Worker Assistance in Smart Production Environments using Pervasive Technologies

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***Abstract* — Recent trends towards digitization in the industrial domain are also driving profound socio-technical changes. On the one hand, these technologies enable shorter product lifecycles and servitization, but on the other hand, the increasing technical complexity of the equipment makes its operation and maintenance a challenge for workers. Assistance systems using pervasive technologies can bridge the gap between the abilities of the workers and the demands of handling technical complexity by enriching workplace activities with relevant, context-dependent information. In this paper, we present an application that replaces a conventional, paper-based maintenance manual with digital, Augmented Reality based instructions that are delivered at the appropriate place and time.**

Keywords—Industry 4.0, Cyber Physical Systems, Augmented Reality, Complexity, Maintenance, HoloLens

I. INTRODUCTION

Technological progress in the field of embedded systems is resulting in a convergence of digitalization, the physical environment and human activity. The term *Cyber Physical Systems* (CPS), referring to the "tight conjoining of and coordination between computational and physical resources" was coined in 2010 [35]. A CPS is a system with embedded software, which is able to record, evaluate and act on data via dedicated, multimodal user interfaces while simultaneously communicating with other cyber physical systems across the globe [15].

In the manufacturing context, the term *Industry 4.0* has been used frequently to define a convergence of CPS, Internet of Things (IoT), cloud computing and cognitive computing. Besides interoperability, information transparency and decentralized decisions, technical assistance using pervasive technologies, where assistance systems can "support humans by aggregating and visualizing information comprehensibly for making informed decisions and solving urgent problems on short notice" [17] has been defined as one of the design principles of Industry 4.0. Such production environments are also labelled as 'Smart Production Environments' or 'Smart Factories' [22][29]. While on one side these environments are becoming increasingly 'smart' and information rich, on the other side they are highly complex, networked information systems [37]. Owing to the heterogeneity and complexity of these systems, their repair and maintenance poses challenges for companies, technicians as well as operators [5][31].

In this paper, we present a concept that demonstrates how end-users can be empowered to tackle the maintenance of complex CPS by learning and carrying out repair tasks which are typically reserved for service personnel. We validate this concept by implementing a prototypical AR-based maintenance application for a 'smart' machine. In the following section, we describe the overall research problem in more detail, before looking at related work in section III. In section IV, we define relevant functional requirements and in section V give an overview of the prototype. Section VI illustrates the application in use, and in section VII we conclude the paper and identify areas of further research and implementation.

II. PROBLEM SCOPE AND DEFINITION

In the industrial domain, information processing hardware and software is increasingly complementing electro-mechanical processes that exhibit highly dynamic behavior and variable operating conditions [33]. For end-users who traditionally might not have the training in the diverse domains that comprise CPS, understanding the operation and maintenance of such systems poses a challenge of informational complexity [8].

In addition, many developed countries are making efforts to transform their manufacturing industry. After sales services are a part of a product purchase decision, also known as *Servitization* [36]. The term *Product Service System* (PSS) [26] has more recently been coined as a special case of servitization, which focuses on creating a product with value added capability in mind, for instance machines capable of hosting a variety of interactive devices that can guide users to perform non-routine tasks in order to reduce downtime.

With the help of pervasive and augmented reality technologies [28], it may be possible to supplement the users' gathered knowledge with the required technical details or help them learn newer skills at the workplace [1]. In the next sections, we aim to:

- Identify tasks, which usually have to be carried out by qualified personnel, but could potentially be performed by users supported by pervasive technological aids.
- Select a suitable technology for our need based on functional and usability requirements.
- Create a use case scenario and a user interface (UI) prototype.
- Design and develop an application as a proof-of-concept demonstrator.

III. RELATED WORK

Some form of digital assistance in maintenance tasks has become the norm as machines and products themselves

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incorporated digital components. For example, the use of ECU (electronic control unit) in cars made the use of a computer necessary during routine maintenance. One of the first systems to combine sources of digital information in aid of maintenance was *Interactive Electronic Technical Manual* (IETM) [21], which replaced paper manuals with a mobile computer through which multiple sources of information could be linked. However, the repair technician must still refer to a different medium for information other than the physical machine to be repaired, which increases the possibility of errors [6]. Hence, one of the primary requirements in the domain of machine maintenance has been to "incorporate instruction and assistance directly within the task domain, visually integrated with the equipment the user is maintaining" [16]. Technologies such as Augmented Reality (AR) are well suited to this application, as information can be placed at suitable locations in the user environment.

The effectiveness of AR-based assistance in comparison to paper-based instructions has been demonstrated in various studies [38][34]. Several prototype applications in the domain of component assembly have been demonstrated using different forms of augmentation, such as Head Mounted Displays (HMDs) [7], in-situ projection [32][4] and hand-held mobile devices [12]. Nee et al. [24] and Fite-Georgel [6] provide a comprehensive overview of various AR projects in the industrial domain.

Each AR technology has its own strength and weakness, and thereby lends itself suitable for a specific form of industrial work. While HMDs enable hands-free work, they have been cited to be bulky and unsuitable for long term use [3][9]. Conversely, in-situ projection is inherently immobile during operation [7]. Smart phones and tablets hit the middle ground, while restricting hands-free operation.

Since the mid-1990s, several projects have demonstrated the applicability and viability of AR applications in the domain of industrial maintenance. For example, Feiner et al. [10] described and prototyped the first maintenance and repair scenario supported by AR, known as *KARMA* (Knowledge based AR for Maintenance Assistance), where the user was guided step by step to repair a printer. The *ARVIKA* consortium, established in the late 1990s, represented one of the biggest mobile AR projects in the domain [13]. In 2004, *ARVIKA* demonstrated an application scenario where a head-mounted device assists a user in troubleshooting, maintenance and repair in the field. AR technologies have also been implemented as remote collaboration tools for maintenance experts to collectively solve problems [23]. More recently, Re and Bordegoni [30] presented a prototype that makes use of a handheld device on which relevant instructions are displayed. In these projects, the detection of the device pose is done by placing trackers at suitable locations in the user surroundings. However, the use of marker-based AR technology in these scenarios is problematic because a free line of sight between the AR device and the marker is not always guaranteed. Secondly, the number of AR markers increases as more and more information needs to be displayed.

The ideal AR solution, therefore, needs to be robust in feature recognition, marker less tracking, efficient pose and orientation estimation. In addition, it is desirable to have all the information processing and communication performed in real-time on a mobile device.

IV. Functional and Domain Specific Requirements

In this section, we examine specific technical and cognitive requirements which influence technology selection and information presentation requirements in order to build a concept for our prototype.

A. *Types of Maintenance Work*

In the field of maintenance, three primary "modes" of maintenance are distinguished [6]:

- *Preventive* or *scheduled maintenance* that needs to be carried out at regular intervals to prevent breakdowns.
- *Corrective maintenance* which is a typical problem-solving scenario where the equipment has broken down and needs to be restored back to working order.
- *Predictive maintenance* where sensor data is continually evaluated and compared against statistical models based on past trends to predict failure before it occurs.

B. *Cognitive Needs of a Maintenance Scenario*

As shown in Table I, Neumann et al. [25] divide a maintenance operation into two portions: informational and workpiece. According to the authors, "document related activities tend to be cognitive, workpiece related activities tend to be kinesthetic and psychomotor, and both involve visual and auditory factors".

TABLE I. Cognitive Needs for Maintenance

Informational Portion	Workpiece Portion
· Direct attention to storage medium · Read, comprehend, interpret, calculate · Understand Speech · Form hypotheses · Transpose information from documents to workpiece	· Direct attention to workpiece · Inspect, discriminate, compare, select, align · Orient to sound, interpret sound · Adjust or actuate devices, detect movement · Manipulate devices

Studies showed that the cognitive time, defined as the time not engaged with the devices or instruments, accounts for about 50% of the total task time [27]. If we are to reduce the overall task time, it is desirable that both informational and workpiece aspects are combined into a single activity.

Only the visual and auditory factors are "common" to both informational and workpiece tasks, hence the preferable solution should be "hands-free". On the other hand, the factory environment may be too noisy for speech input, therefore some form of gesture input is a possible alternative.

V. PROTOTYPE

The prototype system was built up in the *SmartFactoryOWL* [2], a facility for demonstrating industrial research projects in the context of Industry 4.0. As a technical basis for our demonstrator, we use a *Kannegiesser Speedline* laundry folding machine (see Fig. 1). The *Speedline* is a “small piece folder for hospital, hotel and wellness applications” [20], embedded with various electrical, light and pressure sensors. During its operation the machine itself can detect any anomalies and report them to the user, but from the application domain of the machine, it would be safe to assume that the typical user of the machine is not trained in repair and maintenance.

Fig 1. Kannegiesser Speedline laundry folding machine [20].

The user manual distinguishes between two types of personnel qualifications for usage and maintenance of the machine, the ‘user’, who knows the safety concept of the machine, can recognize and attend to safety risks and has been instructed in using the machine, and the ‘qualified personnel’, who have the required training, knowledge and experience to carry out maintenance and verification tasks on the machine. Maintenance tasks, as displayed in Table II, are then assigned to workers according to their skill and training level.

A. *Application Specific Requirements*

Table II showcases the organization of the maintenance tasks and their relative intervals. The first column indicates the time interval (24h, weekly, monthly or after a fixed number of hours). The second column contains references to the concrete task(s) to be performed. The third column lists the required qualification of the personnel. On paper, the description of the maintenance task is given in only a line or two, but in actual usage the work is divided into multiple steps. Informationally, each step here consists of the following components:

- *Location:* The size of the machine makes finding the part to be serviced a noticeably time-consuming component of the step, especially for tasks that are not performed frequently
- *Instruction:* What to do and how to do it.
- *Associated Risks:* The prescribed level of correctness and necessary precautions to be taken under each step.

TABLE II. EXEMPLARY MAINTETANCE PLAN FOR A LAUNDRY FOLDING MACHINE

Interval	Maintenance Task	Personnel
Daily (24 h)	Ensure the safety mechanisms are operating by activating them. ⇨ Refer to chapter 12.3.4 on page 82	Operator
	In case of changing machine noise, for example during folding process, adjust and if necessary, replace the defective components. ⇨ Refer to chapter 12.3.1 on page 80.	Skilled Personnel
	Clean the control enclosure including transformer with a vacuum cleaner. ⇨ Refer to chapter 12.3.6 on page 84	Electrically qualified personnel
Weekly (170 h)	Clean the conveyer belts check their fitness for use. ⇨ Refer to chapter 12.3.3 ‘Conveyer belt cleaning’ on page 82.	Skilled Personnel
Once in two weeks (350 h)	Remove lint from rollers and belts.	Skilled Personnel
Monthly (700 h)	Check the drive belt tension. ⇨Refer to chapter 12.3.2 on page 80.	Skilled Personnel
2000 h	Replace the filter for control enclosure ventilation. ⇨ Refer to chapter 12.3.5 on page 83	Skilled Personnel
4000 h	Replace the drive belts. ⇨ Refer to page 80.	Skilled Personnel

Curiously, the sequence of information as presented in the manual does not reflect the actual requirement in performing everyday steps as presented above. While the maintenance manual for the machine does mention the associated risks for different components, they are all grouped together in a separate section of the user manual. Similarly, the user manual shows the location of components as shown in Fig. 2. In comparison to a trained technician, an everyday user who in the future might be tasked with these maintenance operations, understanding the user manual alone is a daunting task. It would be desirable to combine the informational and locational aspects of the different steps into a single application that presents information as needed.

B. *Use Case Scenario*

Prior to the implementation, a use case scenario was constructed, which takes the concrete requirements of service technicians und operators into account. In the current use case, the user is informed through a mobile device (in this case a smart watch) that maintenance on a machine is to be performed. The level of detail on a device such as the smart watch is lower compared to a device with a larger screen, therefore the user needs to switch to a device that can support a different form of modality such as an HMD.

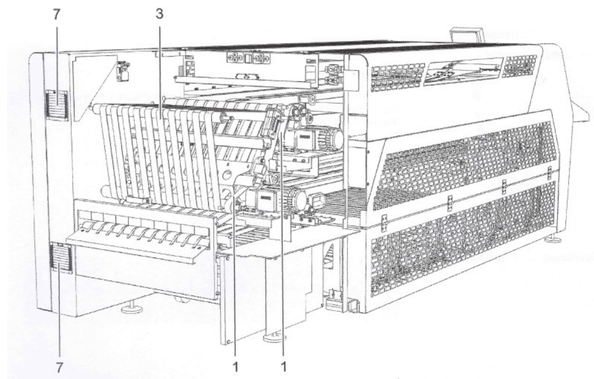

Fig 2. Location of machine components as shown in the user manual.

In the next step, the user scans a unique identifier on the machine, for example a QR code, to obtain relevant information about the machine data. The context shifts from a factory floor to the particular machine in question, as displayed in Fig. 3. At this point, the application has the information it needs to select the relevant tutorial and display it to the user. The selection of the tutorial can be done on an accompanying device such as a smartphone or a tablet.

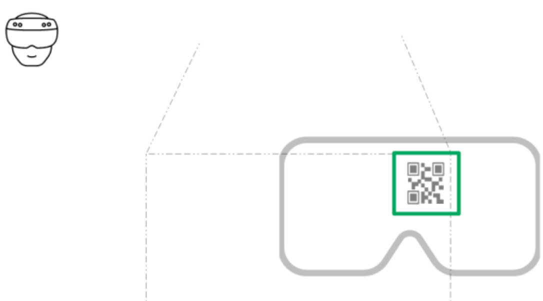

Fig 3. Scanning the QR code on the machine (Hololens icon by Laura Hernandez from the Noun Project).

Once the user chooses a relevant tutorial, instructions are displayed on how to disassemble a particular part on the machine, both in the form of 3D information overlay as well as photos and videos. The 3D overlays take care of the locational aspect of the maintenance step, while photos and videos can be used to display the desired state of the component from the view point of the user at a suitable position in the current physical context, that is, either above the machine surface or on the side where this information overlay does not interfere with the users' line of sight.

With the HMD on, the user then proceeds to see points where the machine cover is to be unscrewed via 3D arrows (Fig. 4). Two-dimensional elements such as a text description of the current step, photos/videos and interactive buttons are displayed.

C. System Design

After conducting a review of several devices available on the market, the *Microsoft HoloLens* was the only device capable of supporting our requirements. As noted in the use case scenario, while a machine can be uniquely identified through a QR Code, this code also presents a "physical anchor" or a reference point in 3D relative to which a virtual environment can be created. The *HoloLens* is capable of situating a physical object as a 'spatial anchor' for the virtual world, which serves as a frame of reference for more than one hologram in a local proximity.

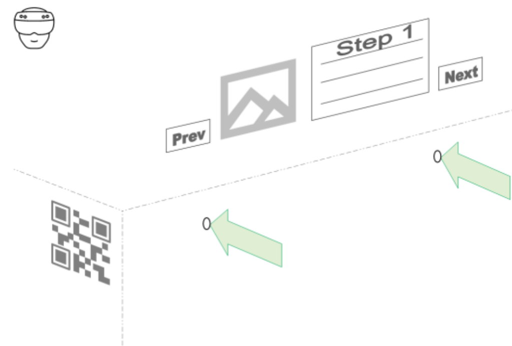

Fig 4. Displaying appropriate instructions through the HMD (Hololens icon by Laura Hernandez from the Noun Project).

Communication with the *HoloLens* is established via a TCP server, while media elements such as pictures and videos are served via a REST API. The client and the server both agree upon using a common "StepData" class that contains information about a particular step, as shown in Table II.

TABLE III. STEP DATA STRUCTURE

Variable Name	Description
TutorialName	Name of the current maintenance task
StepNumber	Current step number out of total steps
TotalSteps	Total number of steps in this task
Instruction Text(s)	Variable amount of text to be displayed
Media URLs	URLs to the image/video to be displayed
Coordinates (x,y,z)	The coordinates of the part to be serviced w.r.t. the calibrated coordinate system.
Status	Status of the current task (running/cancelled/completed)

VI. APPLICATION DEMONSTRATION

In this section, we give a brief description of the application in use. The list of available tutorials is displayed on a secondary screen, such as a tablet or a PC that runs the backend GUI. It is assumed that such a display is the primary mode of interaction in a maintenance context and the *HoloLens* is used only when guidance is needed.

The UI for the *HoloLens* application is constructed around two UI objects. An interactive central "console" is displayed at a fixed location (Fig 5, 6). From this console the user can step through the tutorial steps, access the settings menu or exit the application. Since the user may have to walk around the machine to access different parts, the console always faces the user and is placed at a location that is always visible.

The space around the machine consists of two components, a locational component and a task component. 3D objects, designed to guide the user attention to a particular part or area. An arrow, shown in Fig. 7, is used to indicate a location. A marked quadrilateral, as shown in Fig. 11 outlines an area that needs the users' attention. Displaying a combination of the two elements is also used, to first point the user to the correct location on the machine and then highlight a specific area (Fig 8).

VII. Conclusion and Future Work

In this paper, we reported on the development of an AR-based assistance application focusing in particular on industrial maintenance tasks that are not described in detail in the instructions manual or are too infrequent to be memorized. The application is intended to be used by users who are not typically trained to be service technicians, such that they can take over relatively simple tasks. The focus of the work presented here was not the development of AR technology, rather we aimed towards gaining an understanding of the context of use of AR technology in industrial usage scenario. As AR devices gain robustness, the focus may shift from AR technology itself to understanding and implementing context awareness in use. Libraries such as *ARCore* [19] and *ARKit* [18] are examples of several toolkits which will expand the applicability of AR applications.

We would also like to highlight some limitations and point out areas of further research and development. Firstly, learning the use of the *HoloLens* is assumed in this implementation. In a real-world scenario, a new user may have to spend some time to learn how to interact with the *HoloLens* itself. As shown in Fig. 5 and 6, only gesture and visual modalities are used to interact with the application, which means that user focus is diverted to the activity console to read and comprehend the instructions for each step. Approaches towards multi-device interaction may better harness the strengths of each modality, for instance a tablet is well suited to text manipulation instead of AR glasses.

Further, adaptability of the application to user needs should not be ignored [14], and need to be tackled with techniques in machine learning and behavior modelling. Lastly, a user evaluation would also be helpful to figure out further UI and interactivity improvements.

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Fig 5. Activity console.

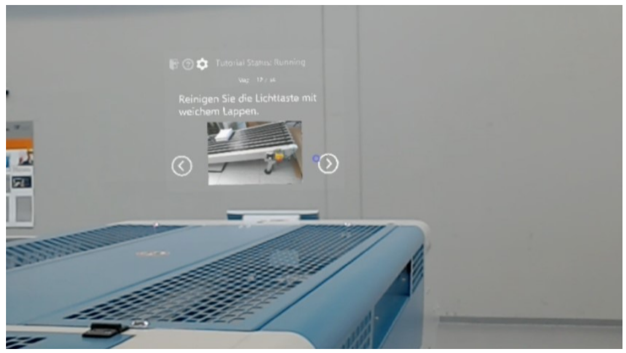

Fig 6. The *activity console* is visible at all times.

Fig 7. Guiding user attention to the part in question.

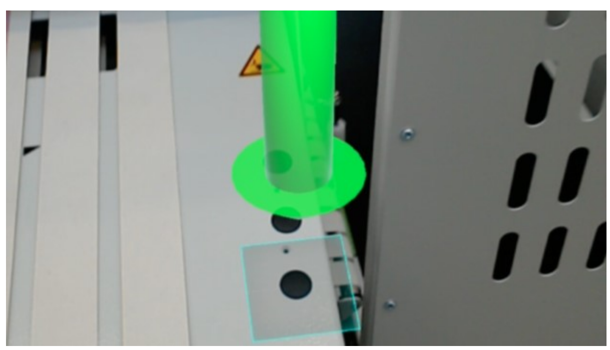

Fig 8. Marking an area.

References

[1] Aromaa, S., Aaltonen, I., Kaasinen, E., Elo, J., Parkkinen, I. (2016). Use of Wearable and Augmented Reality Technologies in Industrial Maintenance Work. In: *Proceedings of the International Academic Mindtrek Conference*, ACM Press, New York, USA, pp. 235-242.

[2] Büttner, S., Mucha, H., Robert, S., Hellweg, F., Röcker, C. (2017). HCI in der SmartFactoryOWL – Angewandte Forschung & Entwicklung. In: M. Burghardt, R. Wimmer, C. Wolff, C. Womser-Hacker (Eds.): *Workshop-Band Mensch und Computer 2017*. Gesellschaft für Informatik, Bonn, Germany.

[3] Büttner, S., Röcker, C., Sand, O. (2016). Using Head-Mounted Displays and In-Situ Projection for Assistive Systems – A Comparison. In: *Proceedings of the 9th ACM International Conference on Pervasive Technologies Related to Assistive Environments* (PETRA'16), ACM New York, USA, Article No. 44.

[4] Büttner, S., Sand, O., Röcker, C. (2017). Exploring Design Opportunities for Intelligent Worker Assistance: A new Approach Using Projection-Based AR and a Novel Hand-Tracking Algorithm. In: A. Braun, R. Wichert, A. Maña (Eds.): *Ambient Intelligence. Proceedings of the European Conference on Ambient Intelligence and the Internet of Things* (AmI'17). Springer, Heidelberg, Germany, pp. 33 - 45.

[5] Chun, I., Kim, J., Kim, W., Lee, E. (2011). Self-Managed System Development Method for Cyber-Physical Systems. In: T. Kim, H. Adeli, A. Stoica, B. H. Kang (Eds.): *Control and Automation, and Energy System Engineering.* Communications in Computer and Information Science. Springer, Berlin, Heidelberg, pp. 191-194.

[6] Dhillon, B., Liu, Y. (2006). Human Error in Maintenance: A Review. In: *Journal of Quality in Maintenance Engineering, 12*(1), pp. 21-36.

[7] Dhiman, H., Martinetz, S., Paelke, V., Röcker, C. (2018). Head-Mounted Displays in Industrial AR-Applications: Ready for Prime Time? In: F. Fui-Hoon Nah, B. S. Xiao (Eds.): *HCI in Business, Government and Organizations.* Springer, Cham, Switzerland, pp. 67 - 78.

[8] Dhiman, H., Plewe, D., Röcker, C. (2018). Addressing Uncertainties in Complex Manufacturing Environments: A Multidisciplinary Approach. In: W. Karwowski, S. Trzcielinski, B. Mrugalska, M. Di Nicolantonio, E. Rossi (Eds.): *Advances in Manufacturing, Production Management and Process Control*. Springer, Cham, pp. 103 - 114.

[9] Didier, J.-Y., Roussel, D., Mallem, M., Otmane, S., Naudet, S., Pham, Q.-C., Bourgeois, S., Mégard, C., Leroux, C., Hocquard, A. (2005). AMRA: Augmented Reality Assistance in Train Maintenance Tasks. In: *Proceedings of the ACM/IEEE International Symposium on Mixed and Augmented Reality* (ISMAR'05), pp. 1 - 10.

[10] Feiner, S., Macintyre, B., Seligmann, D. (1993). Knowledge-Based Augmented Reality. In: *Communications of the ACM*, 36(7), pp. 53 - 62.

[11] Fite-Georgel, P. (2011). Is There a Reality in Industrial Augmented Reality?. In: *Proceedings of the ACM/IEEE International Symposium on Mixed and Augmented Reality* (ISMAR'11), pp. 201 - 210.

[12] Flatt, H., Koch, N., Röcker, C., Günter, A., Jasperneite, J. (2015). A Context-Aware Assistance System for Maintenance Applications in Smart Factories based on Augmented Reality and Indoor Localization. In: *Proceedings of the 20th IEEE International Conference on Emerging Technologies and Factory Automation* (ETFA'15), September 8-11, 2015, Luxembourg, pp. 1268 - 1271.

[13] Friedrich, W., Jahn, D., Schmidt, L. (2002,). ARVIKA-Augmented Reality for Development, Production and Service. In: *Proceedings of the ACM/IEEE International Symposium on Mixed and Augmented Reality* (ISMAR'02), pp. 3 - 4.

[14] Funk, M., Dingler, T., Cooper, J., Schmidt, A. (2015). Stop Helping Me - I'm Bored! Why Assembly Assistance needs to be Adaptive. In: *Adjunct Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing the ACM International Symposium on Wearable Computers, pp. 1269 - 1273.*

[15] Geisberger, E., Broy, M. (2012) (Eds.). *agendaCPS: Integrierte Forschungsagenda Cyber-Physical Systems*. Springer, Berlin, Germany.

[16] Henderson, S. J., Feiner, S. K. (2007). *Augmented Reality for Maintenance and Repair (ARMAR)*. Department of Computer Science, Columbia University, New York, USA.

[17] Hermann, M., Pentek, T., Otto, B. (2016). Design Principles for Industrie 4.0 Scenarios. In: *Proceedings of the Hawaii International Conference on System Sciences (HICSS'16)*. IEEE, Washington, USA, pp. 3928 - 3937.

[18] https://developer.apple.com/arkit/

[19] https://developers.google.com/ar/

[20] https://www.kannegiesser.com/de/en/products/detail/speedline.html

[21] Jorgensen, E. L., Fuller, J. J. (1993). The Interactive Electronic Technical Manual. In: *Proceedings* of the *ASNE Logistics Symposium.*

[22] Lucke D., Constantinescu C., Westkämper E. (2008). Smart Factory - A Step towards the Next Generation of Manufacturing. In: M. Mitsuishi, K. Ueda, F. Kimura F. (Eds.): Manufacturing Systems and Technologies for the New Frontier. Springer, London, UK, pp. 115 - 118.

[23] Lukowicz, P., Timm-Giel, A., Lawo, M., Herzog, O. (2007). WearIT@work: Toward Real-World Industrial Wearable Computing. In: *Pervasive Computing*. 6(4), pp. 8 - 13.

[24] Nee, A. Y. C., Ong, S. K., Chryssolouris, G., Mourtzis, D. (2012). Augmented Reality Applications in Design and Manufacturing, In: *CIRP Annals*, 61(2) pp. 657 - 679.

[25] Neumann, U., Majoros, A. (1998). Cognitive, Performance, and Systems Issues for Augmented Reality Applications in Manufacturing and Maintenance. In: *Proceedings of the Annual International Symposium on Virtual Reality*. IEEE, Washington, USA, pp. 4 - 11.

[26] Oliva, R., Kallenberg, R. (2003). Managing the Transition from Products to Services. In: *International Journal of Service Industry Management, 14*(2), pp. 160 – 172.

[27] Ott, J. (1995). Maintenance Executives Seek Greater Efficiency. In: *Aviation Week & Space Technology*, 142(20), pp. 43 - 44.

[28] Paelke, V., Röcker, C. (2015). User Interfaces for Cyber-Physical Systems: Challenges and Possible Approaches. In: A. Marcus (Ed.): *Design, User Experience, and Usability: Design Discourse*. Springer International Publishing, Switzerland, pp. 75-85.

[29] Radziwon, A., Bilberg, A., Bogers, M., Madsen, E. S. (2014). The Smart Factory: Exploring Adaptive and Flexible Manufacturing Solutions. In: *Procedia Engineering*, 69, pp. 1184 - 1190.

[30] Re, G. M., Bordegoni, M. (2014). An Augmented Reality Framework for Supporting and Monitoring Operators during Maintenance Tasks. In: *Virtual, Augmented and Mixed Reality. Applications of Virtual and Augmented Reality*. Springer, Heidelberg, Germany, pp.443-454.

[31] Ruiz-Arenas, S., Horváth, I., Mejía-Gutiérrez, R., Opiyo, E. Z. (2014). Towards the Maintenance Principles of Cyber-Physical Systems. In: *Strojniški Vestnik – Journal of Mechanical Engineering,* 60(12), pp. 815 – 831.

[32] Sand, O., Büttner, S., Paelke, V., Röcker, C. (2016). smARt.Assembly – Projection-Based Augmented Reality for Supporting Assembly Workers. In: Lackey S., Shumaker R. (Eds.): *Virtual, Augmented and Mixed Reality*, Lecture Notes in Computer Science, Vol. 9740, Springer, Switzerland, pp. 643 - 652.

[33] Sierla, S., O'Halloran, B. M., Karhela, T., Papakonstantinou, N., Tumer, I. Y. (2013). Common Cause Failure Analysis of Cyber–Physical Systems Situated in Constructed Environments. In: *Research in Engineering Design*, 24(4), pp. 375 - 394.

[34] Tang, A., Owen, C., Biocca, F.,Mou, W. (2003). Comparative Effectiveness of Augmented Reality in Object Assembly. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI'03). ACM New York, USA, pp. 73 - 80.

[35] US National Science Foundation, https://www.nsf.gov/pubs/2018/nsf18538/nsf18538.pdf

[36] Vandermerwe, S., Rada, J. (1988). Servitization of Business: Adding Value by Adding Services. In: *European Management Journal*, 6(4), pp. 314 - 324.

[37] VDMA (2012). *Management Summary zur Tendenzbefragung 2012 – Bedeutung der Informations- und Automatisierungstechnik in den Produkten des Maschinen- und Anlagenbaus*. Verband Deutscher Maschinen- und Anlagenbau.

[38] Zheng, X. S., Foucault, C., Matos da Silva, P., Dasari, S., Yang, T., Goose, S. (2015). Eye-Wearable Technology for Machine Maintenance: Effects of Display Position and Hands-Free Operation. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI'15). ACM New York, USA, pp. 2125 - 2134