or text is used, requiring manual input. From the software perspective, instructions are divided into near-based (user head position) and tracking-based (physical elements). Near-based instructions offer a step-by-step menu, activated when environment tracking is unavailable. Tracking-based provides immersive guidance, automatically enabled with Vuforia Area Target tracking. A palm menu appears only when a user gestures to show their wrist in the HoloLens camera.

4. User study

A user study was conducted to evaluate usability of the AR prototype developed to assist in tool change tasks and perceived workload put on the user while using the system. This user study consisted of three steps, first each participant was testing the AR system, guided by the main author of this paper. Secondly, each participant was asked the questions in the questionnaire, guided by the second author who filled in the template. At the end each participant was asked three structured questions. In total this evaluation took 30 minutes for each participant. A total of 7 participants (4 operators, 3 maintenance technicians) evaluated the developed system. The participants had an average of 18.2 years of experience in their job role (SD = 16.2).

4.1. Task for participants

The task for the participants consisted of using AR HMD with our developed software to complete a tool change task in a production environment at the company shop floor. Two questionnaires to access perceived workload and usability of the developed system were used respectively, NASA-TLX and System usability scale (SUS). A semi-structured interview consisting of three main questions was also conducted after the test. The questions were as follows: How did you experience the instructions in HoloLens (the system) following your own routines for tool change? Do you consider the AR technology to be designed appropriately to the instructions of a tool change? If yes, how and explain. If not, please suggest an alternative working area. In what way do you prefer to receive and use instructions? Additionally, participants were video-recorded, both their first-person view from HMD and their reactions using a stative-mounted camera.

4.2. Analysis

Situation awareness (SA) model with focus on complexity [31, 32] was used as a basis for analysis of the qualitative data. SA can be understood as *"an internalized mental model of the current state of the operator's environment"* [23]. Endsley [23] notes that SA exists only in the mind of the human operator. We used SA to access whether and how the developed prototype supports SA with regards to complexity. Complexity in this context relates to the complexity an operator's experience regarding work content, layout, tools, support systems, and work instructions.

Factors that are relevant are for example, number of system components or degree of interaction with the system. In addition, the decisions made using the system will influence the operator or maintenance personnel's complexity of working with a task and increase the number of goals they experience. In connection to the situation awareness model, four codes were identified and used for the data analysis of the questionnaire and interview questions: *complexity*, *interface design*, *system capability*, and *user preference*.

5. Results

5.1. Results from the design and development process

During the pilot study, all three users had difficulty interacting with digital buttons and needed to be guided through how a button is pressed. This was due to in-depth perception and a lack of feedback. The users unfamiliar with the procedure were unable to identify the type of tool and therefore the same tool for every user was used for the final evaluation. We experienced difficulties with proceeding to the next instruction including users familiar with the procedure continuing as they remember the procedure not following the instructions; users expecting instructions to move automatically in all cases; sometimes instruction became out of the user's field of view. Additionally, the users had difficulties interacting with the physical elements while holding a physical object. Therefore, hand interaction was exchanged for eye interaction using dwell time to press a button.

5.2. Results from final evaluation

This section presents results after analyzing SUS and NASA-TLX questionnaires, compared to average scores for interactive systems from the literature [33, 34]. Responses from the interviews that were coded, resulting in four categories including: *complexity*, *interface design*, *system capability*, and *user preference* are also presented here.

5.2.1. Questionnaires

Starting out with analyzing the SUS scores for our AR prototype, it can be beneficial to translate SUS numbers to more meaningful adjectives. Using an empirically established mapping suggested in the literature [33], average SUS scores of 50.9, 71.4, 85.5, and 90.9 correspond to usability adjectives "OK", "Good", "Excellent", and "Best Imaginable" respectively. The SUS (System Usability Scale) score achieved in our evaluation was 77.9 (SD = 12.6), considered as good compared to the threshold of 68. NASA-TLX average score is 21.5 (SD = 15.6), corresponding to medium workload with mental workload subscale being somewhat high [34] as can be seen from Table 1.

Table 1. Scores for sub-scales of Nasa-TLX ranging from 0 to 100 (0 – low demand, 100 – high demand)

Mental Demand	Physical Demand	Temporal Demand	Performance	Effort	Frustration
33.6	24.3	12.9	25.0	10.7	24.3

5.2.2. Interviews

The complexity of the AR system was perceived as low or lower by five out of seven participants, two of which commented on the instructions provided as "simplified" or "little too basic". One participant evaluated the complexity of the system as medium and suggested use of different modalities to lower the complexity. One participant rated the complexity of the application as high pointing out that AR needs education and therefore prior training solely in AR would lower the complexity of the system. *Interface design* was welcomed positively by most of the participants. It was mentioned that the interface had easy steps to follow, good visuals, good form of instructions and that the system is easy to understand. One highly experienced user mentioned that having such AR support is not needed, however, the procedure is pictured exactly the way has he performs tool change. *System capability* received probably the most diverse comments. Two participants mentioned its suitability for novice users, following standard procedures. One participant reflected on its capability to replace written instructions and no need to ask other employees or colleagues for help. Another participant rated the system as "highly capable" while another participant rather felt it would be needed to perform the procedure manually first and then in HoloLens, to be able to benefit from the system. *User preference* regarding training was captured after completing the evaluation session. The majority (four out of seven) still prefer apprenticeship to fully learn how to perform tool change. When it comes to what they would prefer to use AR for except for tool change, the comments ranged from visualization, training, education, troubleshooting, or inspection.

6. Discussion

6.1. Previous work experience vs. previous experience with technology (AR).

Analyzing results revealed challenges in distinguishing whether participants' feedback on AR technology for a specific procedure is influenced more by their work experience or their general technology proficiency. Instances varied, with a 36-year-experienced maintenance technician struggling with AR acceptance, while an operator with limited work experience adapted seamlessly, possibly due to better IT skills. Despite maintenance employees' general expertise, they struggled as novices in the tool change situation, impacting AR's perception. Being a novice in a novel situation with new technology can burden working memory, reflected in increased mental workload, as noted by Endsley [23]. However, no consistent pattern emerged in perceived workload or system usability among novices in our study. It's crucial to acknowledge that these findings are influenced by the study's limited participant count. Difficulties using AR for some can also be caused by HMD being a huge technological step that the users are normally not used to. Generally, the shop floor personnel have lower technical skills [35], however they easily adapt to new technology when introduced. We could therefore expect that over a longer period, the acceptance of AR technology would increase. Many promising systems in related literature [20] recruited young participants with some degree of experience with AR for evaluation which typically does not reflect the demography and skills of a shop floor personnel.

6.2. User preference of training style

Even though most of the participants had no problem using the proposed AR systems and all of them acknowledged the benefits it can bring to the workplace and some of them even enjoyed the experience. Yet, apprenticeship is the training style that dominates among the preference of the participants. Three of the participants specifically mentioned that they would use AR as a secondary option when apprenticeship is not available. Two other participants would prefer AR mainly for training and education purposes and use other options such as paper manual in case of not remembering part of a procedure.

6.3. Design and development of an AR artifact for factory use

6.3.1. Design of virtual elements

Key lessons learned from this study regarding AR design center on optimizing user interaction. Ideal placement of interactive menu items relative to the user's view or linking them to real-world controls enhances AR system accessibility. Visual cues are crucial when virtual elements are outside the user's field of view. Clear instructions for Head-Mounted Display (HMD) interactions are vital for user familiarity. Adapting virtual elements to the user's perspective ensures consistent visibility and mitigates ergonomic limitations of HMDs [3]. Recognizing moments when hands-on tasks are prioritized informs alternative interaction methods like gaze-based or voice interaction [3]. Placing interactive elements within the field of view minimizes unnecessary movement, enhancing accessibility and user convenience[36]. Implementing these insights ensures an intuitive and user-friendly HMD interaction experience.

6.3.2. Environment features to inform design and development of AR tool

We highlight crucial considerations for effective augmented reality (AR) technology development in production environments. It is important to replicate real-world elements at suitable scales to synchronize virtual objects, facilitating a comprehensive understanding of user interactions during development and testing. Object recognition aids in assessing task progressions, and long-term functionality requires adaptability to changing environments. Evaluating ambient sound levels is essential for optimizing user experiences with sound cues and voice commands. Addressing these environmental features underscores the need for informed design and development strategies to enhance adaptability and efficacy across diverse settings in AR tools [36].

6.4. System adaptivity

System adaptivity is crucial for enhancing work procedures by improving speed, reducing frustration, and increasing operator awareness. Our AR system demonstrated adaptability by adjusting instructions based on whether the environment or its elements were tracked. Additionally, the system recognized user actions in some steps, adapting without manual confirmation. These steps align with the goal of creating context-aware systems [37]. Context-aware systems leverage surrounding context to provide task-specific information or services to users. While the ideal scenario involves directly obtaining and visualizing machine data in the HMD, this was beyond the scope of our work.

6.5. Limitations

One of the main limitations of the study was that a video recording was intended to be used as a part of the method and to be included in data analysis. However, due to technical problems with the camera we were able to record a full session only for some of the participants and therefore decided not to include this data in the analysis.

Another aspect to note is that we evaluated the proposed AR system both by operators and maintenance technicians when maintenance technicians have a limited knowledge of the tool change procedure compared to the operators which could have impacted the results. This was also the reason we did not take quantitative measures into account, such as task competition time, because the different job roles of the participants would probably cause significant differences here as well.

7. Conclusion

The study aimed to design, develop, and evaluate an AR support system for tool change, utilizing an AR HMD to ensure a standardized procedure. The system's adaptiveness and reduced user interactions were emphasized, evaluated in a real production context by 7 operators and maintenance technicians. Results indicated good system usability with a moderate cognitive workload. Participants agreed that the software serves as a training tool, eliminating the need for verbal instructions from experienced users. However, the preference for apprenticeship-style training persisted among participants.

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