Operator 4.0: From failure analysis to augmented reality maintenance of a CAN bus system

L.A. Pérez Alvarez

University of Twente, Faculty of Engineering Technology,
Drienerlolaan 5, 7522 NB, Enschede, The Netherlands
l.a.perezalvarez@student.utwente.nl

ABSTRACT: The fourth industrial revolution aims to introduce new technologies to reach a higher interconnection between humans, information technology, and machines, making industrial processes more efficient. However, this interconnection and its consequences have not been deeply addressed. This thesis explores one specific technology that is increasingly applied in maintenance operations, which has shown plenty of benefits, being the empowerment of operators one of the most important. This technology is augmented reality (AR), which shows a digital augmentation superimposed on the real-world environment. The focus of this thesis project is to start from the failure analysis of a specific train component and then design an AR application that aids the operator in the maintenance process. Results are presented, followed by a discussion of the findings and recommendations to implement this technology on a grander scale.

Key words: augmented reality, railway, CAN-bus, failure, maintenance, troubleshooting, train

1 INTRODUCTION

Machine-human symbiosis is becoming a reality in today's industrial world. Human beings cannot be indifferent to this new way of life in which operators and machines work in a much more interconnected and advanced way than ever. The fourth industrial revolution, or Industry 4.0, introduces different technologies such as the Internet of things (IoT) and cyber-physical systems (CPS) to the factory of the future in search of this machine-human symbiosis. These improve industrial performance by making processes more efficient and interconnected, using resources in a better way, and even creating a more inclusive working environment where the operator is the key to development [1].

Information Technology (IT) and Operation Technology (OT) are part of this digitization era. Despite their historical and apparent differences in their field of application within industry, today, it is argued that their integration could bring significant benefits such as better control, performance, and monitoring [2] [3]. Augmented reality (AR) is one of the most promising examples of ITs within Industry 4.0 with an increasing application, especially in the maintenance field. The focus is on improving effectiveness and efficiency regarding "remote maintenance support, teleoperation, system monitoring, and training" [4] [5]. Education, medicine, industry, and entertainment are some of the most recurrent research topics. However, the convergence of IT-OT within the railway maintenance field and the effects on the train operators' role have not been studied. One of the reasons is that due to the long life cycles of existing systems and cumbersome approval and development processes, digitization in the railway maintenance sector is still a challenge [6].

In order to address this lack of information, it is helpful to narrow the analysis to specific information technology and its potential convergence with a specific operation technology. By demonstrating that the introduction of AR is feasible, the implementation of this technology to industrial maintenance practices would open plenty of possibilities. The synergistic interaction between IT, OT, and workforce is expected to cause a socially sustainable revolution, translated into improving the cognitive capacities of the operator of the future [1]. Encouraged operators could carry out demanding and time consuming tasks without the need to be experts, thus avoiding unnecessary costs that would be entailed without these technologies. Considering that new affordable technologies have been developed throughout the years, making AR price competitive.

This research aims to explore the possibilities of Operator 4.0 based on the needs of a railway company. These needs are focused on the failure analysis and integration of augmented reality in the maintenance operations of its trains using existing AR devices. For this, an AR application will be designed to help the operator respond to a specific failure case given by the Nederlandse Spoorwegen (NS), the main Dutch railway passenger operator. It is worth considering that the demonstrator should not be dependent on the device used to run the AR application; this translates to the need for standardization and, therefore, exploration of the convergence of IT and OT.

2 METHODOLOGY

The methodology applied to fulfill the objectives of this investigation consisted of the following parts:

- Literature review of the main topics
- Failure analysis of specific component/system
- Troubleshooting formulation
- Solution design & development
- Discussion of results

Failure analysis is an analysis of the potential risks or failures of a product or process that helps a designer to understand their impact and try to prevent or solve adverse outcomes [7]. In order to develop a failure analysis, different techniques can be used. A top-down type analysis also known as fault tree analysis (FTA) was developed as a first step, considering the failure modes present in the specific component/system given by NS. For this analysis, a deep investigation of the working principles of the system was conducted, and reliable expert information was considered as the failure case complexity requires experimental knowledge. In addition, company experts collaborated by handing their investigation on system failures to narrow the analysis scope to the most critical components on the train.

As a second step, once the failure analysis was developed, a better overview of how to proceed with a clear and structured corrective maintenance process intended to be integrated into an AR application to aid the operator. The FTA was used as a starting point to classify the main overarching failure modes in groups so that the manual could be structured in a more organized way. The main objective is to empower the operator, and therefore the app demanded high intelligibility and clarity.

Finally, the AR demonstrator was designed and developed considering the different types of AR currently existing and the available tools for the study. There are two main categories of augmented reality, triggered augmentation that uses stimuli to initiate and view-based augmentation that projects without reference to the environment. Within these two categories, six different types emerge. These different types can be classified by their complexity, considering the time and conditions required for development [8]. Marker-based, markerless, and location-based are the leading and most used AR types. Due to the project's time constraints and, most notably, the conditions of the given failure case that will be better explained in section 4, marker-based and markerless AR were feasible options. Marker-based is a triggered augmentation that uses markers (i.e., physical objects or paper-based patterns). When the device's camera identifies the markers, it projects 2D or 3D elements of information designed and linked previously in specific software. On the other hand, markerless applications can be deployed by just clicking or selecting the app [9]. The increased usage of AR has brought more technological tools that make switching between both types of AR easier. For the design of this demonstrator, markerless AR was used. Concerning the information projected, 2D elements will be projected, given the complexity of the system and the unavailability of 3D CAD files.

The software used to develop the AR app consisted of Unity, a software to create 2D and 3D experiences, mainly used by developers to create video games. Unity aid with the design of the projected visuals because of its user-friendly environment and excellent compatibility with other building engines and different operating systems [10]. Although the application was designed to be used independent of the device, due to availability and quality, the selected hardware was the Microsoft HoloLens; a head-mounted display device that runs mixed reality applications. The HoloLens features a gyroscope, accelerometer, and magnetometer accompanied by cameras, microphones, and various sensors, giving the user an incredible experience.

3 LITERATURE REVIEW

3.1 Information technology/Operation technology convergence

Information technology is defined as using technologies such as computers or smart devices that generally use software applications to collect, store, and manipulate data. Typically IT is intended to help with planning, decision making, and management processes by improving effectiveness and efficiency since it is an interconnected system, it is flexible and standardized [3]. As a consequence, IT decreases the amount of human intervention and mistakes.

On the other side, Operation Technology concerns industrial control and operations management and, in contrast to IT, focuses on the functioning of specific jobs. It has to do with a specific solution for a given problem [11], which causes a decrease in standardization which means that unique equipment, software, and hardware, must be developed for a specific task. The development of computer-based operational technologies has optimized the production, maintenance, and control processes of different industries to the point that they "sustain the modern economy and business world" [2].

The railway sector has incorporated significant developments through IT on their back-office and trains and OT on their assets. With advancements in the management of rail traffic and train technology, increasing automation and control [11]. However, there is a gap between train technology and the level and frequency of digitization of train operators into maintenance operations. Pressure lies then on the need first to increase smart devices usage frequency (e.g., AR technologies) and second, facilitate information flow from OT to IT and vice versa. The benefits of this interconnected structure will result in "enhanced monitoring, control and decision making, enhanced performance, flexibility, and operational excellence" [3].

3.2 Operator 4.0 and Augmented Reality on Maintenance operations

The concept of Operator 4.0 encompasses the collaboration of operators and technological developments in order to develop complex tasks and solve demanding issues. The operator 4.0 is described as an operator which aided by the use of machines, CPS, and new technologies introduced by Industry 4.0, enhances his cognitive and physical capabilities to perform in a more innovative and interconnected working environment [1] [12]. It is expected that the production industry will become increasingly automated; however, maintenance procedures will still require human intervention. Maintenance operations comprise about 60-70 % of the product life-cycle costs; here, the relevance of optimizing the process and the reason why about 25 % of Industry 4.0 technologies are introduced in the field of remote maintenance [10].

Industry 4.0 has seen the emergence of new and more advanced ITs such as Augmented Reality, which is the superposition of virtual images into the natural environment [13]. Using AR, maintainers can follow super-positioned written or simulated instructions in a real-time interactive way, thus enabling failure analysis and reparation or replacement of certain malfunctioning parts in a user-friendly approach. Technologies such as AR support the envision of an interconnected work ecosystem that enables human-centric development. The opportunity to improve operators' physical and cognitive capacities is present while optimizing processes instead of outdistancing workers [1].

The first projects that applied AR for maintenance purposes were ARVIKA and ARTESAS, both in the automotive and aerospace industries. ARVIKA, more specifically, was used to facilitate the cabling procedure on jets. The research has shown that the application of AR was in principle implemented mainly by military forces due to its capability of reducing task complexity. ARMAR is an example of a project adopted by the department of defense of the USA; its aim was focused on remote maintenance of military vehicles, where information could be exchanged and displayed overlaid [14] [15]. Operator training is another research and application topic as AR replaces old-fashioned training methods with a more interactive experience, making the learning process more efficient and less time-consuming. Different devices support AR applications nowadays; the technological advances in cameras and sensor technologies make AR possible in smartphones and tablets. Besides these portable devices, different head-mounted devices have been developed and are available on the market today. [16].

4 FAILURE CASE: CAN BUS SYSTEM

NS company indicated their interest in analyzing the CAN-bus system of their Verlengd InterRegio Materieel (VIRM) trains, a series of double-deck electrical multiple units (EMU). According to the information given by the company, the malfunction of the CAN bus can cause train stoppage of up to three days, and the current corrective maintenance is based on a trial and error troubleshooting procedure.

4.1 CAN bus introduction

In order to proceed with the failure analysis, the system working principles must be investigated first. The Controller Area Network (CAN) is a communication system widely used for data transmission in different applications as in the automotive and aircraft sector [17]. Trains and other vehicles use a CAN-bus system to facilitate real-time communication between each electronic control unit (ECU), which controls systems as the airbag system, the ABS, or the climate system [18]. CAN bus replaces the point-to-point wiring that would be necessary to allow communication between all of these systems with a serial bus that solves serious cost and reliability issues [19]. Physically speaking, this system commonly consists of a pair of twisted wires that use a voltage difference to send information signals. These two wires that connect the different ECUs in a vehicle are the CAN-H (high speed) and CAN-L (low speed) that are driven to a dominant (logic level 0) or recessive state (logic level 1). The wires are terminated at both ends by 120 Ω terminator resistors to avoid reflection of the signal in the bus[20]. Fig.1 gives a better overview of the system architecture.

As it can be observed, each node represents an ECU which in a vehicle can be used by different critical (e.g., braking) and non-critical (e.g., climate) systems. The ECUs of each node are connected through a CAN controller, which stores and sends the information from the host processor to the bus or vice-versa, Fig. 1. The transceiver is basically in charge of converting the single-ended signal given by the ECU to the CAN differential signal used by the bus, which is basically like converting the signal to an understandable language [21].

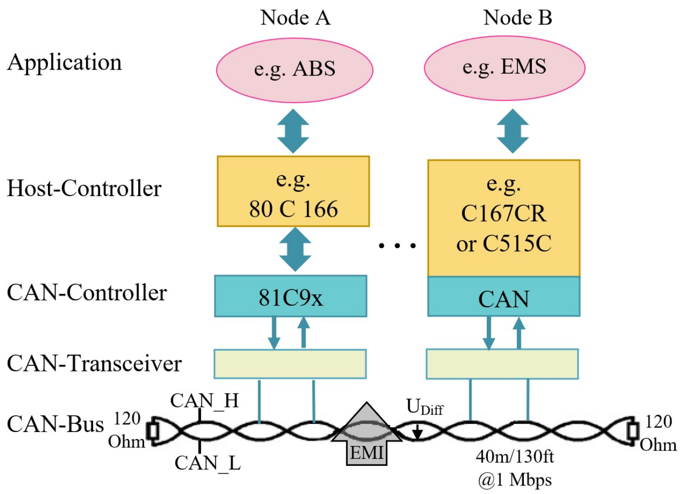

Fig. 1: Architecture of CAN-bus. Modified from [21]

The communication process of the bus will not be explained as it is rather complicated and is out of the scope for the matter of the project. However, it is essential to know about the error handling procedure of the system. CAN bus protocol has specific error detection and fault confinement mechanisms. There are five different error checks performed at bit level that determine successful or unsuccessful transmission. Regarding the fault confinement mechanisms, each node has error counters that will determine the error state of the node depending on the number of the counter [21]. See Fig. 2.

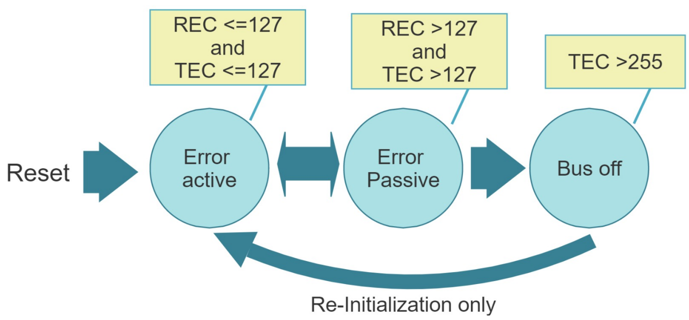

Fig. 2: Error states depending on error counter number. Modified from [21]

There are three error states; "error active," "error passive," and "bus off." Error active is the default state and typically allows data transmission and reception of the node; in error passive, transmission is possible after waiting for 8 bits after the last frame transmitted. The bus off state stops all communication transmission from the specific node. The counter depends on communication success; if a frame is successfully transmitted, the counter decreases a specific number, in case of transmission errors, the counter will increase. If the bus reaches the bus off state, the counter can not decrease, and the system must be reinitialized [17] [21]. In 2, TEC is the transmit error counter, and REC is the receive error counter.

4.2 Failure Analysis

Now that the system is better understood at the data layer level and its error handling was explained, it is paramount to investigate the possible causes of communication failure at the physical layer level. Before proceeding with the CAN bus physical analysis, it is necessary to understand which ECU's are connected to the bus and their function on the train. Trains have different kinds of communication systems, and the CAN system is only one of those; it connects specific controllers in charge of certain specific functions. NS facilitated access to the FMEAs of three different systems connected through the CAN bus. These FMEAs facilitate the identification of the systems that are most affected by a CAN-bus failure. The systems were analyzed based on different aspects using a comparison procedure similar to the one used in the FMEAs, with a scale from one to ten being one the minimum and ten the maximum of each parameter.

The different systems and the individual evaluation are illustrated in Fig. 3. In the figure, the parameter "CAN issues" represent the number of CAN-related failures found in each system's FMEA, and the parameter "Result" indicates the chosen system.

Systems / Parameters	Water & Waste system	Climate system	Door panel system
CAN failures	2	1	0
Frequency	4	5	/
Severity	5	2	/
Detection	3	2	/
Results	60	20	0

Fig. 3: Comparison table for critical system classification

According to Fig. 3, the water and waste system shows more frequent and severe CAN bus failure. This is important to consider because, in the end, this analysis will better indicate to the operator which of the systems is causing more disruptions in the train and should be addressed first. The main issue is that the exchange of information is unreliable due to improper interface communication. The main consequence of this lack of communication is that the status and maintenance information about the toilet system of the train and waste system of the train is not shown or is incorrect. On the other hand, the climate system failures due to CAN irregularities affect the heating, ventilation, and air conditioning (HVAC) system, causing the train's mainly wrong temperature or airflow control. In addition, it could be identified that the door panel system does not present any CAN bus failure and that most of the problems are due to the corrosion of components. However, these kinds of failures are rare, not severe, and easily detectable. Fig. 4 shows the climate module of one of the NS trains with the CAN-H and CAN-L wires connected.

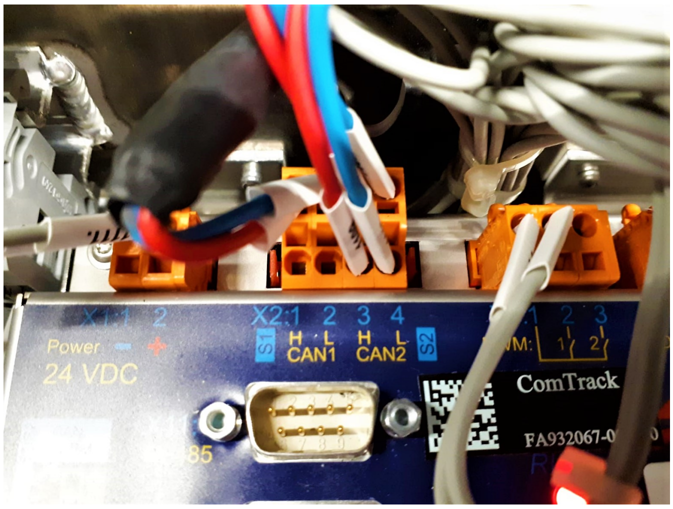

Fig. 4: CAN wires connected to the the climate module. (A.T. Kok, personal communication, June, 2021)

These failures can have different causes, and this section focuses on giving a detailed classification of the root issues that lead to complete train breakdown. Communication problems can be caused due to failures with; a specific system on the train connected to the CAN bus, the CAN bus itself, or the central computing unit (CCU). As explained previously, the target is the analysis of the CAN bus system only; therefore, investigation on specific systems and the CCU is not considered. Fig. 5 shows the final FTA focused on the CAN-bus system.

4.3 Troubleshooting

According to the company, operators are trained by the leading supplier Stadler in train maintenance. The failure information given to the operators specifically about the CAN system is minimal. The operators nowadays depend on a device called CANtouch,

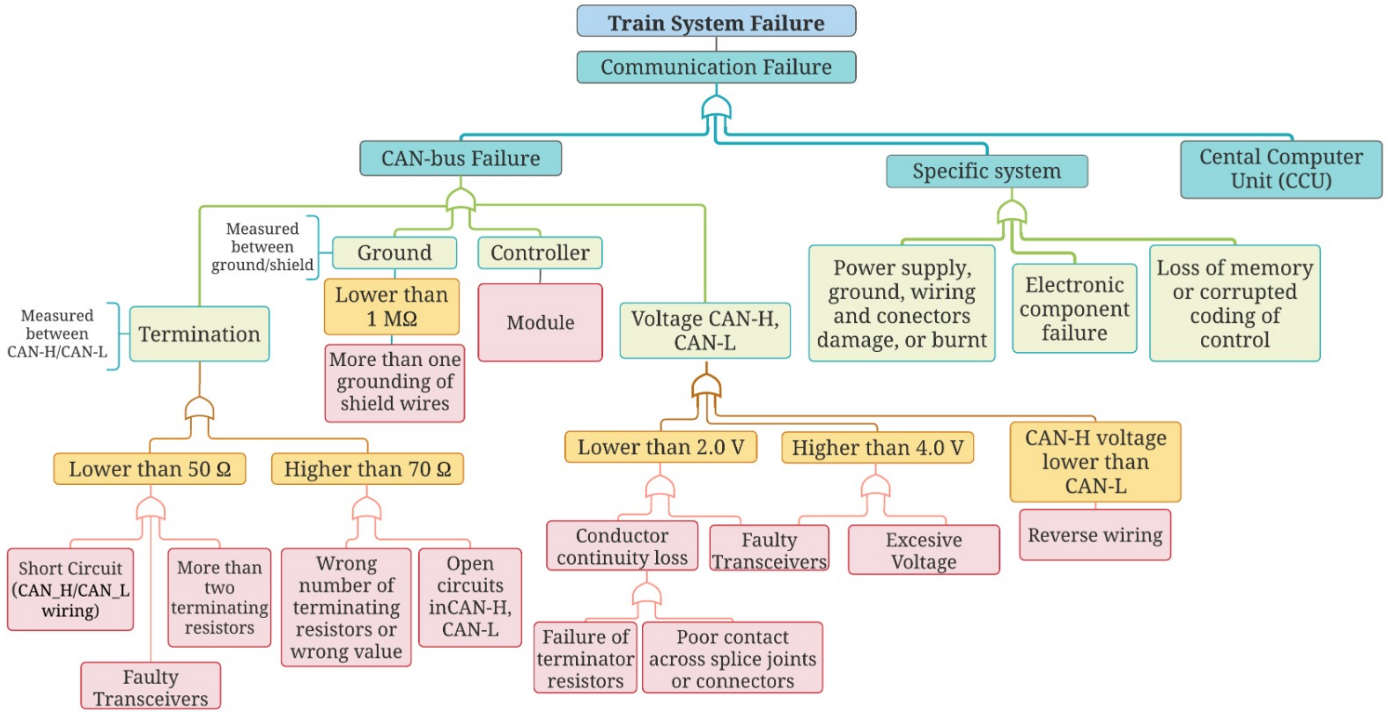

Fig. 5: Fault tree analysis of the CAN bus system

which serves as a diagnosis device connected to the CAN system, giving indications of the location of the error. Nevertheless, it can be time-consuming, inaccurate and if not available, the operators must do the troubleshooting process manually without a straightforward process. Therefore the troubleshooting procedure in case of train malfunction caused by this system is not done correctly.

From the FTA, important information was noticed. Four main failure groups can lead to CAN system failure, and the identification of these groups was vital to the design of the maintenance process in the app. For the troubleshooting procedure, experts' research and practical work [22] [23] [24] were taken into consideration. All the instructions are action verbs that specify each step that must be followed to fix any problem successfully. It has to be noted that this troubleshooting procedure is standard, and in case the problem persists, the other components as the different ECUs or the CCU, should be analyzed in a similar approach to get a complete overview. However, this process would take more time and expertise in reliability engineering, software engineering, and maintenance engineering, and of course, close interaction and knowledge of the system itself.

A summarized version of the instruction manual for the failure identification is depicted in Fig. 6. This procedure now represents a set of organized guidelines that will help the operator to keep a better overview of the process, increasing its efficiency. The figure shows six overarching groups; in addition to the four failure modes visible in the FTA, faulty transceivers can be identified using a different procedure based on measuring DC resistance. A recommendation section was also added to ensure optimal inspection of the system.

5 RESULTS & DISCUSSION

The previous section presented important information that was used as input for the development of the AR solution. This section will focus on the solution design and development. As unity was the program used to create the application's visuals, it was necessary to set the program for mixed reality development. Unity facilitates all the processes; however, as the first device used for the demo is the HoloLens, extra features and packages were demanded to build and run the app correctly and smoothly as the MRTK package, which facilitates the creation of buttons compatible with the AR device.

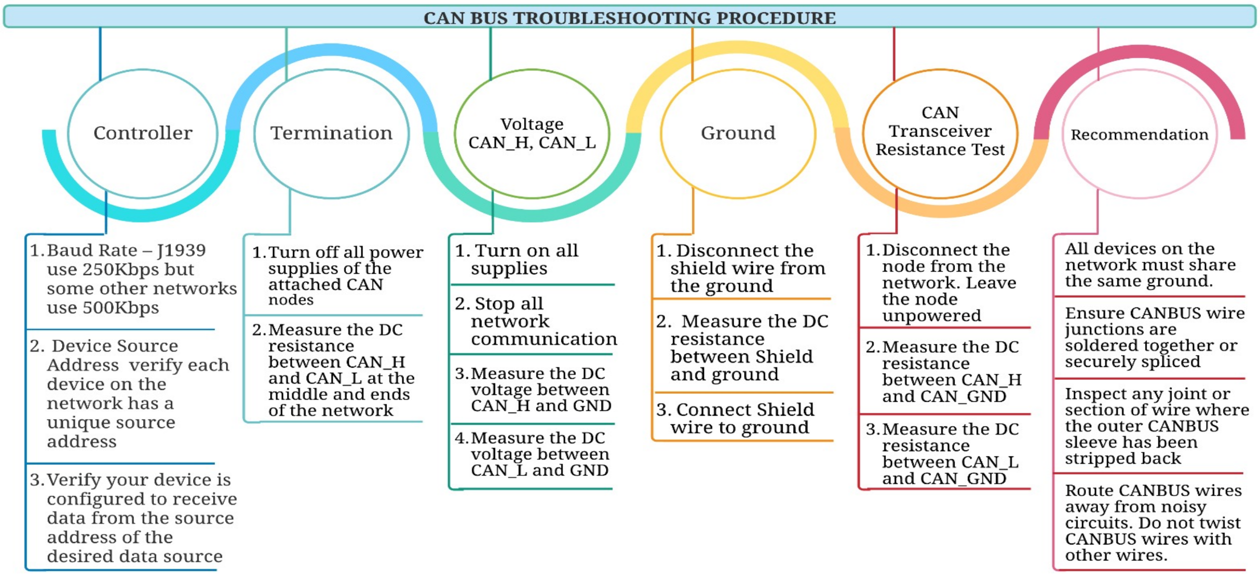

Fig. 6: Troubleshooting procedure for the CAN bus system

The demo is called *"CAN bus diagnostics"*, and there are four interfaces. The **"Main interface"** of the demo, displayed in Fig. 7, shows the start and quit buttons. In addition, the settings button, which is intended to display different options like language translation or speech recognition. The aim was to make the app functional, user-friendly, and also visually attractive. The operator using the Hololens device will open the app, and the image will appear as an interactive hologram with the NS company's colors on it. In the case of this study, the hologram will appear as a 2D overlaid in the operator view field in the actual work environment. This 2D hologram can be located in the operator's preferred spot to avoid visual obstruction during the maintenance while still granting the application's good visibility. The transparent background with only the frame, buttons and letters ensure low eyestrain and prevents possible motion sickness.

The **"Introduction interface"** provides safety considerations for the user and a short description of the app basics. It is important to remember that this kind of technology can be risky if not consciously used. For this reason, it is stated in yellow italics that the app was designed only for NS mechanics or engineers. Furthermore, a default order for the troubleshooting is divided according to the main failure modes. As shown in Fig.8, this interface introduces a "Modes" button, enabling the operator to navigate freely through the different modes in case the default way is not desired. Consequently, the **"Modes interface"** acts as a navigation portal to the different failure overarching sections.

Fig. 7: CAN bus diagnostics "Main interface"

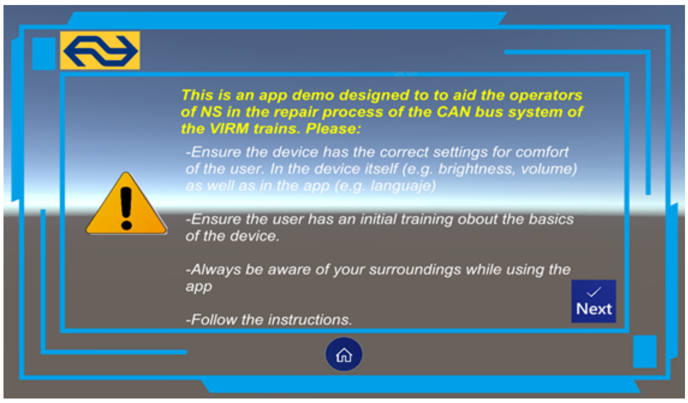

Fig. 8: CAN bus Safety recommendations

The **"Instructions interface"** is the last and contains the essence of the app. An example of a list of steps and understandable figures that were implemented for the maintenance of termination failure Fig. 9.

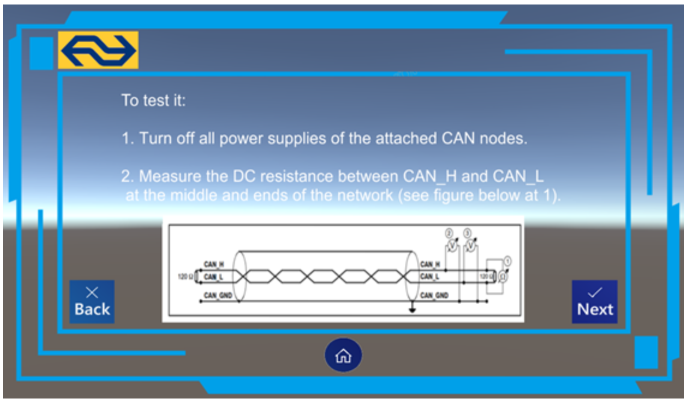

Fig. 9: Instructions for termination failure detection

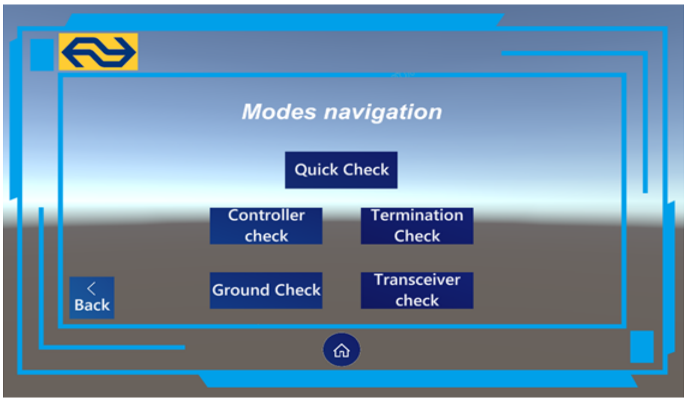

Fig. 10: Final ”Modes interface”

Even though the desire was to get some quantitative data to evaluate the program's benefits to the operator, the NS company could not allow access to the repair shops or the operators. The app's first version was sent to two engineers working on the company, a reliability engineer and an expert engineer on the CAN bus system. From their feedback, some changes were applied. The experts expressed the impracticability of measuring the voltage between CAN-H and CAN-L, as all communications in the network would need to be stopped. Consequently, the voltage section of the demo was removed. Due to the detailed analysis and design, the engineers recommended making an even summarized version. Therefore, another version was implemented to the original demo. The new version is called ”Quick check” and contains six key steps regularly encountered as the failure root. The ”Quick check” version button was added to the ”modes interface” and is placed first in the default order of the app so that only in case the quick check does not provide a solution the extended version will continue. The final ”Modes interface” can be observed in Fig. 10

6 RECOMMENDATIONS

Some aspects of this investigation can be improved to enhance the solution quality in the future. It should be stated that the current health situation worldwide did not allow the company to give access to its repair stations to observe its trains and acquire more practical knowledge based on the experience of the company's workers. In addition to giving a better insight into the CAN bus itself, its location on the train would give a better understanding of the workspace, which would be an imperative input to consider while developing the app. Due to this and because the system has a relatively complex operation, this app represents a first but essential step towards total human-machine interconnectivity. In terms of software development, many other features can be added to utilize the full potential of AR. The implementation of each additional feature is proportional to the time invested in its design, so it would take much more time than is available for the current project. Depending on the accessibility to 3D CADs, the holograms could be presented as 3D animations or even videos. Another exciting feature is the remote assistance that solves distance obstacles and facilitates communication via holograms in which the engineer can show procedures in real-time to the operator. Optimal IT/OT convergence should be further investigated to allow the storage and exchange of training data taken from the AR app to create databases with information about successful failure detection. Machine learning is an option that would provide valuable predictions for future malfunctions by creating and processing these databases, thus leading to an improved linkage between IT and OT.

7 CONCLUSION

This thesis project's main objective was to investigate the possibilities of transforming current maintenance procedures by using analysis and innovation to improve procedures' efficacy, efficiency, and quality. Based on Industry 4.0, IT, and OT, a final solution was proposed to explore the interconnection between these topics, often addressed separately. Initial work on the interconnection between IT and OT was intended as control and decision making processes are enhanced by the app developed. However, machine learning or IoT are examples of crucial developments needed to accomplish a significant interrelationships. The study of the CAN bus shows an example of transformation: taking the current lack of a structured and organized procedure inside the company through the failure analysis of the system to end with a supportive AR application. The methodology applied considered the standardization aspect of the project, which enables replicability to create a solution for any other required components, devices, or systems in the railway industry and possibly other industries. Unity and Visual studio, the programs used, provide the possibility of building the app for different devices working on, for example, android and IOS. The analysis and the developed application provide a virtual manual that displays clear instructions to the operator overlaid in the work zone, representing many benefits for the mechanic, such as interactivity, time-saving, and interconnection. The benefits offered to the company by using AR are the ease of storage, updating, and translation if desired. However, the most critical benefit is empowering the workforce to use new technologies, adapt to the factory of the future, and support their cognitive development.

8 ACKNOWLEDGEMENTS

The author wants to thank the given support and supervision of Dr. A. Martinetti and Ph.D. candidate Sara Scheffer. Thanks to the recommendations of A. Kok, NS engineer. The Ministry of Education of Ecuador and SENESCYT are acknowledged for the scholarship granted to the author. Finally, the author expresses his gratefulness to his family and girlfriend for their unconditional support and friends for being a source of motivation and guidance for this project.

REFERENCES

1. D Romero, J Stahre, and M Taisch, The operator 4.0: towards socially sustainable factories of the future., *Computers and Industrial Engineering*, (2020), 139.
2. A. M. TITU and A. STANCIU, Merging operations technology with information technology, In: *Proc.* , *2020 12th International Conference on Electronics, Computers and Artificial Intelligence (ECAI)*, (2020), 1–6.
3. Francis Pol Lim, A research analysis on the convergence of information and operational technologies in business, *Journal of Next-generation Convergence Information Services Technology*, (2016), 5(1).
4. H. Regenbrecht, G. Baratoff, and W. Wilke, Augmented reality projects in the automotive and aerospace industries, *Ieee Computer Graphics and Applications*, (2005), 25(6):48–56.
5. D Mourtzis, J Angelopoulos, and V Zogopoulos, Integrated and adaptive ar maintenance and shop-floor rescheduling, *Computers in Industry*, (2021), 125.
6. Antonio Berrios Villalba, How to speed up digitization in the railway [viewpoint], *IEEE Electrification Magazine*, (2020), 8(1):76–75.
7. Jim Glansey, Failure analysis methods what, why and how, (2006).
8. Amanda Edwards-Stewart, Tim Hoyt, and Greg Reger, Classifying different types of augmented reality technology, *Annual Review of CyberTherapy and Telemedicine*, (2016), 14:199–202.
9. Anuroop Katiyar, Karan Kalra, and Chetan Garg, Marker Based Augmented Reality, *Advances in Computer Science and Information Technology (ACSIT)*, 2(5):441–445.
10. Fotios K. Konstantinidis, Ioannis Kansizoglou, Nicholas Santavas, Spyridon G. Mouroutsos, and Antonios Gasteratos, Marma: A mobile augmented reality maintenance assistant for fast-track repair procedures in the context of industry 4.0, *Machines*, (2020), 8(4):88.
11. Mark Kraeling and David Fletcher, Railroad Assets: Information and Operational (IT/OT) Convergence, *Product Management and Architecture, GE Transportation*, 11 2017, 1.
12. David Romero, Peter Bernus, Ovidiu Noran, Johan Stahre, and Åsa Fast-Berglund, The Operator 4.0: Human Cyber-Physical Systems & Adaptive Automation Towards Human-Automation Symbiosis Work Systems, *IFIP Advances in Information and Communication Technology*, (2016), 488:677–686.
13. Miguel Núñez-Merino, Juan Manuel Maqueira-Marín, José Moyano-Fuentes, and Pedro José Martínez-Jurado, Information and digital technologies of Industry 4.0 and Lean supply chain management: a systematic literature review, *International Journal of Production Research*, (2020), 58(16):5034–5061.
14. W Wei, L Songgui, L Haiping, L Taojin, Q Jue, and Q Ang, Augmented reality in maintenance training for military equipment, *Journal of Physics: Conference Series*, (2020), 1626(1).
15. D. Mourtzis, V. Zogopoulos, and E. Vlachou, Augmented Reality Application to Support Remote Maintenance as a Service in the Robotics Industry, *Procedia CIRP*, (2017), 63:46–51.
16. Steven J Henderson and Steven K Feiner, Augmented Reality for Maintenance and Repair (ARMAR), (2007).
17. B. Gaujal and N. Navet, Fault confinement mechanisms on can: Analysis and improvements, *IEEE Transactions on Vehicular Technology*, (2005), 54(3):1103–1113.
18. J.P. Acle, M.S. Reorda, and M. Violante, Early, accurate dependability analysis of CAN-based networked systems, *IEEE Design and Test of Computers*, (2006), 23(1):38–45.
19. Jiří Kotzian, Ivo Rehberger, and Vilém Srovnal, Can Bus Communication Modelling, *IFAC Proceedings Volumes*, (2003), 36(1):347–350.
20. Jarosław Jajczyk and Krzysztof Matwiejczyk, CAN bus diagnostics, (2014), 12:376–385.

21. Inc. Siemens Microelectronics, Canpres version 2.0, (1998).
22. Kvaser, Augmented Reality Application to Support Remote Maintenance as a Service in the Robotics Industry — Elsevier Enhanced Reader.
23. Esd electronic system design gmbh, CAN-Troubleshooting Guide Rev. 1.1 Seite 1 von 8 esd electronic system design gmbh CAN-Bus Troubleshooting Guide.
24. Enovation Controls, CAN BUS Troubleshooting Guide (with Video) – Enovation Controls Help Center.