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Augmented reality for IT/OT failures in maintenance operations of digitized trains: current status, research challenges and future directions

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Abstract

The railway industry is moving towards a complex socio-technological system that relies on computer control and human-machine interfaces. Digitization and convergence of information technology (IT) with operational technology (OT) becomes increasingly important. Therefore, enabling innovations, lowering costs, increasing safety systems, enhancing performance, and increasing flexibility gains. In this scenario, opportunities arise for Augmented Reality (AR) capabilities to enhance maintenance operations of digitized trains. Initial research and tests have enabled training technicians and assistance of train drivers during specific activities by facilitating interactions with machines that go beyond traditional training manuals. Despite the positive results AR has shown, there are no specific indications available regarding the 'deployability' of the technology related to maintenance tasks. This position paper presents arguable boundaries and challenges for a structural appraisal of AR on maintenance operations of IT/OT converged trains. Potential AR solutions and specifications were based on current maintenance operations. Semi-structured interviews and surveys were conducted with maintenance providers to determine existing challenges. Moreover, the paper comprises an analysis to reveal the potential application AR has in maintenance procedures of digitized trains. Finally, this paper provides future research directions of AR technologies related to maintenance procedures of trains.

Keywords: Augmented Reality; Maintenance; Digitized trains; IT/OT failures

1. Introduction

Over the last few years, the railway industry is experiencing a tidal wave of digital transformation whose impact is complex. This industry is a socio-technical system that is becoming increasingly concerned with digitization. Key performance indicators (KPIs) for railway operations remain the same, but each of them will show a positive impact from the application of digital technologies. Technological innovations of trains and traffic management systems create new services and commercial business cases [1]. Overall competitiveness and performance improve by exploiting data-based services with for example: artificial intelligence techniques, merging real and virtual worlds, autonomous driving, Internet of Things, and blockchains that innovate the railway system. The railway industry aims to have safe, high-quality, and sustainable transport and maintenance operations. Maintenance costs depict a significant proportion of the life-cycle costs of trains, where fleet maintenance costs significantly exceed the initial investment costs. A fundamental part of supporting trains throughout the entire life-cycle of a train is therefore maintenance.

Digitization and convergence of information technology (IT) with operational technology (OT) becomes increasingly important for railway operations to achieve less maintenance cost, efficient, and reliable operations. Here, IT is defined as an engine that accepts data flow as an input to deliver new data flow but does not interfere with the physical world [2]. OT is a

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set of devices and processes that act in real-time on physical operational systems. Because of digitization in the railway industry, maintenance of new trains is more often focused on (remote) inspections based on data rather than on physical assembling and disassembling components. An additional result of digitization is more IT and OT systems are implemented into trains. IT/OT convergence lowers costs, reduces risks, enhances train performance, and reaches flexibility gains [2]. Convergence generates more data, data relationships, and dependencies, thereby requiring early identification of critical interfaces. However, the convergence of IT/OT is highly complex due to the involvement of different independent systems, technologies, stakeholders, equipment, and methods [3]. Finally, failure within the boundaries of IT/OT converged systems is thereby largely unpredictable and increasingly involute.

Based on a case study, it was found that failures are not yet fully understood by today's asset and fleet managers. In addition, knowledge of IT is limited and only present in a few departments. Furthermore, the collaboration between IT and maintenance departments lacks coherence. As a result, only a few employees have competence in both IT and OT of the train, creating an IT/OT failure knowledge gap. Therefore, understanding and structuring IT/OT systems is of great importance for the railway industry. In order to meet this interest, this research aims to examine the use of Augmented Reality (AR) as a tool for identifying, prioritizing, and providing solutions to failures related to IT/OT converged systems. AR is capable of showing the right information in the right context to support users in finding this malfunction [4]. AR is a technology, mature enough to be widely deployed in maintenance operations, testing, and training of converged IT and OT trains. However, challenges of deployability and integration of the technology must be dealt with. An overview of this position paper is presented in figure 1.

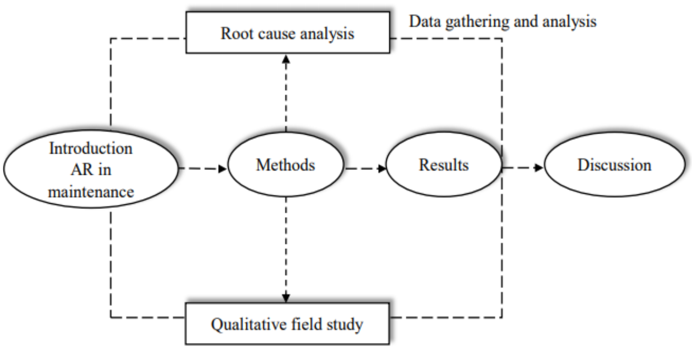

Figure 1. Position paper outline.

This research investigates the use of AR as a tool mainly for IT/OT failure analysis. Failure analysis is a method used in product development to determine weaknesses and technical risks. As a result, it optimizes the use of resources. Identification, prioritizing, and structuring of IT/OT failures enables designers to perform failure analysis during the conceptual design. This analysis through AR is recognized as a powerful tool to improve quality and reliability during product development.

2. AR status in maintenance operations

When assessing the current AR status in maintenance operations, a brief specification of AR application fields is required. A clear AR tool description helps to understand the technology which will be used in this research. System boundaries are presented next to evaluate the current technology implementation status. All information results in positioning AR tools in different maintenance fields.

2.1 Specification of AR technology

AR techniques can be used to visualize contextualized virtual information at the appropriate time and location within the working environment. Potential applications of AR in industrial ecosystems are primarily focused on maintenance, service, inspection, device diagnostics, repair of complex machinery, and training [5]. Easier understandable instructions are provided as computer-generated information superimposed upon the actual equipment, and step-by-step explanation of tasks. A report on mechanics' capability of viewing virtual information panels that overly the real image of engines and see through the machinery without disassembling components was already proposed in 1993 [6].

Typical AR systems include components such as visualization/capturing device, interaction device, and tracking system [6]. Capturing technologies are collecting environmental data and can be viewed by the user with superimposed information. Visualization devices are used to display the results of image processing. Interaction devices are used for commands that affect information processing and displaying. Tracking technologies are essential for identifying user position and provides correct information when augmenting the environmental scene itself. Technical and technological issues related to development and implementations of AR are debatable elements. Most studies that review technological solutions for visualization either use mobile devices or Head-Mounted Displays (HMDs) [7]. Mobile devices need to be held in the hand when used and therefore potentially hinder maintenance tasks. HMD solutions leave the hand free, allowing for a more natural and intuitive hand-based interaction with virtual objects. Two main categories of tracking systems can be defined: marker-based tracking and marker-less tracking [9]. Marker-based solutions use tags placed on elements that let the AR system recognize it and allows it to convey additional information. Marker-less systems are for example hybrid tracking methods, feature tracking or natural markers. Nowadays, marker-less AR is the preferred image recognition method depending on the environment's real features rather than identifying markers. This method eliminates the need for object tracking systems. Marker-less systems require computer-aided design (CAD) models, 3D point clouds, or plane segments. Therefore, a complete and accurate data structure is essential.

2.2 Prior research AR in maintenance

A case study in aircraft maintenance training and operations support suggests that AR technology can improve maintenance task's efficiency [10]. The production environment also provides multiple cases in which AR performs like a work support system in a challenging and complex environment [11]. All cases demonstrate positive results regarding AR and complex maintenance procedures in terms of efficient, reliable, and safe operations.

2.3 Current status of application AR in the railway industry

Previous research has been conducted within the railway industry for adopting AR technologies to train technicians and to assist train drivers during specific operations [12]. A proof of concept was proposed by targeting the main advantages: increasing operational efficiency and training. Despite the positive results AR can achieve, several questions remain unanswered regarding the deployability of these emergent solutions.

3. Methodology

To examine whether AR can be a suitable tool for identifying, prioritizing, and providing solutions to failures related to IT/OT converged systems, a case study is performed for the Dutch Railway company (NS). A qualitative field study is used to support the initial root cause examination by providing more and detailed data analysis of the current situation. This field study supports the motivation of the research by verifying whether the failure of complex IT/OT systems can be detected and further investigated by using AR tools.

3.1 Characteristics interviewees

Participants of this field study were employees of NS. The majority of the group was all within the department of NS-technology. Participants were selected based on their knowledge on IT/OT convergence, data collection and management, innovative technology and maintenance operations knowledge. In total, 28 individuals were selected for interviews representing 35% of the total sample size. This sample size is sufficient within this specific field of knowledge to generate correct information [13]. Table 1 shows the field of expertise of the interviewees, some experts had knowledge within multiple fields.

Table 1. Expertise knowledge.

Focus area	Number of experts
IT/OT convergence	14
Data collection and management	8
Innovative technology	3
Maintenance operations	24

3.2 Field study procedure

The dataset was gathered by using a combination of theoretical sampling and purposive sampling. This results in a process of data collection whereby codes are collected and data analyzed. Based on the analysis, theories can be generated. Interviews were held online in times of Covid-19. Online platforms are suitable for qualitative research to conduct individual interviews as well as small focus groups. Participants were informed about the topic of interest prior to the interview. Each interview was scheduled to take approximately one hour. Semi-structured interviews were used to allow specifying initial questions, if necessary existing questions were specified or innovative questions were proposed to be more precise. During the interview, analytic notes were made. A summary of the interview was shared and discussed with the participants to verify the outcome.

3.3 Field study analysis

Qualitative data was analyzed by performing theoretical latent analysis [14]. Six steps are required to process data from the interviews: (1) familiarize with data, (2) generate initial codes, (3) search for latent themes, (4) review themes (5) define and name themes, and (6) product report. To systematically analyze complex phenomena hidden in the unstructured data, ATLAS.ti is used [15]. The analysis was based on open coding procedures in which codes are not pre-set but developed and modified during the coding process. Quotes of interviewees were assessed and many potential themes are generated for coding. After scoping the content of each theme, thematic analysis can be performed. Throughout the entire study, a constant comparative analysis is performed to find consistencies and differences enabling refinement of the concepts.

4. Root cause analysis through Ishikawa diagram

Preliminary analysis of utilizing AR technologies within maintenance procedures of NS revealed multiple complex and interdependent problems. Understanding, structuring, and prioritizing problems allows obtaining clear and transparent problem identification. A widely-used method in the rail transport sector is Root Cause Analysis (RCA) by recognizing the problem in a structured way. Different problem sources are distinguished and all directly causing an overall effect on identifying IT/OT convergence failures. Quick identification of root cause problems in NS can be achieved by using the causal diagram of Ishikawa, one of the multiple options for performing an RCA. This tool is a suitable instrument in problem-solving methodologies and not only for the analysis of quality characteristics. Recognizing root cause problems enables companies to implement focused and specific improvement actions [16]. The Ishikawa diagram for finding proper tools to identify, structure, and solve IT/OT problems in the current maintenance procedure of NS is presented in figure 2. The diagram is based on interviews and documents collected from NS. Firstly, the factors that affect the utilization of AR technologies are specified. The cause for the failure leads to different failure sources. Secondly, failure causes are grouped into major categories to identify and classify these failure sources. Thirdly, the root causes of the problem can be specified. Lastly, the company can address root causes by allowing specific improvement actions.

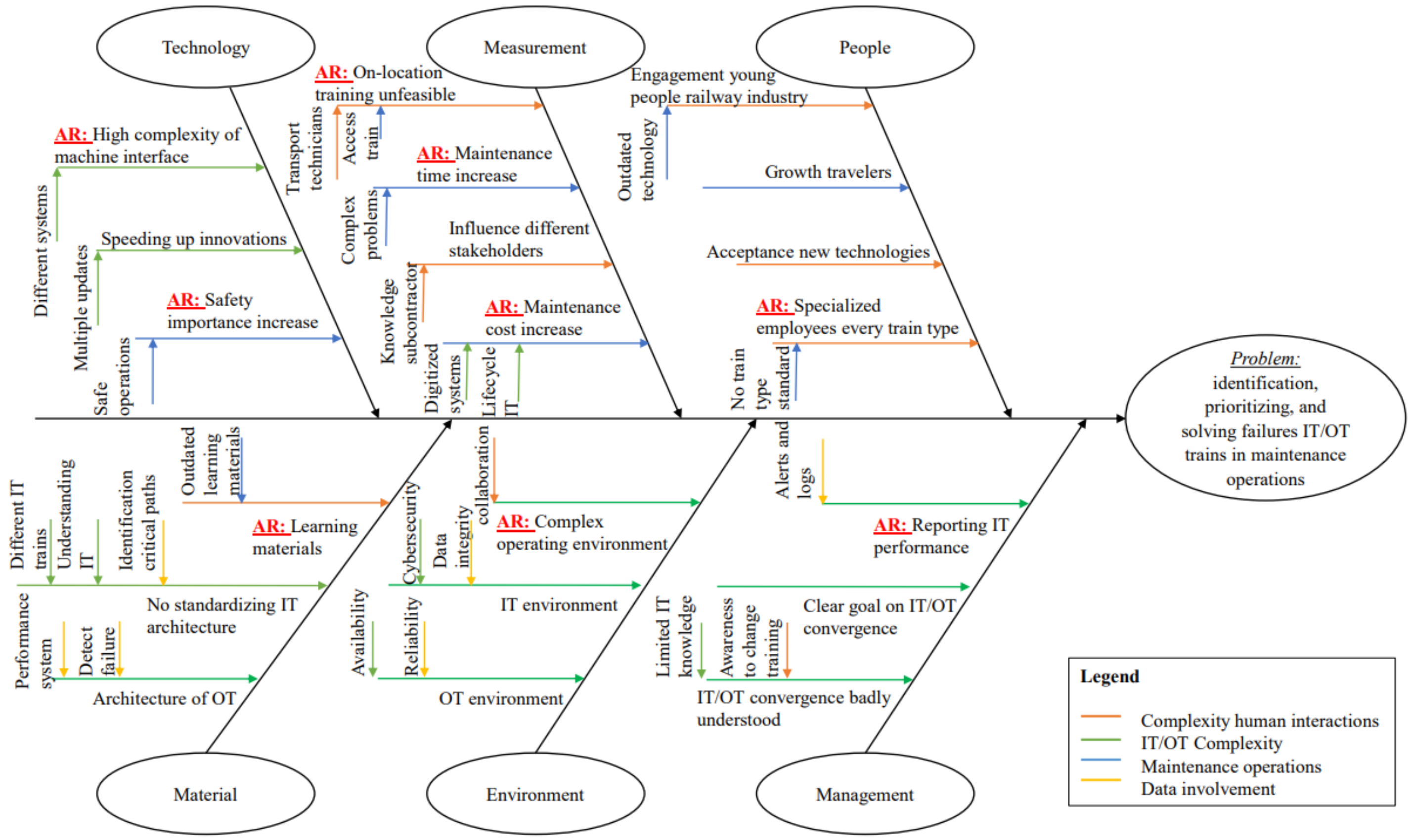

Figure 2. Root cause analysis using the Ishikawa diagram.

5. Field study results

Participants were questioned about four main topics: IT/OT convergence, data gathering and management, transition maintenance procedure, and AR potential application fields.

5.1 Qualitative analysis results

From the interview results, 44 codes were generated. The codes were divided into 8 themes. Table 2 represents examples of how quotes were categorized and form a theme.

Table 2. Quote, category and theme division.

Quote	Code	Theme
AR can be performed on the revision of components, brake cylinders, bearings and low voltage installations.	AR for support maintenance work	Potential applications for AR
Sensitive data needs to be protected at all times	Data related to complex problems	Data complexity
Preventive maintenance of IT/OT systems is in the development phase and currently only used for high-risk cyber-security operations	Comparison of maintenance procedures	Maintenance procedures
IT/OT convergence is difficult due to the complexity of the systems, involving different technologies, employees, equipment and methods	IT/OT complexity	IT/OT failure
A continuous connection between shore and operation is required but not always established	Connection failure	Failure causes
It becomes possible to predict when a failure occurs using data	Future potential of data	Future steps

5.2 IT/OT convergence

Unsurprisingly, 17 individuals are experiencing difficulties with IT/OT convergence. The interviewees mentioned that the convergence of IT and OT systems is becoming more important in the next decade. IT/OT convergence failure is mostly caused by new or incompatible IT systems, software bugs, connection failure, and complex configuration management. Table 3 presents the most occurring failure causes of IT/OT systems. IT/OT complexity represents 41% of all failure causes.

Table 3. Most occurring failure causes of digitized trains in NS.

Failure type	Number of times mentioned by interviewee [%]
Connection failure	15.9
IT/OT complexity	41.3
Mechanical failure	11.1
Software bug	20.6
Configuration management	11.1

Participants did recognize the importance of digitization, citing benefits such as: increased reliability and operability of trains, less downtime, less maintenance cost, and on-time traveling. Other often mentioned topics were about the importance of cybersecurity in which confidential data needs to be protected from cyber-attacks or data leakage.

5.3 Data gathering and management

The results of the field study revealed that data gathering and usage were both considered to be highly complex tasks. Digitized trains generate a lot of data; this large amount of data is stored and protected. Different data types can be distinguished: (1) event data based on diagnostic system and failures, and (2) sensor data which relies on current component condition. However, not all data is analyzed or used. In-house knowledge is not sufficient to be able to transfer all data. Currently, too much data is generated such that it becomes difficult to distinguish and prioritize data. The quality of data highly depends on the data source, this should be accurately representing real and actual data. Finally, data is partially owned by NS, depending on train type and contracts drafted with stakeholders.

5.4 Potential AR applications

Figure 3 presents potential AR application solutions specifically mentioned by the interviewee. The most frequently mentioned examples were: (1) fault detecting, (2) providing work descriptions, (3) inspecting components, (4) remote control, and (5) assistance for specialized work. Different AR application fields can be distinguished. Maintenance application fields offer the best potential for AR technologies. In total, 72% of the interviewees consider maintenance as a good application field.

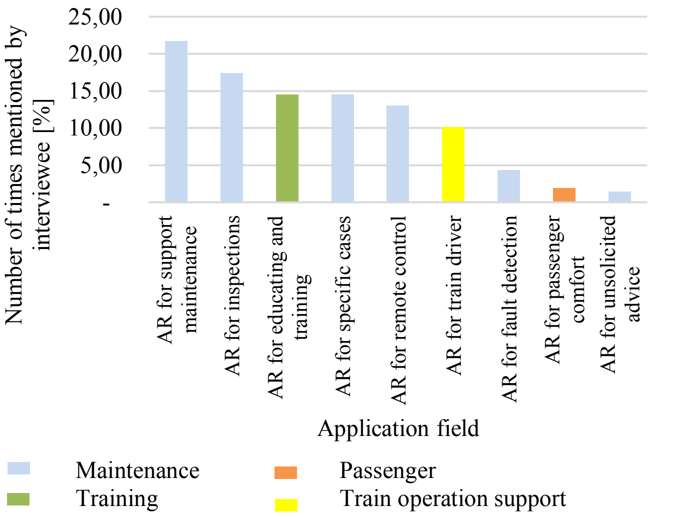

Figure 3. Potential AR applications based on qualitative field study.

5.5 Transition maintenance procedure

Maintenance operations are currently more based on performing corrective and preventive tasks rather than predictive tasks. New IT/OT systems require a different maintenance setup and thus a new and improved maintenance concept. The life cycle of IT systems is significantly shorter compared to hardware systems. Digitized trains can self-diagnose failures by sensing and monitoring current train component conditions. In the future, NS aims to perform primarily predictive maintenance by gathering and analyzing data on the way to Prognostics and Health Management. Failure complexity and transition of maintenance procedures are important to consider as well. When new technologies are introduced, local ambassadors are often used. Local ambassadors test and promote new technologies. Based on the field study, it is estimated that 75% of the technicians will accept the new technology if the tool is user-friendly and supports the work. The AR technologies should be developed in such a way that the use of them does not require intense additional learning trajectories.

6. Discussion

Due to different systems and technologies, machine interfaces are highly complex. From the qualitative analysis, the following benefits of digitization can be drawn: (1) to have safe and reliable operations, (2) less downtime, (3) less maintenance cost, (4) and on-time traveling. The Ishikawa diagram showed that the following root causes can be formulated: (1) increased complexity of IT/OT converged systems, (2) entanglement of failure types, (3) involvement of different stakeholders, and (4) transition towards digitized maintenance operations.

6.1 Root cause analysis

IT/OT becomes increasingly important for the railway industry in the next decade. Operating systems such as cybersecurity and operating physical components are relevant for IT/OT converged trains. Not all converged IT/OT systems have the same, safety requirements, reporting structure, and environment. This means that configuration management must always be up to date.

Failure types highly depend on component lifecycle, knowledge of systems, and complexity of procedures. Based on the Ishikawa diagram and the qualitative field study, the most common failures are: (1) connection failure, (2) IT/OT complexity, (3) mechanical failure, (4) software bugs, and (5) insufficient configuration management. Most failures are caused by complicated IT/OT systems which are often badly understood by the asset manager. This complicatedness is caused by having different and more IT systems on the train and the interdependency of those systems. Due to the digitization of trains, new trains possess more and different functionalities. Current maintenance operations need to be transferred into digital-oriented and data-based approaches. Structured, complete, and clear data is required for AR tools. Proper data sources are not always available, resulting in inaccurate data. Also, data exchange systems are not up-to-date in all occasions. Train data, such as sensor and event data, is gathered and stored in a centralized data repository. The transition to a digitalized maintenance concept creates opportunities to use AR for failures related to converged IT/OT trains.

Different stakeholders are involved such as system integrators, (sub)contractors, and technicians or engineers. Clear collaboration is required to transfer knowledge between stakeholders. Currently, technicians and engineers have limited IT knowledge which is required for configuration management and maintenance of those new technologies.

Specific AR maintenance application fields are (1) fault detection, (2) inspections, (3) unsolicited advice, (4) remote control, (5) special cases, and (6) support of maintenance tasks. Applying AR in maintenance operations ensures early identification and a better understanding of failures, analysing and visualizing component degradation, remote control and assistance, work instructions, assistance for specialized work, and to alert technicians when performing high-risk tasks.

Acceptance of new technology is key when it comes to introducing AR. Concepts need to be introduced properly, preferably by using local ambassadors. The added value of the new technology must be clear and user-friendly.

6.2 Future directions

In the next few years, the transition into digitized maintenance operations will be extremely important for the railway industry as data and real-time monitoring are paving the way towards predictive maintenance procedures. To achieve this, data needs to be exploited for both analysis and making causal connections. Data regarding IT/OT failures needs to be more structured, organized, and prioritized before being able to getting a better insight into systems. Information management must be clear and ensure secure operations. Both IT and OT departments are required to collaborate for broader knowledge sharing. AR opens the way towards structuring and recognizing failures of digitized trains. It is therefore strongly believed that AR is a proper tool to be deployed for maintenance operations in the railway industry.

7. Conclusion

The research presented in this paper suggests that identification, prioritizing, and solving failures of IT/OT converged trains can be performed by using a tool such as AR. Relevant research challenges and future directions in applying AR to complex environments are proposed. Regarding the deployability of technology, it has been shown that the tool can be used in different applications of the maintenance operation. In this article, we proposed a novel direction for providing future directions of AR in maintenance operations for IT/OT converged systems which allow non-experts to take top-level decisions. AR can be used as a tool to support maintenance operations by identifying, structuring, and provide solutions to IT/OT failures of digitized trains.

Although AR has been proven to have good potential in maintenance, repair, service, and inspection, many of these applications are still at the prototype stage and have not found significant adoption in the industry. Looking at the industrial sectors where AR has been used, it is difficult to identify a sector that is especially benefitting from AR technologies [17]. Many technical studies were carried out only in laboratory settings, without implementing the AR system in a real context [7]. Existing real case scenarios lack AR solutions that target specific areas. Prototyping of AR technology in combination with maintenance operations should be evaluated. Different case studies are required to analyze the effect AR has as a tool for identifying, structuring, and solving IT/OT failures. Experts from the industry can verify proposed solutions before direct adoption of results. Other future works will include the implementation in the process of a tool for assessing the ergonomics and economic aspects of the AR application.

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