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Dynamic Visualization in Project/Service Lifecycle
DYNAVIS

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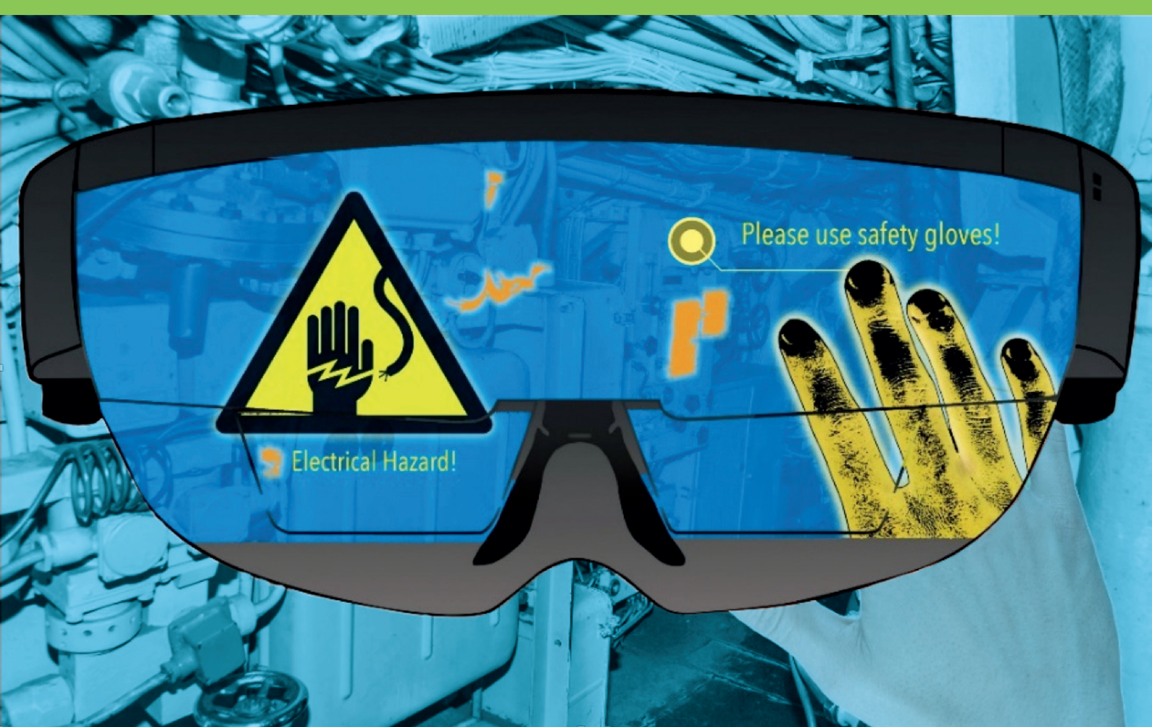

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DYNAVIS Dynamic Visualization in Project/Service Lifecycle

FINAL REPORT OF THE RESEARCH PROJECT 2016–2018

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The past few years have proven that digitalisation and Industrial Internet are transforming manufacturing, products and competition in practically all industries even deeper and faster than expected. A strong, recent phenomenon within industrial digitalisation is the growing interest in Virtual Reality (VR) and Augmented Reality (AR) technologies. These technologies will change how companies serve customers, train employees, design and create products and manage their value chains. There are already some early industry success stories on using these new technologies, but the real breakthrough is just getting started.

Applying VR/AR-technologies to complex industry products like lifting devices, elevators, or power plants is demanding. The key objective of the Dynavis project has been to accelerate the progress from research or concept phase to early field prototyping and further to mature global business practices. This acceleration objective has been reached in a most impressive way. Co-operation between the industry partners and research institutes has been intense and several of the created research pilots and prototypes have led to immediate continuation projects in the participating industry companies.

This first final report from DIMECC LIFEX program describes the pilots and prototypes, which were implemented in the public research part of the Dynavis project. I want to present warm thanks and congratulations for both Tampere University (TAUCHI) and VTT teams. Your expertise and enthusiasm made Dynavis an exceptionally successful public-private-partnership project. Project results, including this report, sure serve as stepping stones towards new national or international research activities.

I also thank companies Konecranes, KONE, Wärtsilä, SSAB, 3D Studio Blomberg and eeedo for their excellent contributions and co-operation. Similarly, I want to thank Business Finland for the partial funding of the Dynavis joint project.

Arto Peltomaa
Program Manager
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TABLE OF CONTENTS

1 INTRODUCTION

The Industrial Internet and Internet of Things (IoT) do not only mean digitization, i.e. producing data and making it available. An important part of the development is utilizing the data in different work activities. In maintenance, work, information needs are related to preparing for a maintenance visit, problem-solving, carrying out maintenance tasks and reporting. The predecessor to the DYNAVIS project, part of the DIMECC S-STEP programme (DIMECC, 2017), studied knowledge sharing solutions for mobile maintenance work and the project developed several industrial showcases of novel interaction tools and service practices.The user evaluations of the showcases showed that smooth access to situationally relevant data in situationally relevant mode and automatic or effortless reporting will increase both productivity and work satisfaction. The data needed in maintenance work can be existing documentation, measured data or information produced by peers.

In the DYNAVIS project we have focused on the challenge of visualizing data, information and knowledge dynamically, taking into account the usage situation and the user. Key issues have been how to make people aware of contextually available data and how users could contribute as knowledge sharers with contextual memos, tips and comments. These features were appreciated in the earlier S-STEP user studies but more research was needed to develop feasible concepts that service technicians would accept to their daily work. In the DYNAVIS project, the aim was to design, on a concept level, dynamic visualization for different product/service lifecycle activities related to industrial maintenance.

Many work tasks are becoming knowledge intensive as a result of the industrial internet and IoT: people are provided with access to various information and measured data. To get the actual benefit of the information and data in daily work, it should be contextually relevant and it should be provided in a contextually relevant form. Dynamic visualizations will tackle these challenges. In addition, more room will be given to users as information providers, as peer2peer information has turned out to be interesting and useful in practice, and novel interaction technologies allow smooth and effortless information collection and utilization. The overall goal of the DYNAVIS research project was to provide the most efficient means for dynamic visualizations and data collection for service technicians.

In the public research project DYNAVIS, VTT and TAUCHI together with the participating companies, developed novel dynamic visualization solutions. The aim was to develop, in parallel, new tools and new work practices in actual industry cases. The results of the project include descriptions and illustrations of dynamic visualization concepts, together with user evaluation results that reflect user acceptance of the concepts. The most promising concepts were implemented as demonstrators or prototypes for industrial pilots. The demonstrators and prototypes were evaluated with potential users.

In this final report, we first briefly describe the research project in Section 2. Then, in Section 3 we describe the dynamic visualization concepts, how we co-created the concepts and also evaluation results. In Section 4, we describe the demonstrators and prototypes implemented in the project as well as their evaluation results. We also present the results of a literature review that focused on the safety and ergonomics of AR solutions. In Section 5, we present conclusions.

2 THE PROJECT

The work in the DYNAVIS research project was carried out by VTT and (TAUCHI) Tampere University. In addition to the participating research partners, the project was funded by Business Finland, KONE, Konecranes, Wärtsilä, SSAB, 3D Studio Blomberg and eeedo. The DYNAVIS project started in September 2016 and ended in December 2018. The project was part of the DYNAVIS entity, which also included Konecranes's Business Finland funded development project. The DYNAVIS community included the two research partners, VTT and TAUCHI, and company representatives from KONE, Konecranes, Wärtsilä, SSAB, 3D studio Blomberg and eeedo. The community was coordinated by DIMECC, which also organized regular meetings for the group.

The aim of the research project was to define an overview of dynamic visualization concepts, and to make working prototypes of the most promising concepts. The project was targeted to pilot the solutions in actual industrial use as much as possible. Collaboration with the DYNAVIS community companies provided good possibilities for industrial piloting. The industrial partners also provided valuable support in choosing the most promising visualization concepts for implementation as well as in the actual design processes.

The DYNAVIS research partners are grateful for the support of the DYNAVIS community. Special thanks to KONE, Konecranes, SSAB and eeedo for the collaboration in implementing and evaluating the solutions.

3 DYNAMIC VISUALIZATION CONCEPTS

The developed visualization concepts illustrate solutions where maintenance personnel can get information of the existence of situationally relevant information and can get easy access to the information. The project produced a set of generic dynamic visualization concepts, which we present in this section. The most promising ones were implemented as demonstrators or actual prototypes in collaboration with the industrial partners, as described in Section 4.

3.1 Concept definition process

The concept definition process started with a workshop with industrial experts, where key information flows and the most relevant knowledge needs were identified. In a series of workshops with industrial experts from the participating companies, we gradually defined the overall dynamic visualization concepts. The concepts were visualized, and the visualizations were evaluated by industrial experts. The most promising concepts were implemented into industrial solutions.

The initial concepts were defined based on the results of a workshop held at KONE May 2017. Experts on maintenance, product documentation, training and R&D participated in the workshop. The participants first discussed and illustrated current operations and information flows using pre-defined personas. In the second phase, the participants ideated future information flows utilizing new technical enablers such as artificial intelligence. The results of the workshop were presented, and feedback was gathered at KONE in a results workshop in June 2017.

In the initial workshop at KONE, the following conclusions were made:

1. A lot of people and information is needed in maintenance operations – information flows are complex and there are risks of missing important information. Differences in languages, cultures, and customers also raise challenges

2. Artificial Intelligence (AI) systems can have a significant role in the future – AI systems can analyse faults and service needs, create service requests and provide people with the information needed. They can also assign personnel for maintenance tasks based on their competences.
3. Augmented Reality (AR) solutions can be used for step-by-step guidance, remote guidance and supporting safety. AR systems could also be used to monitor how the maintenance operation proceeds. The guidance could be personalized in many ways.
4. It should be possible to propose changes to the official guidance. Grounded guidance is important for motivation
5. Training could become more focused and personalized. Virtual environments and gamification could be utilized. It is also important to facilitate training on-site while working
6. Knowledge sharing and feedback from the field is a way to engage and motivate people
7. Competence databases can be maintained based on monitoring the maintenance operations and training
8. Customer experience can be improved with the solutions as well, e.g. by easy access to maintenance data but no obligation to react unless needed.

The generic concepts were created based on these results. The concepts were presented to the DYNAVIS community (the research project participants and company representatives) and feedback was gathered at a workshop in September 2017. In this workshop, the focus was on three new concepts: Digital twin, Safety precautions and Captivating training experience. Based on the feedback, VTT and TAUCHI had a workshop in October 2017, and as a result suggestions on concepts that could be implemented were made. VTT refined the concepts in November 2017 to take into account all the feedback and double-checked in order to include ideas from the initial workshop. Final concepts were illustrated and the illustrations were presented to the DYNAVIS community for feedback in a DYNAVIS meeting in January 2018. The feedback was focused on the presentation of the concepts and the details. Later on, the concepts were presented to KONE and Konecranes for acceptance before being shared within the DYNAVIS community. The final visualizations were evaluated with KONE and Konecranes company representatives in two workshops at KONE.

3.2 Dynamic life cycle visualization services

Figure 1 illustrates the resulting overall approach to dynamic visualization services of the future. At the core of the entity is an Artificial Intelligence (AI) system. That system gathers data from different sources, analyses the data and provides contextually relevant data to different situations, both internally in the company operations and to the customer. The AI system also maintains a competence database, and uses the database in allocating maintenance tasks to field personnel. The AI system initially supports the maintenance supervisor but can gradually take over the role of the task allocator.

The tools for the maintenance personnel are illustrated, as five small balloons, in Figure 1: Contextual guidance, Captivating learning experience, Visual lifecycle data, Supporting Safety and Knowledge sharing tools. In all these tools, dynamic visualization can be utilized as illustrated in the next sections, where we describe the concepts and propose visualization ideas.

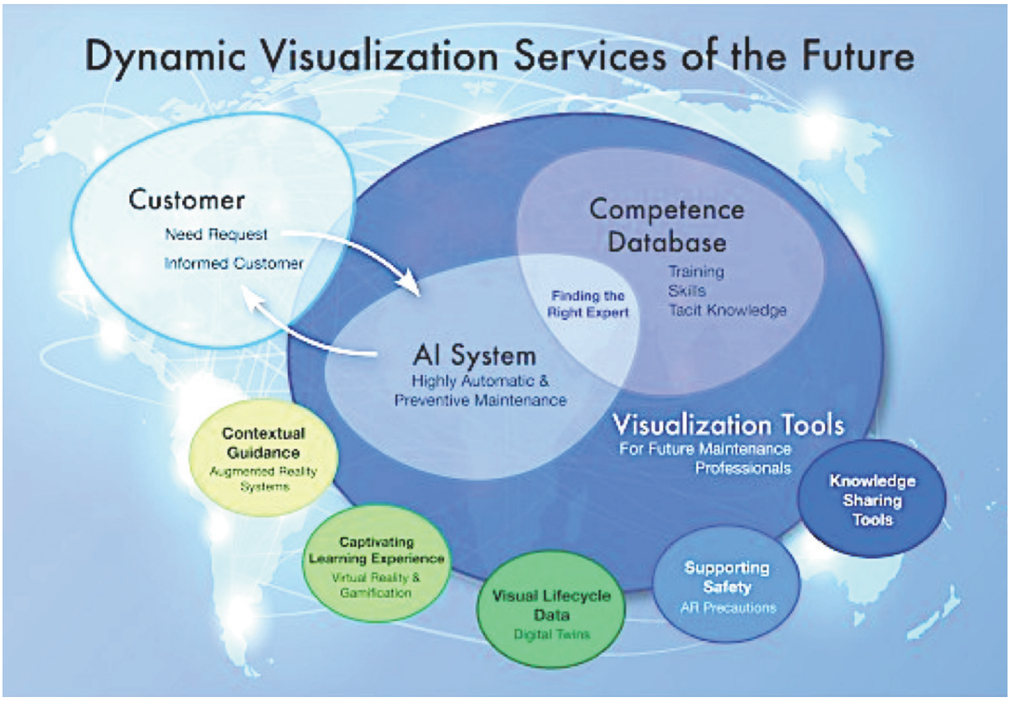


Figure 1. Dynamic visualization services entity.

3.2.1 Contextual guidance with augmented reality

Before the site visit, the technician gets a ready-made smart information package to support preparation for the visit. The information is personalized: the technician arriving on site, the device he is using, diagnostics of the environment and a log of previous visits. Spare parts are ordered automatically, by the intelligent system, to the site.

With AR glasses, the maintenance professional gets the necessary guidance during the maintenance operation (e.g. video/animation). The possibility to operate with voice commands keeps the hands free. The guidance is personalized based on competence level. Personalization utilizes analogues to the worker's previous tasks in the guidance. Additional information can be searched for with a voice-recognizing search engine. The technician can add personal notes to the material, to support similar tasks in the future.

Every now and then, the technician may need to have look at what is happening in the control room or in the cabin: this is supported by remote video views.

Stepwise animated guidance can be given based on the monitored status of the task. The technician can proceed to the next phase only after it has been identified, with the AR glasses, that the previous step has been carried out correctly. Image recognition can be utilized for this. The appropriate maintenance procedure can be monitored by checkpoints (correct operations in the right order). Alternatively, the checkpoints could be monitored by IoT data (instead of just being reported by the technician).

The guidance is grounded to train the user to understand why things have to be done in a certain way. This is also important for motivation. The information usage is logged to learn to provide better support in the future.

Contextual guidance was already studied in the predecessor project, S-STEP, and many ideas were illustrated and implemented there (Kaasinen et al., 2018). In the DYNAVIS project, an AR Workflow system was implemented in collaboration with KONE. It provides contextual AR guidance and an easy and efficient way to produce AR guidance (Section 4.1).

Figure 2. Smart personalized information package. The maintenance technician gets this information package before going to the site and (s)he can study it, e.g., while travelling to the site.

Figure 3. Personalised guidance during the maintenance operation. Stepwise guidance covers finding the maintenance site and target, fault analysis, finding a solution and reporting. Earlier similar cases familiar to the technician are used as supportive material.

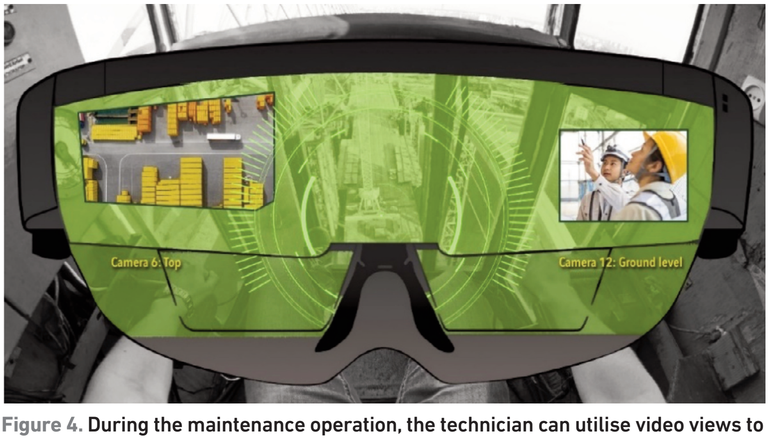


Figure 4. During the maintenance operation, the technician can utilise video views to other locations as needed.

3.2.2 Rewarding knowledge sharing

The technicians should have a possibility to give feedback to the official guidance. This can take place, e.g. by annotation, entering extra-data by speech (look and feel, automatic classification and "filing" the content). The proposed changes need to be evaluated and checked for possible risks before they can be accepted. A competence database can define the priority level of the feedback on the guidance. The moderation process prevents disseminating risky or unnecessary practices. The technicians should get feedback on their own change request: was it accepted/or not, why and how is the proposal proceeding. Changes in official guidance and other information need to be disseminated to the field, e.g. with the virtual twins.

The technician can even propose a new way to do the maintenance operation. A model procedure can be stored on video or as a set of photos. The technician needs to be qualified enough to get this option, e.g. 1-year's experience with the particular machine model in question. However, advice coming from experienced technicians is not always correct, so the amount of work experience should not be the only criteria to accept change requests.

The operators and technicians can choose to take initiative in their work, e.g. senior operators can operate more machines in one location and make the work more efficient. They can also share tacit knowledge and use their knowledge for teaching the system.

Rewards and bonuses should be received for good and accepted suggestions. Performance driven rewards can be based on how the worker has utilized the guidance or how active (s)he has been in suggesting new practices. In a novice's case, the system can detect if he has learned the operation and the new skill is included in the personal competence list. The operators can be measured according to their skills, safe and efficient work, and helping of others, and rewarded accordingly.

We did not create separate illustrations of knowledge sharing because the implementation of the AR Social Media application was already started at the beginning of the DYNAVIS project and the application illustrated the intended functionalities. However, many knowledge sharing features are included in the other visualization concepts.

The knowledge sharing theme was already studied in the preceding S-STEP project (Kaasinen et al., 2018). In DYNAVIS, the Augmented Reality Social Media (AR SoMe) was integrated into eeedo's messaging system to support knowledge sharing between maintenance technicians and the supervisors. The system was designed and implemented in collaboration with Konecranes and eeedo (Section 4.2).

3.2.3 Visual lifecycle data with Digital Twins

The maintenance professional has all the information accessible via the machine's "digital twin", i.e. instructions, diagrams and the life cycle data the machine has stored. The data is presented personalized, based on the technician's competence level, e.g. measurement data is interpreted to indicate what can be concluded of it.

In the digital twin 3D model the recent fault codes are highlighted and pointed to the referred components.

The intelligent system provides support through data available about previous troubleshooting cases on the same equipment, data about similar conditions (machine model, fault codes, etc.) as well as previous events (e.g. previously failed components, successful solutions, remarks about components, technical notes etc.).

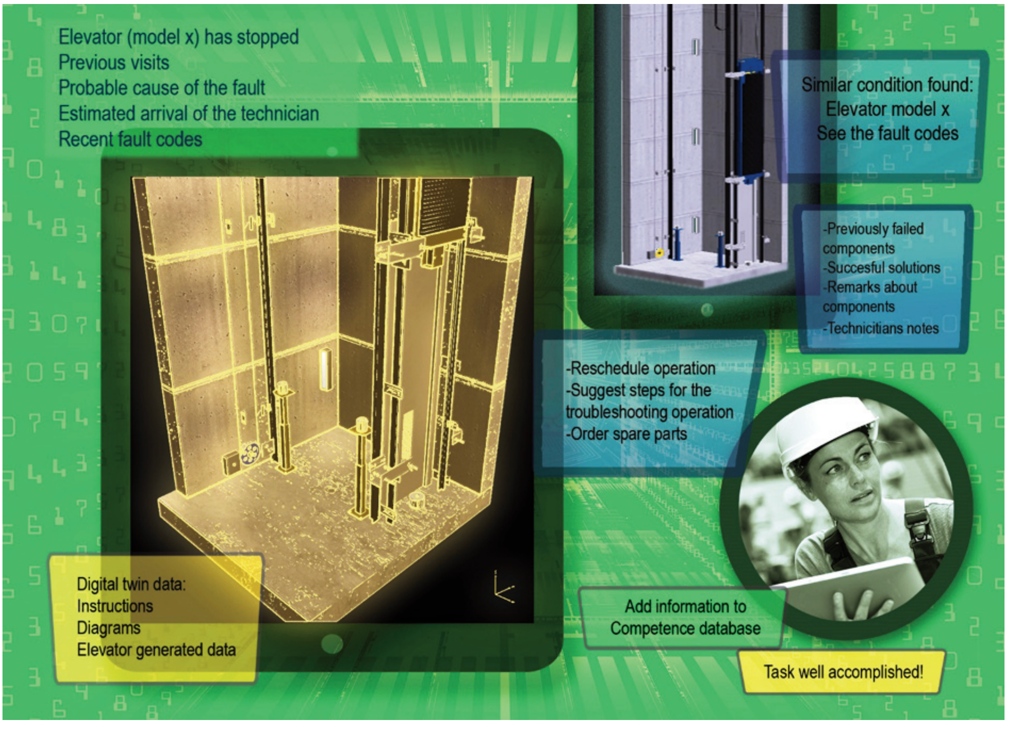


Figure 5. Digital twin as a platform for lifecycle data

Should any spare parts be required, the intelligent system will take care of ordering them to the maintenance site in advance. The system updates the customer cloud and machine info panels according to the estimated time of the replacement operation.

After the malfunction is located and fixed (or rescheduled), the operator dictates the steps of the troubleshooting operation to improve the quality of the provided data for the next occurrence of a similar case. Together with the technician, the AI system analyses the troubleshooting process to learn for future cases.

The intelligent system pre-fills the maintenance report based on context and action recognition. The technician accepts the pre-filled report and can add extra notes. The intelligent system may ask details for the maintenance report, and present positive or constructive feedback on the report and the operator's actions. The competence database is updated based on the actions carried out.

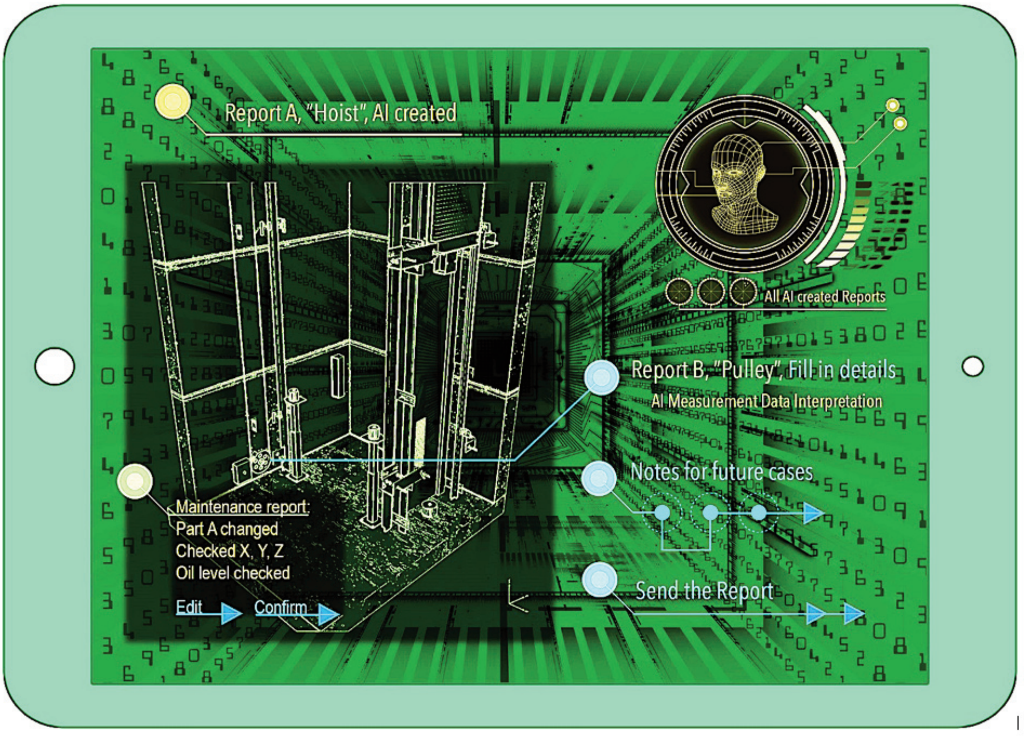


Figure 6. AI-assisted reporting with the digital twin. The AI system automatically generates a draft report to be complemented and accepted by the technician. The technician can also add notes, either for personal use or to be shared.

In DYNAVIS a demonstration of the Digital twin was implemented in collaboration with Ruukki (SSAB) (Section 4.3).

3.2.4 Supporting occupational safety with augmented reality precautions

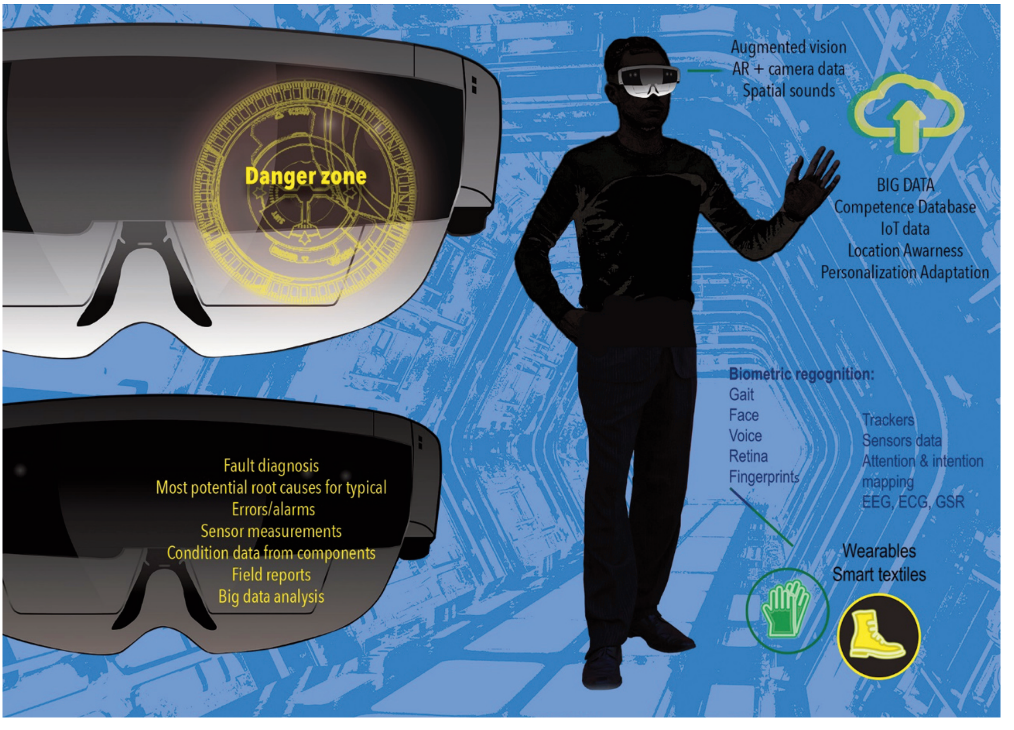


Figure 7. Supporting occupational safety.

When immersed in a fault search, the technician may not identify risks. (S)he can be supported by AR and positioning technology. Hazardous area and object visualization can be notified in the augmented view (e.g. danger of falling or electric shock). If the service technician is about to make a mistake, he is warned; e.g. you are opening a cover but the main power is still on. The position of the service technician's head and limbs can be monitored with wearable sensors to warn about moving in hazardous area. IoT data may indicate, e.g. that the machine is moving.

Risk assessment could be supported with an AR application that asks questions according to a checklist as the technician enters the site. Alternatively, the AR application could identify risks automatically (e.g. risk of getting stuck or risk of falling). Machine vision can be used to check that the technician is wearing all the appropriate safety equipment (helmet, shoes etc.).

In DYNAVIS, a demo of a safety support system was implemented in collaboration with KONE (Section 4.5).

Figure 8. Safety system checks that the technician is wearing the required safety equipment for the task at hand.

Figure 9. Examples of safety warnings during the maintenance work.

3.2.5 Captivating learning experience with virtual reality and gamification

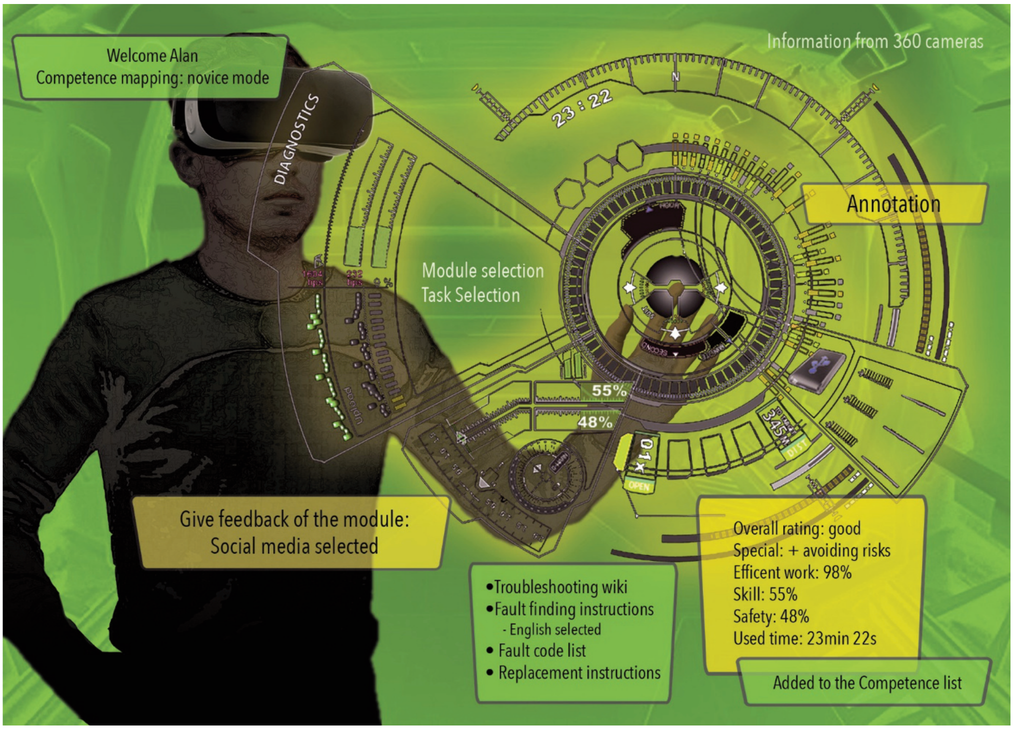


Figure 10. Captivating learning experience.

In a virtual maintenance site, the technician can learn maintenance practices in a realistic environment safely and at his own pace. The system knows if a person is a novice or more experienced and chooses training tasks accordingly, and gives constructive feedback after the tasks are completed. Gamification is utilized to give positive feedback and personalized rewards, which will increase the motivation to learn. The system utilizes the content of the knowledge sharing tools, troubleshooting wiki and competence database.

Training can be continued with on-the-job learning while working at the site (with AR solutions at the actual maintenance site). Focused training can be given just before the technician needs the skill. AR support can also be given in such a way that it supports on-the-job learning, e.g. giving grounding as to why an operation is needed. Operators can also teach the system by suggesting new ways to solve issues.

The system can detect if the technician has learned the operation and the new skill is updated in the competence database. The operators can be measured according to their skills, safe and efficient work and helping of others, and these skills can also be trained.

In the DYNAVIS project, training was studied on a concept level and no demo was implemented.

Figure 11. **Starting personalised training based on personal development plan.**

Figure 12. **Training menu.**

Figure 13. **Stepwise training task.**

Figure 14. **Rewards and sharing results with peers.**

3.3 Evaluation of the final concepts

The final visualization concepts were evaluated in two workshops with 16 participants (4 female/12 male), with an average age of 39 (range 27–55) and an average experience in industrial work of 15 years (range 4–36 years). 13 participants were from KONE and 3 from Konecranes. All participants were interested or very interested in new technologies. Figure 15 illustrates the distribution of the participants' professional expertise.

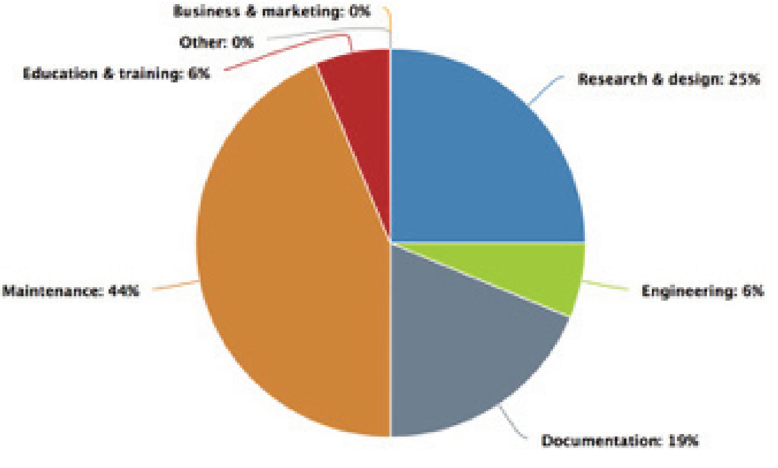


Figure 15. **The expertise area of the participants.**

In essence, the aim of the evaluation workshops was to assess the new concepts for contextual and dynamic visualization of lifecycle data and gain knowledge of the expectations related to the new visualization methods. With a questionnaire, 16 maintenance and other industrial experts (expertise area described in Figure 15) were requested to estimate on a 5-point Likert scale their general impression and usefulness of the presented concepts. Figure 16 presents the results of the general impression and Figure 17 the results of the usefulness of the four Vision concept cases.

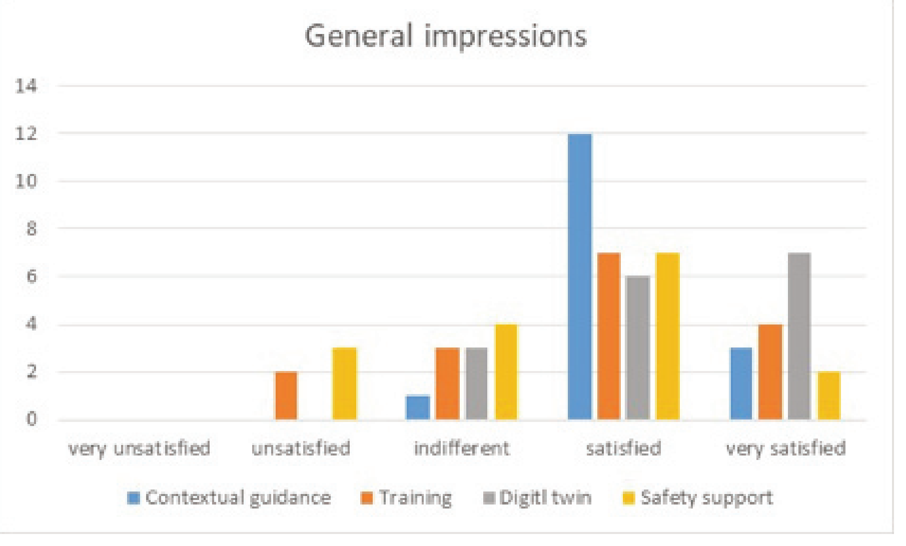


Figure 16. **General impression of the presented concepts (scale: nr of respondents).**

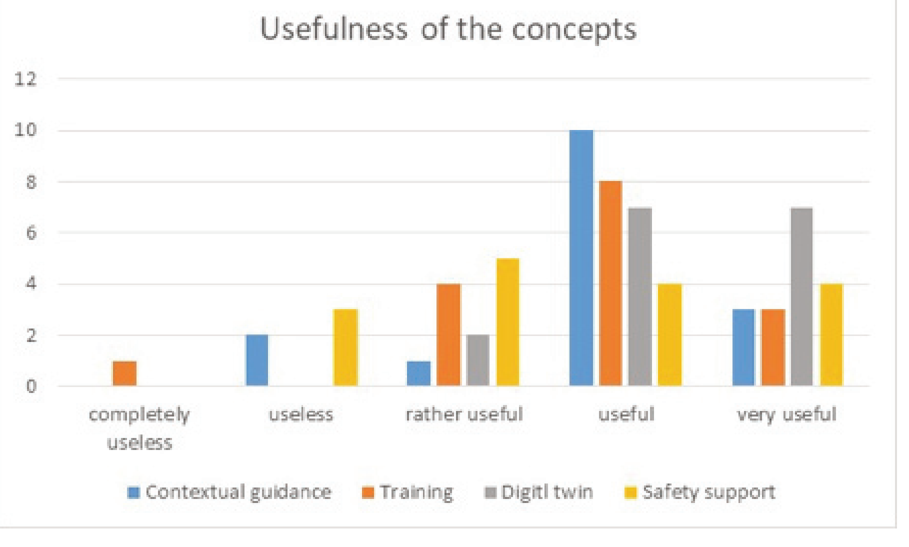


Figure 17. **Usefulness of the presented concepts (scale: nr of respondents).**

According to the results, the most appealing concept case was "Visual access to the lifecycle data with Digital Twins" and "Supporting occupational safety during maintenance operation" was considered the most useful. The results indicate that the questionnaire raters perceived the Vision concepts as more pleasing than useful. In the workshops, the participants indicated that the causes for this were, e.g. the technological maturity, problems in integrating physical and virtual environments and current maintenance operation procedures. However, when it was asked after the workshop session which was the most important case, the participants stated that case "Captivating learning experience with VR and gamification" was the most practical concept to be implemented immediately or in the short-term future. For the other cases the technology maturity expectation was in 5–10 years. In the workshops the participants emphasized that it is important to pre-consider the vision concepts and underlying data, even though the actual full implementations were far in the future.

Although the Vision Concepts utilized AR and VR glasses, in the final evaluations it was asked which devices would be preferred for accessing this type of information? The options were: mobile phone, tablet device, Augmented Reality glasses and Virtual Reality glasses. Regarding the AR and VR glasses it was clarified that the former allows one to see the surrounding environment, while in the latter case the immersion is a more comprehensive experience.

In the Vision Concepts case "Contextual guidance with augmented reality", the information was presented to the maintenance expert with AR glasses. Most participants preferred this option, but quite surprisingly the mobile phone was almost equally preferred as a visual communication channel. None of the experts rated VR glasses as an option, although in the discussion it was mentioned that it could be used while travelling on site. In case "Visual access to the lifecycle data with Digital Twins" the main preference was also the AR glasses, with the mobile phone as a secondary option. In case "Captivating learning experience with Virtual Reality and gamification aspects" there was more dispersion as mobile phone, VR and AR glasses received almost equal preferences. This was somewhat unexpected, as the Visual Concept presented clearly a VR environment. With case "Supporting occupational safety during maintenance operation" the device issue was excluded from the questionnaire, because the concept was so foundationally based on the designated AR technology.

4 IMPLEMENTED SOLUTIONS

4.1 Workflow support with augmented reality

4.1.1 System overview

The AR Workflow system supports smooth workflow by presenting step by step AR instructions to industrial workers. The generic application can be utilized for maintenance, assembly and training. The system consists of two parts, an AR Workflow Editor (Figure 18), and an AR Workflow Viewer (Figure 19). The AR Workflow Editor is a Unity based authoring application, which guides the expert user step-by-step to define all the 3D instructions required to accomplish the work task. The instructions are based on defining animation sequences of the 3D model of the equipment, shown with animated tools, coupled with audio commands, and optional video material of complex work sequences. Additional instructions indicate, for example in which direction the target object should be turned for optimal working direction. The AR Workflow Viewer application then presents the augmented instructions to the worker. A demonstration case was implemented in collaboration with KONE.

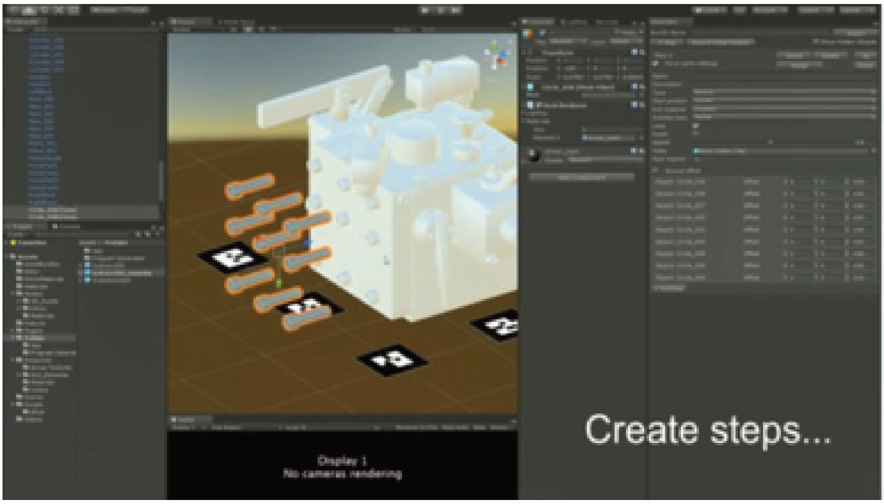


Figure 18. **The AR Workflow editor.**

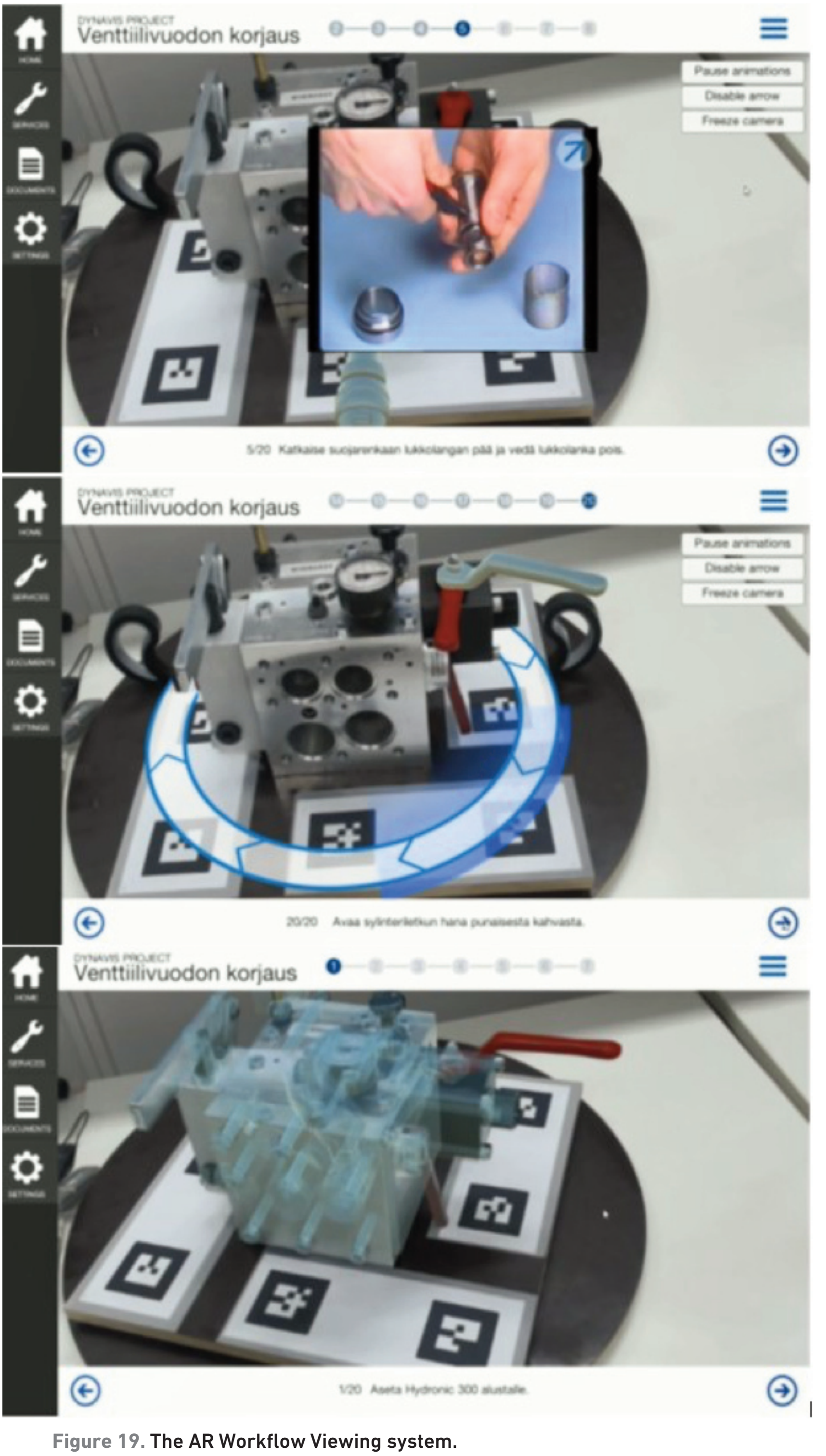


Figure 19. The AR Workflow Viewing system.

The AR Workflow demonstration was developed to support performing a maintenance operation for an elevator hydraulic control unit. The purpose was to give guidance by visualizing the maintenance steps using 3D models of the control unit and written step descriptions. The 3D information was augmented to the maintenance technician on a tablet device in front of the worker, with an external camera behind the worker matching the worker's view of the target.

The demonstration system consists of (1) the elevator hydraulic control unit equipped with visual tags to enable the AR guidance and (2) AR guidance software running on a tablet device. The tablet device (HP Elite X2 1012) utilizes Windows operating systems. The AR guidance software was created with the Unity development platform so the software can be utilized in other operating systems too. In addition, the demo system utilizes VTT's ALVAR augmented reality SDK (www.vtt.fi/multimedia) to enable AR features. The ALVAR tracker enables marker based tracking, planar image tracking and 3D point cloud tracking. In this study, tracking is based on multiple markers. The markers are placed on a rotating plate to which the control unit is attached.

The AR guidance on tablet combines the camera view and 3D model parts of the hydraulic control unit (Figure 19). The 3D objects are shown in the correct locations related to the control unit. The 3D objects are supplemented with animations that illustrate and highlight which parts, e.g. screws should be detached or assembled and in which order. The users can pause animations and freeze the camera view by using control buttons on the lower right corner, for example freeze the camera view while animation is still running. The progress of the task steps can be seen on the top of the user interface (UI). On the bottom, instructions for the task steps are visible. By using arrows on the bottom of the UI, users may proceed to the next step or go back to the previous one. The system also includes exploded images of the hydraulic control unit and a few guidance videos.

4.1.2 User evaluation

The AR Workflow was evaluated in a user study with KONE in autumn 2017. The goal was to evaluate user experience, user acceptance and safety issues. In addition, the purpose was to gain understanding of the kinds of postures users adopt when using a tablet-based AR system for instructions. Seven male participants took part in the study. The average age was 45 years (range 20–62 years). The participants were working at KONE and they had different roles related to maintenance and training.

Two of the participants had some experience of the AR systems, three participants knew the AR term and two participants did not have any previous experience of AR. Interviews, questionnaires and video recordings were used for data collection. The participants performed a maintenance task guided by the AR Workflow system. The maintenance task took around 20–30 minutes.

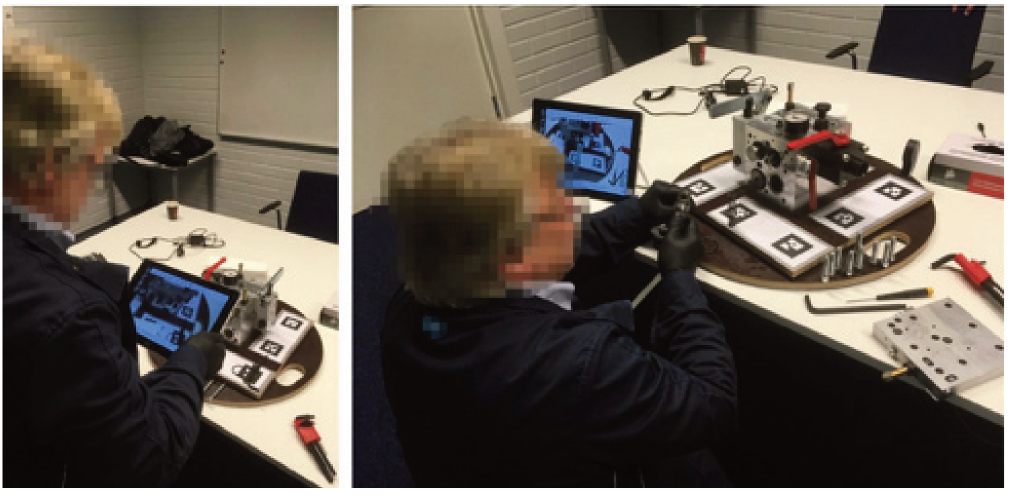


Figure 20. **User evaluation of the AR Workflow system.**

Overall, user experience of the AR system was positive. In addition, overall reaction to the system and user acceptance were good. The participants agreed that the system was easy to use and easy to learn to use. They saw that using the AR system would make their work easier, information would be easy to find and the information was seen as trustworthy.

The participants thought that the AR system was a good tool for learning. Instead of watching videos the user can do real tasks with the AR system. However, there were doubts as some details such as tightening screws or avoiding hydraulic oil leaks could be challenging to learn with the AR system. AR systems can be utilized easily in the field and, with AR, support tasks can be executed without extensive experience and skills. AR systems could help to standardize processes and ways of working. However, there were concerns related to how robust the system would be in the field. The participants did not feel that changing focus between the AR demo and the maintenance task was obtrusive. Focus was more on the task performance (because it is the primary task).

Three different tablet handling postures were recognized: holding the tablet with two hands, holding the tablet with one hand and placing the tablet on top of the table. The two hands posture was used when selecting the next steps of the guidance. Participants adopted a one hand grip when the instructions guided them to turn around the platform under the maintenance target. The tablet was put on the table when doing the actual maintenance work. In total 12 postures were evaluated. In six postures the exposure to risk of musculoskeletal disorders was small and in the other six postures the risk was at a medium level. In these cases further investigation is suggested and changes may be needed. These postures included body twisting, working with the upper arms raised and a large bend in the trunk.

The participants did not feel that there would be any safety risks when using the AR system. They said that if machines are shut down in the engine room and maintenance persons are paying attention to the instructions nothing should happen. In addition, they said that working with an AR system does not differ so much from working with paper instructions when considering safety issues. However, the use of this kind of AR system does not take away the maintenance technician's responsibility to be careful and to have situational awareness.

Overall attitudes towards the AR-system were positive: user experience was positive and the participants agreed that the system was usable. The participants said that the AR system is especially suitable for training purposes. There were no major safety or ergonomic concerns in the use of the AR system – however, it is important to be aware not to adopt poor postures or to miss safety risks in the environment when using AR systems. The participants did not feel that digital guidance would change the nature of maintenance work much. However, the quality of work could improve because everyone has the same work procedures and up-to-date instructions.

The evaluation results are described in more detail in Aromaa et al. (2018).

4.2 Contextual knowledge sharing with augmented reality

In the user studies in the predecessor project S-STEP, it was found that maintenance technicians felt that the official maintenance instructions were not always clear and detailed enough, and what was actually done in the field was often a more practical way to carry out the maintenance task. Maintenance technicians thought that most of the skills that they need in their work are not gained in training but by learning in practice in the field. The need for sharing knowledge is growing as the machines to be maintained are getting more complex and customized, and no individual maintenance technician could master everything. The contextual knowledge sharing solution aims to provide a platform where maintenance technicians can share good practices related to the maintenance targets.

4.2.1 System overview

An Augmented Reality supported knowledge sharing solution was implemented in cooperation with Konecranes and eeedo (Figure 21). The application incudes augmented notes as a novel interface to social media (Figure 22). The application enables maintenance context based social intranet communication by using AR based tags on a maintenance target. The system consists of Konecranes' mobile maintenance app, eeedo's communication platform and VTT's AR SoMe application for presenting and generating AR-based contextual notes. The knowledge sharing solution is basically a platform for collecting and sharing tacit knowledge. The knowledge sharing solution consists of two elements; a smartphone that service technicians carry and a sophisticated back-end platform that processes, archives and distributes a wide range content for on-demand retrieval in a contextual manner. The users can use a mobile platform to view and add pictures, notes and comments to the communication platform (Figure 23). The AR SoMe application is integrated into the communication platform and it can be launched when needed. Comments and pictures on the AR application are sent to the communication platform. The AR SoMe application is made with Unity and it runs on Android or iOS devices. Similar to AR Workflow solution presented in Section 4.1, AR SoMe is based on VTT's ALVAR augmented reality SDK (www.vtt.fi/multimedia).

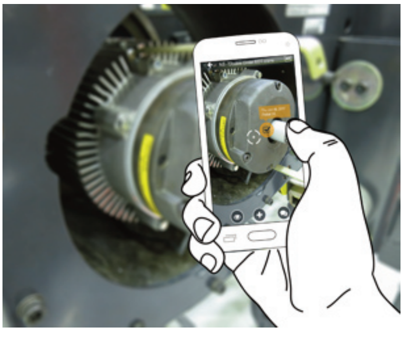


Figure 21. Visualisation of AR SoMe application in use.

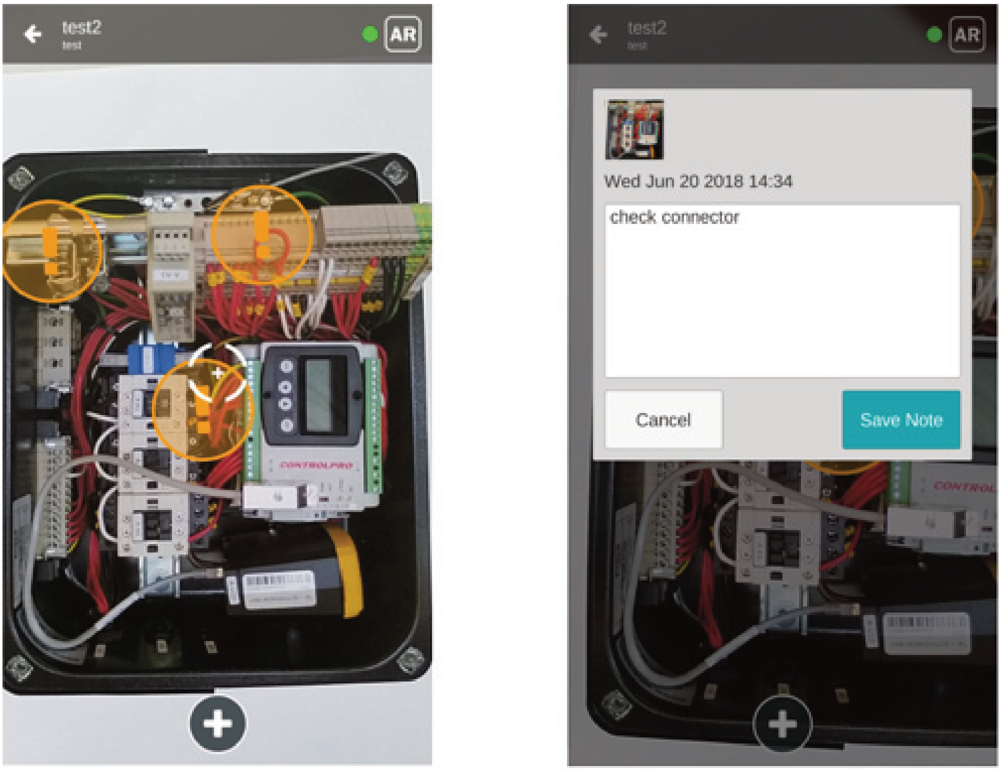


Figure 22. The maintenance personnel can view virtual notes (orange exclamation marks) with the AR some mobile application and add new tags and notes.

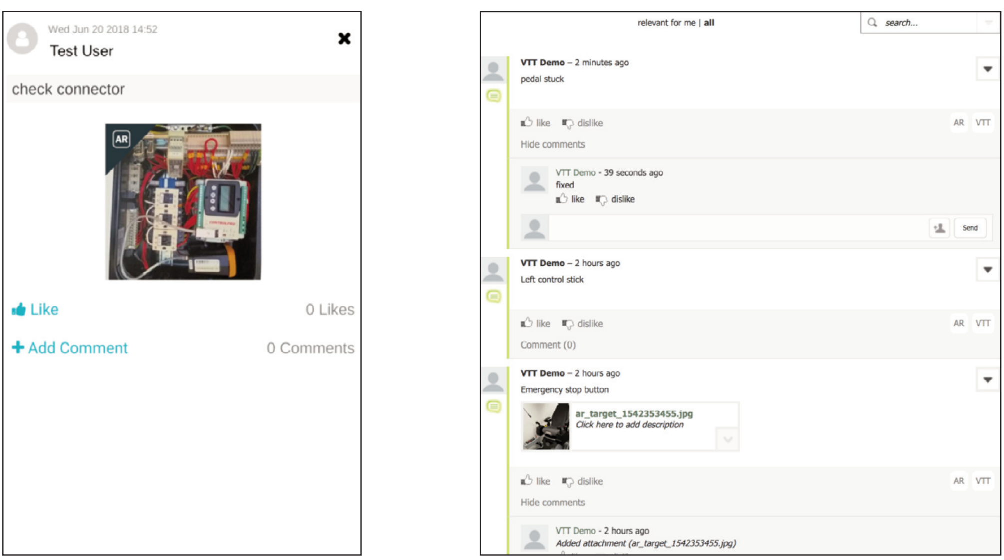


Figure 23. The AR SoMe mobile application content (on the left) is integrated into eeedo's web-based communication platform (on the right).

The idea is that on the communication platform, maintenance personnel can check the conversations and other information related to the maintenance target in question. With the AR SoMe application, maintenance technicians can attach virtual notes to objects in the real world and post comments and likes. On site they can check AR tags and notes on the devices and can add new tags and notes. At the office they can see the AR-based contextual discussions integrated into the other communication platform discussions. The maintenance technician can check AR SoMe discussions related to the maintenance target before the maintenance visit. The knowledge sharing solution enables smooth social media type connection from the office to the field.

The AR-based knowledge sharing solution helps make tacit knowledge visible and encourages operators and maintenance personnel to share knowledge. The solution connects knowledge to physical objects and supports maintaining the machine's individual usage and maintenance history by also storing unofficial communication. The discussions in the AR SoMe can complement and give valuable feedback to the official maintenance documentation. AR SoMe can also be extended to be used as an informal channel to share knowledge with the machine provider.

4.2.2 User evaluation

The developed AR SoMe application was integrated into the overall knowledge sharing solution and the entity was evaluated together with maintenance experts at Konecranes. Two evaluation workshop sessions were held. The sessions were conducted by two human factors researchers from VTT. The first session was at the Konecranes maintenance personnel office in Tampere on 14th June 2018 and the second session was in Hyvinkää on 18th June 2018. Overall five maintenance technicians and two head of maintenance professionals participated the sessions. They all were male and their age range was 26–50 years. Data was collected with observation, questionnaires and interviews. Each workshop took approximately one hour and the workshops included the following phases: 1) introduction to the DYNAVIS project and the AR SoMe application, 2) signing the consent form, 3) filling in the background information questionnaire, 4) introduction to the demo system use, 5) using the demo system oneself, adding and viewing AR notes as well as commenting on notes, 6) filling in the user experience questionnaire, and 7) interviews.

The results of the workshops indicated that information in the AR SoMe application is easily available. Visual information is useful and the system was easy to use. The participants emphasized that smart phones are essential tools nowadays and advanced applications help in their work tasks. It was also mentioned that applications like AR SoMe is something that the participants have been waiting for. It was seen as very useful to be able to add and place notes to views and images. The online communication platform could improve documentation and augmented reality notes were seen as better than traditional paper notes. Maintenance technicians may use paper in some cases, but the notes can drop or they are not noticed and the note content is not added to the company information systems. The system can also give instructional information before maintenance visits. This is a useful feature, especially if the technician is not familiar with the site and its specific maintenance tasks.

Some doubts and development ideas were also presented during the workshops and conversations. The participants suggested that it would be very advantageous if the AR system could automatically recognize the maintenance target and service requests, this would reduce the need to check the work task lists. Integration with the device and component data information, manuals, services requests and spare part information would also be useful. Questions related to different communication levels and approaches were discussed, e.g. realising discussions with co-workers, are there needs for different interest groups, how to contact company service support, and could there be discussions with customers, and/or how to send information to them. It was stated that content management and moderation could be challenging. There could be lot of notes and hence a need for a clear procedure of how to prevent irrelevant information and how to avoid possible information overflow. It was also mentioned that it might be forbidden to take photos at the customer sites.

To conclude, the results support the idea of integrating a virtual notes and communication platform with maintenance activities. The overall attitude towards the AR SoMe application was very positive. Illustrative information is very useful in maintenance work and the AR SoMe application helps to create and share maintenance site specific visual information.

4.3 Digital Twin Browser

Ruukki's near zero energy building (nZEB) in Hämeenlinna was the target when a concrete visual browser for a digital twin of a building was constructed.

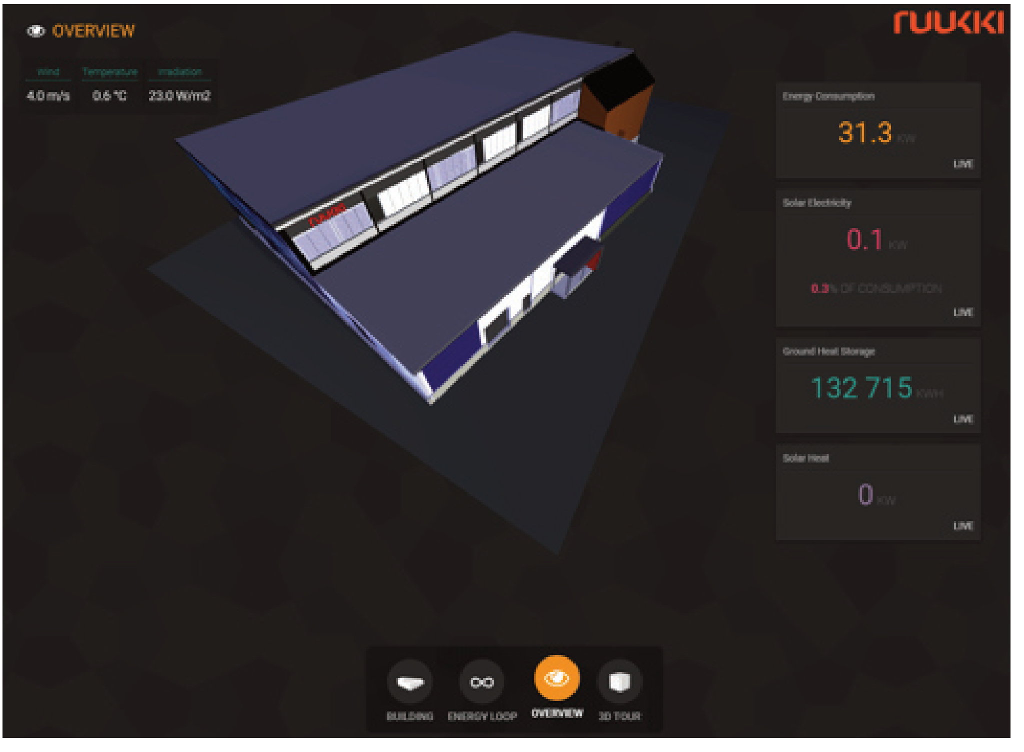


Figure 24. The Digital Twin Browser overview of the nZEB.

The visualization of the nZEB (Figure 24) is a concrete implementation of a digital twin browser. It is a visual presentation of the physical entity, the building. The visualization includes 3D models and hand-optimized 2D visualizations. The practical visualization was built on top of a generic platform for visual digital twin browsers developed in DYNAVIS and VAPRU projects.

Digital twin is a digital replica of physical assets. The concept was introduced in air and space industries where the first examples were constructed. Different kinds of digital twins have been built over the years, some focus more on modeling the target asset, e.g., to optimize predictive maintenance, while others mainly communicate information for people. The developed browser is of the second kind, focusing on efficient communication of information. Development of IoT makes digital twin viable in many fields as almost all technical systems are now capable of communicating data about the working to Internet connected services.

A Digital Twin can consist of

- Design information, e.g., CAD models *(how it was designed)*
- Live data from the real life *(how it is)*
- Simulations, based on the design and data, e.g., for predictive maintenance *(how it will be)*

The developed browser mostly focuses on the first two items. Simulations have also been part of the process but none are included in the final nZEB browser.

The user can navigate between main views of the visualization. Inside the 3D view there is an own navigation hierarchy. Navigation on main level in the application triggers changes in the 3D navigation hierarchy. The 3D material is based on various CAD data and some live data controls it, including real-time position of the sun and status of some doors (open/closed). Various elements in the visualization link to external elements which are opened as iframes on top of the visualization.

The visualization is a single page web application. The browser was built using React framework and ThreeJS library. To use the browser, a modern web browser is needed; the main platform during the development was Google Chrome. A generic web server can be used to serve the application and a separate server provides the data API. These are independent of the browser.

While a lot of different kinds of data is readily available to create such browsers for different needs, many steps still require significant labour. Geotagging is needed in the future to help position and orient different 3D and 2D models correctly in relation to each other. This is particularly important for buildings and other built environment related data. For example, to simulate sun direction requires correct geolocation and orientation. In many cases, positions, rotations, and even the scales of 3D models need to be hand-adjusted as different design systems export models differently in these respects. The models are sometimes also too complex for real-time visualization so simplification is needed at some point.

Data interfaces are increasingly available, but their implementations vary greatly. This not only means that developers often need to implement custom data interfaces but often they also need to figure out ways to make data accessible in secure manner. Furthermore, some of the interfaces provide data at very slow update speed, e.g., once per hour. This rules out many of the usage scenarios. Units and identity of the data and other such metadata should also be delivered with the data, whenever possible. This helps ensuring data quality. Geo-location should be attached also to the metadata of IoT data when possible.

The development has given understanding of the possibilities of such digital twin browsers. The visualization is available in the Ruukki nZEB and it has been efficient in communicating the design of the building to visitors. Other potential users include people using and maintaining the building. As data formats and interfaces mature, providing such digital twins with buildings will likely be commonplace. To investigate the user experiences of the visualization and potential utilization areas for such digital twin browsers, we will collect feedback from the Ruukki nZEB visitors with an online questionnaire linked to the current browser.

4.4 Speech reporting interface

Speech recognition technology has matured to the state where speech-based reporting can be used in industrial maintenance, and a well-designed reporting solution integrated into relevant information systems can improve both the quality and quantity of reporting. Speech reporting interface is a prototype system for evaluating a concept in which a maintenance expert creates a back report of a maintenance call via speech input on-site. It has been implemented as an Android application and allows a technician to dictate parts of reports at different phases of a maintenance visit. The system parses relevant concepts from recognized free-form speech input, generating tags representing report items such as reason, status, action, and component codes which are displayed to the user for review. The application's interface is partly structured and designed according to the KONE back-reporting model to support the work flow of the maintenance expert and to ensure gathering of relevant report data.

4.4.1 Workshop

A workshop with KONE was held in an early phase of the project. Eight specialists from KONE, mostly maintenance developers, attended the workshop. TAUCHI presented speech recognition technology and some related applications utilizing speech interaction developed earlier. Attendees then worked in groups discussing the potential contexts in which speech interaction could be utilized. The workshop resulted in ideas and concepts, of which some were chosen as a base for the speech reporting prototype system (e.g., constructing reports from fragments reported by speech), while others may be implemented later (e.g., speech output to get information about the maintenance call while driving to the site). The workshop was beneficial for our work as it reinforced our initial plans and also produced some new ideas.

4.4.2 System overview

The speech reporting interface consists of an Android application and a remote Python http-server. The server listens for requests with a free-form speech recognition result (a sentence) and returns matching concept information, and the application visualizes the raw speech recognition results while the user is speaking and the found concepts when they have been identified. The application utilizes Google's English-language Android speech recognition and has push-to-talk activation for speech input.

The back-reporting model consists of obligatory and optional entries. In the application's GUI, the obligatory entries are displayed with red placeholders (Screenshots A and B in Figure 25) to ensure that the information is entered, while the optional entries appear as they are recognized (Screenshots B and C in Figure 25). Filled entries appear on a green background. To further support the workflow of a maintenance visit, the interaction is split into three phases:

- *Condition on Arrival* – the obligatory information about the elevator's state when arriving to the site is collected.
- *Issues and reports* – obligatory call reason and optional component–action entries.
- *Condition on leaving* – the obligatory information about elevator's state when leaving the site, including possible reason for elevator not running and the next action.

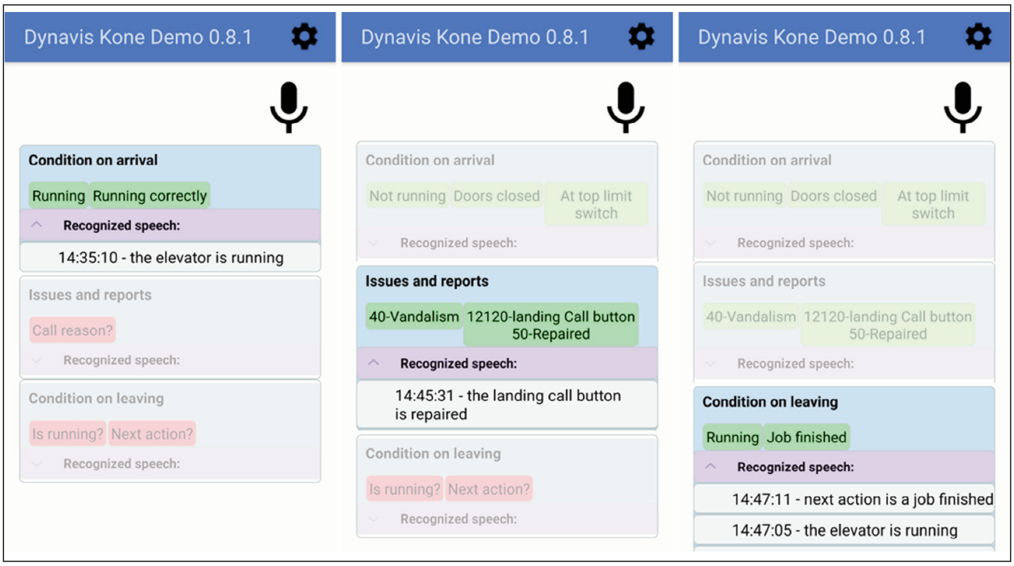


Figure 25. Screenshots of the Speech reporting interface.

For the concept detection from the recognized speech, available concepts are read from content material which is provided in CSV or JSON format. The material is parsed on the server to a VXML-grammar format by a separate grammar parser. The VXML grammars contain the words or phrases for identifying parts of the concepts with a selection of connecting words. Each concept in the grammar contains VXML-tag information, e.g., the concept *'elevator running'* contains a tag *"target=elevatorRunning"* and the concept with component *'landing call button'* and action *'repaired'* contains tags *"actionCode=50, targetComponent=landing call button, componentCode=12120, targetAction=repaired"*. Sentences producing the aforementioned tags would be, e.g., *"the elevator is running", "elevator was running normally"*, or *"the landing call button was repaired".* The server tries to match the incoming speech recognition results with each of the available concepts (>12 500 in the final version, each with multiple different sentence structures and synonyms), extracting and returning the tag information from matches. The matching algorithm can handle varying word orders and synonyms and is able to find multiple concepts from a single sentence enabling users to enter report entries with natural language, as long as the used vocabulary is included in the content material.

4.4.3 User evaluation

The prototype system was first evaluated within TAUCHI by human-technology interaction experts. Next, a separate evaluation measuring the speech recognizer performance was conducted, and finally KONE ran an evaluation with maintenance experts.

Expert usability evaluation

In the expert evaluation, six researchers (5 male, 1 female) from the field of human-technology interaction evaluated the system from usability point of view. Before using the system, participants were given a form describing an example scenario and two evaluation scenarios of maintenance visits. For the evaluation scenarios, the participants wrote their own speech-input sentences they would use to report the described maintenance cases. Next, the participants used the application to report the evaluation scenarios with the sentences they came up with and evaluated the application as proceeded. They wrote their feedback in free form and scored the application's readiness for deployment for real users, i.e., elevator maintenance personnel, on a scale from 1 to 10.

The expert evaluators scored the readiness for deployment as a median of 4. In the feedback, there was criticism on the GUI design, such as need to add scrolling and enlargement of tapping areas. These were addressed in the next version of the application. Another criticized aspect was the accuracy of the speech recognizer, so a separate evaluation to test the recognizer was conducted next.

Speech recognizer evaluation

In this evaluation, 22 participants (15 male, 7 female) recorded a total of 209 sentences to verify the accuracy of the utilized speech recognizer with a separate test application. The speech recognizer and its activation method (push-to-talk) were identical to the Speech reporting application. A sentence randomly picked from the sentences generated by the expert evaluators in the previous evaluation was shown to the user, who then spoke the sentence aloud to the recognizer. Each user was assigned with five sentences, and the recognized sentences were not shown to the user.

Table 1 presents the measured sentence, word, and concept error rates. Deeper examination of the recognition results showed that a few domain-specific words, such as *"kone"* and *"door sill"*, were regularly misrecognized even when spoken by native speakers. For the non-native speakers, there were critical recognition errors such as *"not"* → *"now".* For the native speakers, typical errors were not critical, e.g., *"it is"*→ "its".

Table 1. **Speech recognizer evaluation results.**

	Sentence error rate (SER)	Word error rate (WER)	Concept error rate (CER)
All participants	70%	16%	23%
Native speakers	67%	18%	6%

Based on the data gathered from the speech recognizer evaluation, the models used to parse concepts from the recognition results were optimized further, and frequently appearing "magnetic words" (words getting recognized erroneously instead of the intended words) were added to the model.

KONE evaluation

Six male participants, aged 47 on average, tried the system in an office environment. Four of the participants had experience of maintenance work (17 years on average) and three were native English speakers. In the evaluation, the framework and the application were first introduced to the participants with a summarization of the back-reporting procedure. Next, the facilitator briefly demonstrated the functionality of the application, after which the participants tried the application by first entering anything they came up with, and then by entering a predefined or their own maintenance scenario. After the trials, the participants filled in a questionnaire with 12 statements rated on scale from 1 (Totally disagree) to 5 (Totally agree). The statements and the median results are presented in Figure 26.

Overall, the results are mainly on the positive side. Non-surprisingly, native English speakers rated the statement "The system understood my speech correctly" slightly higher (Mdn=4) than others (Mdn=3). Only two participants rated the first statement, *"It was clear to me what to say to the system"*, lower than 4. One of the most relevant statements, *"Speech input would make maintenance work more efficient"*, was nicely somewhat agreed (rating 4) by all six participants. Considering the other statements, the ratings were quite uniform the deviation between the extreme individual ratings being only one or two.

In the free-form feedback there were a few important notes such as *"Background noise might prevent speech reporting in noisy machine rooms" and "hands-free operation would be useful"*. In addition, it was desired that the found tags should be editable via the application's GUI and via speech input.

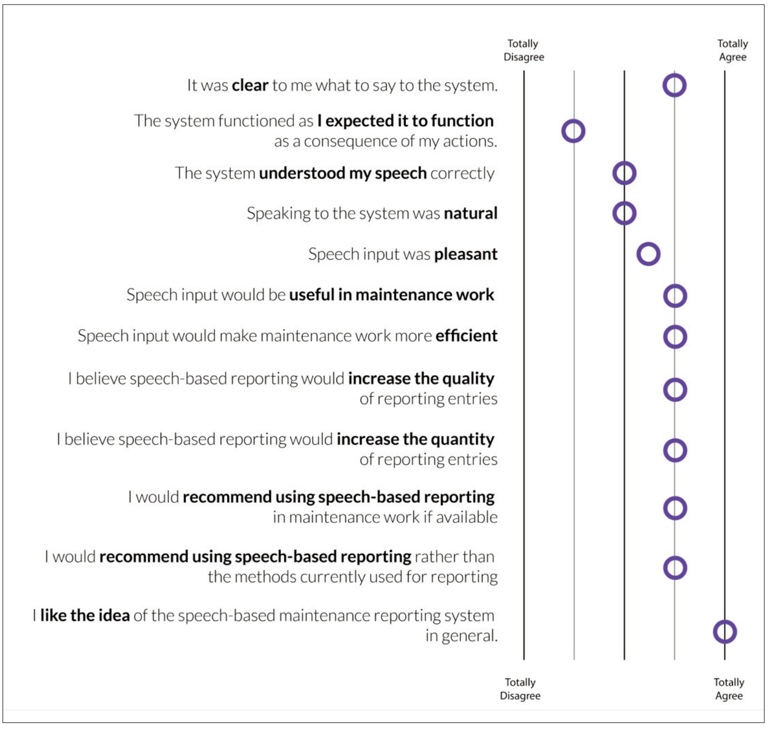


Figure 26. The user experience statements and the median results (n=6) considering the application and speech reporting in general.

4.4.4 Conclusions

The prototype system was developed in an iterative process, where decisions were made based on the feedback, technical challenges, events such as the early-phase workshop with KONE, and the evaluations. During the iterations we found some important challenges which need to be further considered and solved:

- Implementation of hands-free operation mode utilizing dialogue and speech output from the system can improve the utility of the system
- Further testing of a headset which provides decent audio for the speech recognizer in noisy environments is needed.
- Testing of optimal speech recognition activation in hands-free use, e.g., Voice Activity Detection and/or “magic word” activation, should be done.
- One should choose a speech recognizer which:
  - enables utilization of industry specific language models
  - enables long silence timeout

- Implementation of concept, vocabulary, and grammar learning can make deployment of such services efficient.

The maintenance experts showed interest towards the speech reporting concept and prototype and they think that speech input would make maintenance work more efficient. The evaluation results hint that an advanced version could be able to improve the quality and amount of content of maintenance call reports while simplifying the maintenance technicians' reporting task.

On more generic level, the prototype and its evaluations indicate that speech-based reporting is a viable option using today's technology. To create successful speech-based reporting system, various aspects need to be considered. Such systems must support the structure of the work. This means the design must heavily involve the end users. The reporting practices of the organization where it will be utilized must be supported as well. As speech technology is based on models of the language (dictionary, grammar), domain concepts must be included in these models. The systems should also support the language people use in daily life. Again, collaboration with the end users is required early on. With these considerations, functional reporting systems for industry can be created. As the attitudes toward speech-based reporting are on the positive side and both workers and organizations are ready to utilize it, there seem to great potential. With good reporting systems the quality of the reports can be improved as the reports can be generated immediately on site, not afterwards based on random notes and memory. As the reports can also be available sooner, benefits for the organizations can be significant.

4.5 Supporting safety and learning experiences with Mixed Reality (xR)

The xR SafetyKit system demonstrates how augmented reality (AR) and virtual reality (VR) technologies can be applied to the elevator maintenance working processes to ensure safety in the hazard environment of an elevator shaft.

4.5.1 System overview

The system is implemented in VR utilizing the 3D model of an elevator shaft with all relevant technical equipment and tools (see Figure 27). The system simulates the AR glasses field of view (FoV), thus, overlaying the glasses' content over a rectangular area centred to the user's eye position. A virtual environment (VE) allows to test different AR solutions in a safe and controlled environment before actually implementing them, but moreover, the same VE can be utilized for maintenance and safety documentation development and testing.

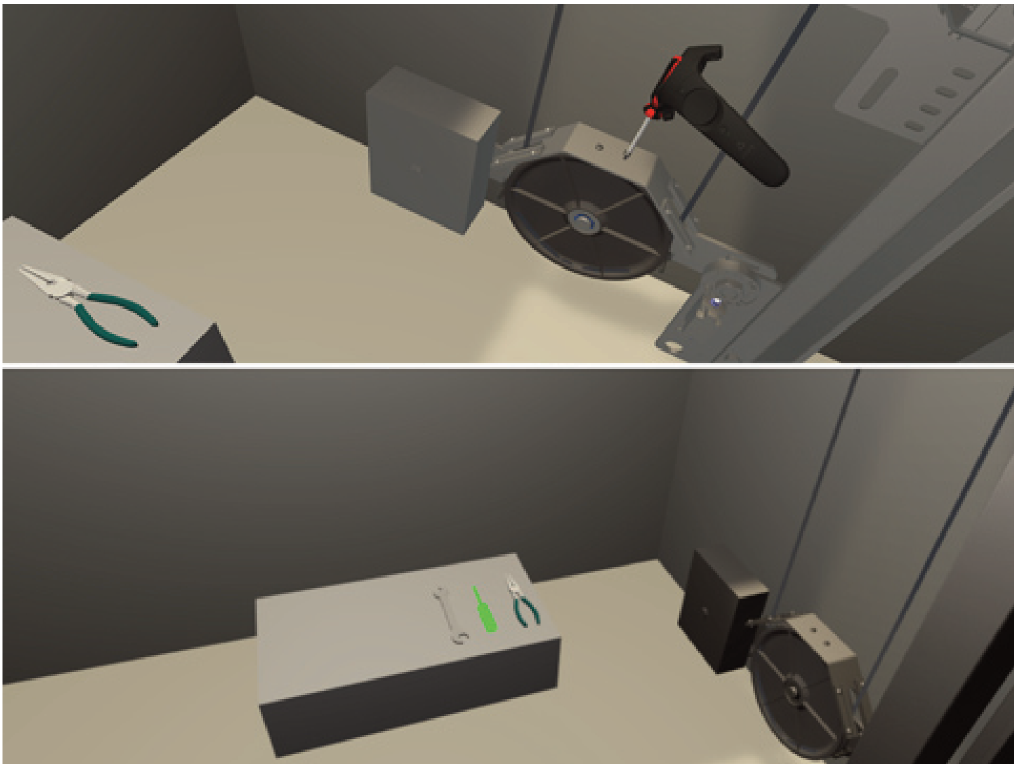


Figure 27. Views from the system with elevator components, tools, and highlights.

Users of the system are supposed to perform the *Remove and Replace Tension Weight* maintenance task in VR the same way they would do it in real-world settings. However, the user is able to teleport in the virtual environment due to physical space constraints of VR setups. Prior to the maintenance tasks, the user is required to go through a training session, designed to help the user to get used to the environment, learn the functionality of the application and the use of controllers.

The VE and AR simulation were constructed using the Unity game engine. We additionally used Virtual Reality Toolkit (VRTK) for some user interactions. Our AR simulation has a horizontal FoV of 40° and a vertical FoV of 27.5° (roughly equivalent to the Magic Leap One headset). The edges of the AR field of view are feathered (Figure 28) in order to avoid visual discomfort. A similar effect can be observed on some existing AR headsets (e.g., Meta 2). As a result, the usable FoV is slightly less than 40°x27.5° (feathering distance 12% horizontal, 3% vertical). Other optical distortions that may be caused by AR glasses were not simulated.

The AR functionality of the application is designed to support safety on two levels: by providing **step-by-step guidance** for the maintenance task and by **informing about potential hazards** in the environment or risks related to the task itself.

The system guides the user by displaying step-by-step instructions in a form of text or pictures on the **Documentation Panel**, a tool that may be freely moved in the 3D space and centred to eye-position when needed (see Figure 28). Thus, the user can place the Documentation Panel to any comfortable place and check the instructions when necessary with a glance. To increase the efficiency of guidance, the system highlights the tools and details that are required to be used during the task (Figure 27, bottom).

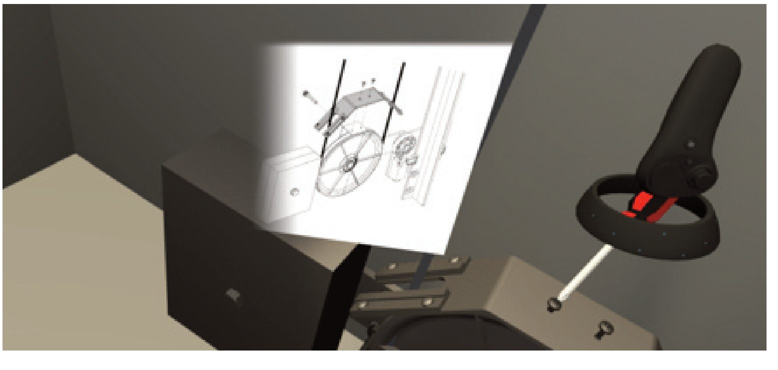
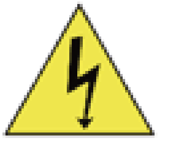


Figure 28. The documentation panel can be moved and placed freely within the 3D space.

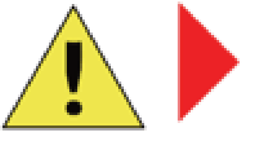
Safety warnings appear in the AR glasses' field of view when the user approaches risky areas either with hands or body, or when the task step involves certain risks. Warnings are categorized as follows:

- *Textual Safety Notification* – is used to inform the user about risks related to the maintenance tasks, e.g., heavy equipment parts. It uses text and picture to explain the risk and augments over the heavy object during the task until the technician proceeds to the next task.

- *Animated Safety Warning* – appears when the user's hand interferes with a risky area and uses an animated picture to explain the risk of an electric shock hazard and a beep signal to raise awareness about the danger. The animation stays visible for 1 second in the risky area after the user has moved their hand away. In case the risky area is out of the AR glasses' FoV, the system informs about the danger with a beep signal and a red arrow pointing at the direction of risk.



- *Audio and Visual Safety Warning* – is used when picture alone is not enough to communicate the risk. Hence, this type of warning uses an image to notify about the danger and voice to explain it. In case the risky area is out of the AR glasses' FoV, the system informs about the danger with a voice output *("Careful, you may hit your head!")* and a red arrow pointing at the direction of risk.



4.5.2 User evaluation

The designed system is suitable not only for testing AR functionality but also for training novice maintenance technicians and new working processes, as well as maintenance and safety documentation development and testing. Three development-user test iterations, i.e., iteration rounds, with KONE experts were conducted. The focus of the testing was on aspects of AR, the usability and efficiency of guidance and safety functionality, and the virtual environment as a platform to connect different departments and synchronize their working processes.

For the user tests, we used an HTC Vive HMD modified with integrated 120 Hz gaze tracking. We logged user data such as gaze, object positions and task progress, and implemented playback for the log data with gaze visualizations (vector and heatmap), using the same virtual environment as in the user tests. To indicate and allow progress in the maintenance task, the virtual objects detect collisions with tools, animate, and play sounds at appropriate moments. Some issues were identified with the positioning and sizing of physics colliders attached to the virtual objects, which caused some key events to be hard to activate. These issues were fixed in the second iteration round.

During the first iteration round, we conducted a pilot study with 4 KONE experts, who explored the prototype freely and participated in a co-design process. The application at that stage included a virtual elevator shaft environment with technical equipment and the Documentation Panel with instructions. Participants shared their visions of the system and suggested features for further implementation.

In the second iteration round, the prototype was enhanced with a task procedure, required tools for the tasks, and one safety warning as a static picture of an electric shock hazard. The warning appeared when the user's hand interfered with a risky area and disappeared when the hand was no longer in danger. The methods used in the study were a scenario for the maintenance task, online questionnaire, and structured interview. The most valuable questionnaire results from the second and third iteration round are presented in Figure 29.

In the second iteration round evaluation, we had 5 participants. They were very receptive of using AR in the field and VR for training and testing purposes; moreover, they were really convinced that this is the future of maintenance work. Documentation Panel was found to be a suitable and efficient approach to visualize work-related instructions in AR. In particular, participants appreciated the idea of using documentation which was "hands-free". Augmented warnings were found to be a useful safety approach to avoid risks in the context of elevator maintenance. However, we found that the safety warnings should be further subdivided into categories and visualized in a different manner, which set the goal for the next iteration round.

At the final stage, i.e., the third iteration round, the task flow was enhanced by highlighting the tools and adding the animations. Additionally, three types of multimodal safety warnings were designed with the goal to understand what modalities are beneficial in such a context. For this reason, we used an additional questionnaire for each warning type, and added a few questions on the safety aspect also to both the online questionnaire and structured interview. In the third and final iteration round evaluation, we had 4 participants.

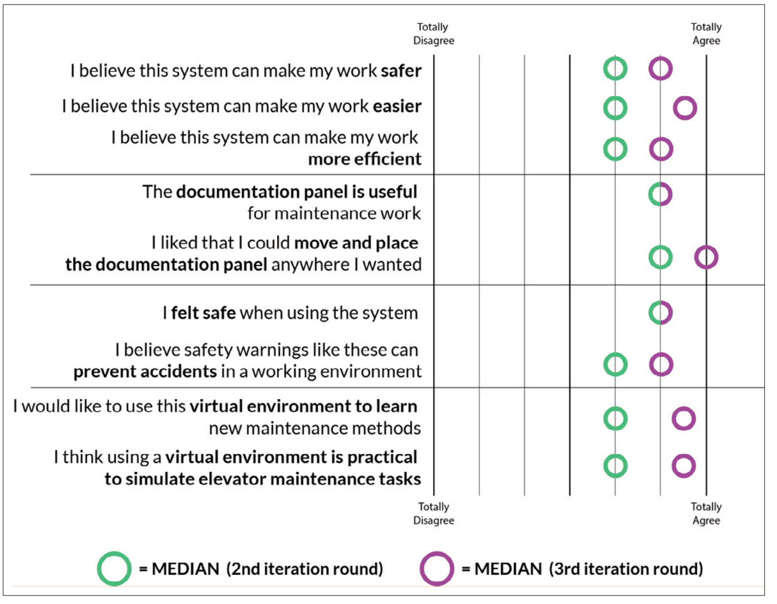


Figure 29. Questionnaire results from the second (n=5) and third (n=4) iteration round evaluations.

4.5.3 Conclusions

Based on our user evaluation results, we formulated a list of design implications for the Documentation Panel guidance in AR:

- Old instructions in XML-format should be redesigned into a new visual format, consisting of short text statements, pictures with colors and animations/videos.
- The text should be big enough to read when the Documentation Panel fits in the FoV in order to avoid unnecessary head movements.
- The Documentation Panel should visualize required tools for a task step (e.g., as a symbol at the left bottom), related risks during the task, and the required safety equipment (e.g., in a form of a warning sign and required equipment icon).
- The system should be able to track safe/unsafe zones to place the panel, so the panel will not cover dangerous places/objects.
- Ideally, the system should be able to track the progress of a task.

Regarding the safety aspects, we found that multiple levels of safety-awareness support is needed for technicians with different experience levels. Experienced technicians do not require extensive notifications and they find them irrelevant, focusing on performance and productivity, while novice technicians would benefit from additional reminders. In analogy with the guidance, we formulated a list of guidelines for AR Safety warnings:

- The safety status/indicator should be implemented into the Documentation Panel (e.g., green-yellow-red shape to indicate the level of hazard during the task).
- When a user interferes with a dangerous area, the visual image should stay over the risky area for 2–3 seconds. In situations, where the danger is outside of the FoV, additional methods should be utilized to point towards the danger (clearly visible and big enough directional arrow, flashing or blinking in the direction of the danger, color-coded safety border around FoV, voice outputs, etc.).
- Safety warnings and notifications should be self-explanatory and contain only relevant information.
- When working in a team, the system should be able to track everyone's actions and report the changes as well as support communication between the team members.
- The system should be able to provide guidance during accidents (e.g., in case of a fire alarm the system should stop all maintenance tasks and guide the worker to a safe exit).

To summarize our findings, the KONE experts were enthusiastic about the possibilities and the usage of both VR and AR in their work. AR was seen as a potential approach to support technicians in their tasks, increase safety, and avoid unnecessary risks in the context of elevator maintenance. VR was found to be an appealing and practical environment to shift the ordinary ways of working into a novel, meaningful, and exciting experience. In conclusion, the user study results showed that despite the still existing limitations of both AR and VR technologies, there is an **obvious need, desire, and benefits to-be-gained** in utilizing these new technologies in the elevator industry.

4.6 Augmented reality and safety – literature review

A small-scale state-of-the-art research was conducted at the beginning of the DYNAVIS project. The goal was to understand the current situation in research related to safety and augmented reality (AR) systems. The focus of the review was on industrial applications, so other domains such as health care, the construction industry, housing and games were not fully investigated. The following topics were discovered:

- AR in use to support safe practices in industry
- Safety of the AR system
- Usability and ergonomics of the AR system
- The attention, situational awareness and cognitive load in AR applications

In the following we describe the results of the literature overview. The overview covers research papers published before 2018.

4.6.1 Augmented reality solutions supporting safety

AR has been used to detect and avoid hazards. Kim et al. (2017) used an image-based AR system to avoid hazards (especially struck-by objects of equipment). Their AR system proactively provides hazard information to workers via wearables (goggles) on a construction site. Kim et al. (2016) investigated the effect of visual warning presentation methods on drivers' performance and braking behaviour in pedestrian collision avoidance. They used a volumetric heads-up-display (HUD). Based on their study, pedestrian collision warning improves driver performance when compared to the baseline (without warnings). Sánchez et al. (2016) studied an indoor evacuation system with Google Glass technology and smartphones. Their goal was to tackle the challenge of providing users with personalized evacuation routes in real time. Based on the user studies, they found that users were satisfied with the Google Glass system. The enhancement of a "safety feeling" in user-robot collaboration has been addressed by Makris et al. (2016). They used an Android tablet in the automotive industry in assembly work. They used AR technology to provide assembly process information, robot motion and workspace visualisation, and visual alerts about potential hazards on the shop floor. Another study used an AR application (on an Android tablet) to support human-robot interactive cooperation (Michalos et al., 2016). They used an AR application for assembly process information provision, robot motion and workspace visualization, visual alerts and production data. They saw that the visualisation of safety areas as well as the trajectory of the robot's end effector could enhance the safety awareness of the operator. Alam et al. (2017) proposed an AR/VR prototype system for a personnel safety system to improve safety, maintain availability, reduce errors and decrease the time needed for scheduled or ad hoc interventions. Dusan and Tesic (2017) present a system based on AR technology that can be useful in reducing risk at work and decreasing the error rate and preventing injuries. The system is intended to project AR instructions directly at the work place. The worker is led step-by-step by the AR-system (tablet) through various work and safety procedures that should be performed. The preliminary results, according to the safety and technology officer's reports, confirm the usefulness of the AR system because no injuries were recorded. Quercioli's (2017) paper presents a technique that uses a smartphone's camera and display, in conjunction with an augmented reality headset (VR BOX II, virtual reality glasses) to allow clear viewing of laser experiments without any risk of laser eye injury. Strengths and weaknesses of the solution were discussed and it was seen that the headset allows a safe and clear view of the laser beam.

4.6.2 Safety of augmented reality systems

There are some studies that have investigated the safety of AR systems. Borgmann et al. (2017) studied the feasibility, safety and usefulness of AR-assisted urological surgery using Google Glass. The implementation of smart glass (SG) use during urological surgery was feasible with no intrinsic (technical defect) or extrinsic (inability to control the SG function) obstacles being observed. SG use was safe, as no major complications occurred for the series of urological surgeries of different complexities. Bretschneider-Hagemes and Gross (2017) compared the use of a monitor, HMD 1 (Vuzix/Google) and HMD 2 (Epson) in forklift operation. Test subjects had a primary task (driving the forklift-truck in a simulated environment according to the instructions) and a secondary task (picking task – the storage location was indicated each time). The study was conducted in a computer-based simulation environment. The paper presents a pilot test setup but does not yet include any evaluation results. Pyae and Potter (2016) discuss players' engagement in playing AR games and propose an engagement model for players in AR games. They discuss four concepts (player, play, presence and place) when playing the game Pokémon Go. They raise issues of the safety of AR games such as personal and road safety, being aware of restricted and dangerous areas, and privacy.

4.6.3 Usability and ergonomics in augmented reality systems

The usability and ergonomics of AR systems have been studied to some extent. Ko et al. (2013) proposed usability principles to consider when designing AR systems. They proposed 22 usability principles organized into five groups: user-information, user-cognitive, user-support, user-interaction and user-usage groups. Usability guidelines and heuristics related to AR are also discussed in Dünser et al. (2007). They discuss affordance, reducing cognitive overhead, low physical effort, learnability, user satisfaction, flexibility in use, responsiveness and feedback, and error tolerance. Sutcliffe and Gault (2004) proposed heuristics for the evaluation of virtual reality (VR) applications that can also be adapted to the use of AR. Funk et al. (2016) did an overview of their studies regarding the use of AR in industry. They listed lessons learned and guidelines related to AR's usability. Kruijff et al. (2010) classified perceptual issues that may occur in AR into five categories: environment, capturing, augmentation, display, and individual user differences.

The ergonomics of AR systems has not been widely studied yet. However, there are studies related to handheld devices (e.g. smartphones and tablets) which can be used as AR devices. Bachynskyi et al. (2015) investigated the performance and ergonomic factors of common touch surfaces (tablet, laptop, tabletop, public display, smartphone/two hands and smartphone/one hand). They found that based on muscle activation laptops are suitable for long-term use, and tablets and tabletops are suitable for long-term use after adjustment or posture support. Young et al. (2012) studied ergonomics when using tablets in four different usage conditions. They evaluated head and neck flexion angles during the study. An AR ergonomics study conducted by Colley et al. (2016) studied how a smartphone based AR browser was used in a poster browsing task. They recognized different interaction styles regarding holding the device, wrist position, stance and movement. They found that users that stood further from the poster were able to complete the browsing test task more quickly than those standing closer to the poster. In addition, different movement styles were identified when standing close or far from the poster: the closer standing user made vertical movements with the device, whereas the further away user relied more on angular tilting of the device. Kerr et al. (2012) evaluated strengths and weaknesses of an arm-mounted AR system in an outdoor environment. They also addressed ergonomic issues such as posture, position and comfort during the study. They did a similar study with HMD earlier (Kerr et al., 2011).

4.6.4 Attention and cognitive load

The attention, situational awareness and cognitive load are issues that can have an effect on safety when using AR systems, and are therefore important to consider. Kim and Dey (2009) compared two car navigation systems; one was an AR system. They also compared older and younger drivers. The AR system was found to be especially useful for older drivers. In addition, the drivers using the AR display system had significantly fewer navigation errors and divided attention related issues. Stork and Schubö (2010) studied human cognition in manual assembly. They discussed the information processing and mental resources (e.g. localization of a relevant part), selective attention and visual search (e.g. search strategies, findability), and task complexity (e.g. number and sequence of assembly tasks). These all are important in the use of AR systems. Results propose that contact analogue and projection systems are faster than a traditional monitor when finding and grasping the right assembly part. Baumeister et al. (2017) evaluated the cognitive load of three AR display technologies: projector based display (spatial AR), Microsoft HoloLens and Samsung Gear VR with monitor instructions. The results showed that spatial augmented reality (SAR) led to increased performance and reduced cognitive load. SAR was the fastest in performance. The monitor was better in performance compared to HMDs. Additionally, it was discovered that a limited field of view can introduce increased cognitive load requirements. Furmanski et al. (2002) have introduced concepts for developing visualisations of occluded information in MR/AR applications. They listed important guidelines when designing obscured information visualization: distance conveyance, proper motion physics, eliminate unneeded AR motion and selective or multiple cues. Polvi et al. (2017) compared the use of an AR-tablet and a picture-based-tablet in an inspection task. The results of their comparative evaluation showed that use of the AR interface resulted in lower task completion times, fewer errors, fewer gaze shifts, and a lower subjective workload. Neumann and Majoros (1998) presented cognitive studies and analyses relating to how AR interacts with human abilities to benefit manufacturing and maintenance tasks. Wang et al. (2016) compared a bare-hand interface AR system to a traditional AR assembly guidance system and to an LCD screen-based digital documentation system. The study revealed that a bare-hand AR interface satisfies users' needs for multi-modal guidance, and can provide suitable and appropriate guidance, so that users can perform tasks more quickly and accurately. Aschenbrenner et al. (2016) used a tablet AR system to support remote communication between expert and novice workers. The system used a tablet PC, the tracking system iSpace, two WLAN networks, and a laptop. They performed a preliminary study and measured situation awareness, load and usability. Kerr et al. (2012) found that attention divided between the AR display and the environment brought up some safety concerns. At least four (out of nine) participants failed to notice they were approaching a road junction, and had to be warned of the approaching traffic.

4.6.5 Summary

As a summary it can be said that the studies of AR safety/ergonomics/usability are quite dispersed. There are several publications that present many different kinds of AR systems and concepts. However, most of them lack proper user studies, especially within industrial environments. In general, the scientific level of some AR user studies is not yet high and for that reason, it is difficult to draw any major conclusions. In the future, it is important to increase the number of scientific user studies related to AR and safety/ergonomics in an industrial context. In addition, attention, cognition and situational awareness need more research because they have an effect on the safe use of AR systems.

5 CONCLUSIONS

With industrial internet and IoT, service technicians are provided with access to various information and measured data. This is making industrial maintenance work more knowledge-intensive. To get the actual benefit of the information and data, it should be illustrative and easily available when needed. The information should be provided in a contextually relevant form during the daily work. Dynamic visualizations will tackle these challenges, aiming to increase productivity, safety, and work satisfaction.

In the public research project DYNAVIS, VTT and TAUCHI together with the participating companies, developed novel dynamic visualization solutions. The aim was to develop, in parallel, new tools and new work practices in actual industry cases. The results of the project include descriptions and illustrations of dynamic visualization concepts together with user evaluation results that reflect user acceptance of the concepts. The most promising concepts were implemented as demonstrators or prototypes for industrial pilots. The demonstrators and prototypes were evaluated with maintenance professionals.

Five dynamic visualization concepts were introduced: 1) Contextual guidance based on augmented reality (AR), 2) Captivating learning experience based on virtual reality (VR) and gamification, 3) Access to visual lifecycle data with digital twins, 4) Safety support with AR, and 5) Contextual knowledge sharing tools that support making tacit knowledge visible. In user evaluations of the concepts with industrial experts, the general impressions were mostly positive. The dynamic visualization approach and the concepts were found useful.

The implemented demonstrators and prototypes include: 1) AR-based workflow support together with a AR content authoring tool, 2) Contextual knowledge sharing with augmented reality, 3) Digital twin browser for easy access to maintenance data, 4) Speech interface for easy reporting, and 5) Mixed reality solution to support safety and learning experiences.

User experience of the AR-based workflow support was positive and the system was found useful, especially for training purposes. There were, however, some concerns related to the robustness of the system in actual field use. The users thought that the quality of maintenance work would improve with these kinds of tools as the tools would give access to up-to-date instructions and the tools would support everyone adopting the same work procedures.

Contextual knowledge sharing integrates virtual notes and communication platform with maintenance systems and activities. The solution supports creating and sharing maintenance target specific visual information. Overall attitude of the test users was very positive towards the solution, and they expected that the solution will improve, ease, and speed up field reporting. Challenges were seen in content moderation and possible information overflow.

The implementation of the Digital twin browser has given understanding of the possibilities of such browsers. Digital twin browser has been utilized in communicating the design of Ruukki's near zero energy building to the visitors but further usage possibilities are seen in maintenance.

Speech interaction will support hands-free operation. Test users thought that the solution would improve the quality of maintenance reports and the reports can be submitted sooner. At the same time, the solution will simplify the maintenance technician's reporting task. As the attitudes towards speech-based reporting are positive and both workers and organizations are ready to utilize it, there seems to be great potential.

Augmented and virtual reality systems in maintenance work can support safety as illustrated with the implemented mixed reality solution. AR can support technicians in their tasks, increase safety, and help avoiding unnecessary risks. The combination of AR and VR provides an appealing and practical learning environment.

However, AR systems may introduce new safety and ergonomics challenges. These issues have not yet been studied much and more studies would be needed especially regarding long-term industrial use in real operational environments.

The dynamic visualization concepts illustrated in the DYNAVIS project present promising solutions for future industrial maintenance work. The solutions have been created in collaboration with industrial experts and they illustrate a wide overview of different possibilities to support the work of maintenance technicians in preparing for a maintenance visit, problem-solving, maintenance operation, reporting as well as learning and knowledge sharing. The visualization concepts can be utilized in considering how to utilize the possibilities of AR, VR, and new interaction technologies in maintenance work. The implemented and evaluated demonstrators and prototypes provide practical examples that can be applied also in other companies, and even in other application areas. The evaluation results highlight what influences user acceptance and what aspects need further development. The technical enablers for AR, VR, and speech interaction solutions are getting mature enough for industrial use. The actual solutions need to be developed in close collaboration with the maintenace workers to get solutions that support their daily work and that increase productivity, safety, and work satisfaction.

6 REFERENCES

Alam, M.F., Katsikas, S., Beltramello, O., Hadjiefthymiades, S., 2017. Augmented and virtual reality based monitoring and safety system: A prototype IoT platform. J. Netw. Comput. Appl. 89, 109–119. https://doi.org/10.1016/j.jnca.2017.03.022

Aromaa, S., Väätänen, A., Kaasinen, E., Uimonen, M. and Siltanen, S. 2018. Human Factors and Ergonomics Evaluation of a Tablet Based Augmented Reality System in Maintenance Work. In Proceedings of the 22nd International Academic Mindtrek Conference (Mindtrek '18). ACM, New York, NY, USA, 118-125. DOI: : https://doi.org/10.1145/3275116.3275125

Aschenbrenner, D., Maltry, N., Kimmel, J., Albert, M., Scharnagl, J., Schilling, K., 2016. ARTab - using Virtual and Augmented Reality Methods for an improved Situation Awareness for Telemaintenance. IFAC-PapersOnLine 49, 204–209. https://doi.org/10.1016/j.ifacol.2016.11.168

Bachynskyi, M., Palmas, G., Oulasvirta, A., Steimle, J., Weinkauf, T., 2015. Performance and Ergonomics of Touch Surfaces: A Comparative Study using Biomechanical Simulation, in: Proceedings of the ACM CHI'15 Conference on Human Factors in Computing Systems. pp. 1817–1826. https://doi.org/10.1145/2702123.2702607

Baumeister, J., Ssin, S.Y., ElSayed, N.A.M., Dorrian, J., Webb, D.P., Walsh, J.A., Simon, T.M., Irlitti, A., Smith, R.T., Kohler, M., Thomas, B.H., 2017. Cognitive Cost of Using Augmented Reality Displays. IEEE Trans. Vis. Comput. Graph. PP, 1–1. https://doi.org/10.1109/TVCG.2017.2735098

Borgmann, H., Rodríguez Socarrás, M., Salem, J., Tsaur, I., Gomez Rivas, J., Barret, E., Tortolero, L., 2017. Feasibility and safety of augmented reality-assisted urological surgery using smartglass. World J. Urol. 35, 967–972. https://doi.org/10.1007/s00345-016-1956-6

Bretschneider-Hagemes, M., Gross, B., 2017. Smartglasses Used by Forklift Operators: Digital Accident Hazard or Efficient Work Equipment? A Pilot Study, in: FH., N., CH., T. (Eds.), HCI in Business, Government and Organizations. Interacting with Information Systems. HCIBGO 2017. Springer, pp. 299–307. https://doi.org/10.1007/978-3-319-58481-2

Colley, A., Lappalainen, T., Määttänen, E., Schöning, J., Häkkilä, J., 2016. Crouch, Hold and engage: Spatial aspects of augmented reality browsing, in: ACM International Conference Proceeding Series. ACM. https://doi.org/10.1145/2971485.2971527

DIMECC. 2017. S-STEP– Smart Technologies for Lifecycle Performance. Final report 1/2017. DIMECC Publications Series No. 11, 2014–2016. https://teknologiainfo.net/sites/teknologiainfo.net/files/download/DIMECC_S-STEP_final_report_ebook.pdf

Dusan, T., Bojan, T., 2017. The application of augmented reality technologies for the improvement of occupational safety in an industrial environment. Comput. Ind. 85, 1–10. https://doi.org/10.1016/j.compind.2016.11.004

Dünser, A., Grasset, R., Seichter, H., Billinghurst, M., 2007. Applying HCI Principles to AR Systems Design, in: Proceedings of 2nd International Workshop on Mixed Reality User Interfaces: Specification, Authoring, Adaptation (MRUI '07).

Funk, M., Kosch, T., Kettner, R., Korn, O., Schmidt, A., 2016. motionEAP: An Overview of 4 Years of Combining Industrial Assembly with Augmented Reality for Industry 4.0. Proc. 16th Int. Conf. Knowl. Technol. Data-driven Bus. 2–5.

Furmanski, C., Azuma, R., Daily, M., 2002. Augmented-reality visualizations guided by cognition: Perceptual heuristics for combining visible and obscured information, in: Proceedings – International Symposium on Mixed and Augmented Reality, ISMAR 2002. IEEE, pp. 215–224. https://doi.org/10.1109/ISMAR.2002.1115091

Kaasinen, E., Aromaa, S., Väätänen, A., Mäkelä, V., Hakulinen, J., Keskinen, T., Elo, J., Siltanen, S., Rauhala, V., Aaltonen, I., Hella, J., Honkamaa, P., Leppä, M., Niemelä, A., Parviainen, J., Saarinen, S., Turunen, M., Törnqvist, J., Valtonen, J. and Woodward, C.2018. Mobile Service Technician 4.0 – Knowledge-Sharing Solutions for Industrial Field Maintenance. IxD&A journal 38/2018. 6–27.

Kerr, S.J., Rice, M.D., Lum, G.T.J., Wan, M., 2012. Evaluation of an arm-mounted augmented reality system in an outdoor environment, in: 2012 Southeast Asian Network of Ergonomics Societies Conference: Ergonomics Innovations Leveraging User Experience and Sustainability, SEANES 2012. https://doi.org/10.1109/SEANES.2012.6299589

Kerr, S.J., Rice, M.D., Teo, Y., Wan, M., Cheong, Y.L., Ng, J., Ng-Thamrin, L., Thura-Myo, T., Wren, D., 2011. Wearable mobile Augmented Reality: Evaluating outdoor user experience, in: Proceedings of VRCAI 2011: ACM SIGGRAPH Conference on Virtual-Reality Continuum and Its Applications to Industry. pp. 209–216. https://doi.org/10.1145/2087756.2087786

Kim, H., Miranda Anon, A., Misu, T., Li, N., Tawari, A., Fujimura, K., 2016. Look at Me: Augmented Reality Pedestrian Warning System Using an In-Vehicle Volumetric Head Up Display, in: Proceedings of the 21st International Conference on Intelligent User Interfaces. pp. 294–298. https://doi.org/10.1145/2856767.2856815

Kim, K., Kim, H., Kim, H., 2017. Image-based construction hazard avoidance system using augmented reality in wearable device. Autom. Constr. 1–14. https://doi.org/10.1016/j.autcon.2017.06.014

Kim, S., Dey, A.K., 2009. Simulated Augmented Reality Windshield Display As a Cognitive Mapping Aid for Elder Driver Navigation, in: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems. pp. 133–142. https://doi.org/10.1145/1518701.1518724

Ko, S.M., Chang, W.S., Ji, Y.G., 2013. Usability Principles for Augmented Reality Applications in a Smartphone Environment. Int. J. Hum. Comput. Interact. 29, 501–515. https://doi.org/10.1080/10447318.2012.722466

Kruijff, E., Swan, J.E., Feiner, S., 2010. Perceptual issues in augmented reality revisited, in: Mixed and Augmented Reality (ISMAR), 2010 9th IEEE International Symposium On. Evaluating Label Placement for Augmented Reality View Management Ronald Azuma, Chris Furmanski HRL Laboratories, LLC {azuma, chris}@HRL.com Abstract View management, a relatively new area of research in Augmented Reality (AR) applications, is about the sp, pp. 3–12. https://doi.org/10.1117/12.237425

Makris, S., Karagiannis, P., Koukas, S., Matthaiakis, A.S., 2016. Augmented reality system for operator support in human–robot collaborative assembly. CIRP Ann. - Manuf. Technol. 65, 61–64. https://doi.org/10.1016/j.cirp.2016.04.038

Michalos, G., Karagiannis, P., Makris, S., Tokçalar, Ö., Chryssolouris, G., 2016. Augmented Reality (AR) Applications for Supporting Human-robot Interactive Cooperation. Procedia CIRP 41, 370–375. https://doi.org/10.1016/j.procir.2015.12.005

Neumann, U., Majoros, A., 1998. Cognitive, Performance, and Systems Issues for Augmented Reality Applications in Manufacturing and Maintenance, in: Proceedings. IEEE the Virtual Reality Annual International Symposium (VRAIS). pp. 4–11. https://doi.org/10.1109/VRAIS.1998.658416

Polvi, J., Taketomi, T., Moteki, A., Yoshitake, T., Fukuoka, T., Yamamoto, G., Sandor, C., Kato, H., 2018. Handheld Guides in Inspection Tasks: Augmented Reality vs. Picture. IEEE Trans. Vis. Comput. Graph. 24, 2118–2128. https://doi.org/10.1109/TVCG.2017.2709746

Pyae, A., Potter, L.E., 2016. A player engagement model for an augmented reality game, in: Proceedings of the 28th Australian Conference on Computer-Human Interaction - OzCHI '16. ACM, pp. 11–15. https://doi.org/10.1145/3010915.3010960

Quercioli, F., 2017. Beyond laser safety glasses: augmented reality in optics laboratories. Appl. Opt. 56, 1148. https://doi.org/10.1364/AO.56.001148

Sánchez, J.M., Carrera, Á., Iglesias, C., Serrano, E., 2016. A participatory agent-based simulation for indoor evacuation supported by Google glass, in: Sensors. https://doi.org/10.3390/s16091360

Stork, S., Schubö, A., 2010. Human cognition in manual assembly: Theories and applications. Adv. Eng. Informatics 24, 320–328. https://doi.org/10.1016/j.aei.2010.05.010

Sutcliffe, A., Gault, B., 2004. Heuristic evaluation of virtual reality applications. Interact. Comput. 16, 831–849. https://doi.org/10.1016/j.intcom.2004.05.001

Wang, X., Ong, S.K., Nee, A.Y.C., 2016. Multi-modal augmented-reality assembly guidance based on bare-hand interface. Adv. Eng. Informatics 30, 406–421. https://doi.org/10.1016/j.aei.2016.05.004

Young, J.G., Trudeau, M., Odell, D., Marinelli, K., Dennerlein, J.T., 2012. Touch-screen tablet user configurations and case-supported tilt affect head and neck flexion angles. Work 41, 81–91. https://doi.org/10.3233/WOR-2012-1337

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