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An innovative methodology for enabling predictive maintenance of ship systems based on Industry 4.0 technologies

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Abstract

Since their introduction, the so-called disruptive technologies related to the development of the Industry 4.0 paradigm have been under the spotlight of industries and companies across various sectors. This trend has also inevitably drawn interest of a very traditional sector such as shipbuilding, with a specific look to design, management and maintenance phases. To remain competitive on the market, shipbuilders and shipowners must ensure high levels of reliability for their ships, directly impacting how maintenance procedures are carried out. In this regard, Virtual and Augmented Realities, combined with other Industry 4.0 technologies such as sensors for real-time data collection and QR-coding techniques, can provide huge benefits in terms of personnel training and simplify operations for on-board technical officers. This paper provides a brief overview of how maintenance in shipbuilding has traditionally been performed in recent years. The authors then present a novel methodology aimed at preliminarily enabling predictive maintenance on board ships, developed by leveraging Industry 4.0 technologies and applied on a real case study based on the engine room of a large pleasure yacht. Specifically, the approach is based on the combined use of Augmented Reality and QR-coding technique and exploits accurate 3D virtual models of both the ship and equipment. These models can be explored and investigated by means of tablets, smartphones, and smart glasses, giving direct access to technical documentation and maintenance instructions in their digital form. Ship system designers and on-board personnel were involved in the initial testing phases to evaluate the benefits of the proposed innovation. The outcomes highlighted a significant reduction in human errors and execution times of ship maintenance operations, along with increased simplification of tasks for crew members.

Keywords: Shipbuilding; Ship Engine Room; Predictive Maintenance; Virtual and Augmented Realities; QR-coding Technology.

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1. Introduction

In the wake of Industry 4.0 innovation process, the shipbuilding industry is keeping the pace to adopt the fundamental principles of this revolution to maintain its importance in the global economy [1–3]. The recently introduced disruptive technologies related to digital transition and automation have become crucial tools to guarantee products reliability and minimise human efforts and errors. In fact, the implementation of advanced sensor networks, Virtual and Augmented Realities coupled with visualisation devices, and Block Chain technology offers significant opportunities for facilitating the exchange of data. In this context, a fundamental activity such as maintenance can greatly benefit from the introduction of new and advanced approaches [4–6]. While other industrial sectors have long recognised its importance and worked constantly to bring improvements, shipbuilding has been notably slower in understanding the economic and safety advantages that an effective maintenance system can offer [7].

Traditionally, shipowners have resorted to corrective maintenance plans based on actions taken only after a failure occurs, with consequences such as the operational downtime, long lead times for the procurement of spare parts, and damage that a failure can cause to other systems. These issues can potentially impact the safety of the crew and passengers as well as the survivability of the ship itself [8]. With the increase in ship dimensions, shipowners began relying on preventive maintenance approaches based on periodic inspections, which allow interventions before damage occurs [9]. However, technologies are advancing furtherly and the next target for shipbuilding should be reaching a predictive maintenance approach. This could be supported by implementing a systematic monitoring of the actual conditions of machinery, enabling in-depth analysis to understand the root cause of problems and basing interventions on these data [10, 11]. Implementing this approach meets the demands of ship maintenance by ensuring precision, agility, versatility and optimization of timing, and represents a significant step towards modernizing the sector and increasing its efficiency at the same time.

In this paper, the authors focus on the crucial theme of maintenance in shipbuilding and aim to provide innovative solutions to accelerate the adoption of the most advanced technologies that can facilitate digital transition in the field. The main aspects of maintenance in shipbuilding, as discussed in Section 2, form the basis for understanding how Industry 4.0 technologies, described in Section 3, can be applied. Finally, in Section 4, the authors describe a novel methodology based on the development of a digital application that leverages Virtual and Augmented Realities and QR (Quick Response) coding technologies. The proposed solution aims to preliminarily enable predictive maintenance on board ships, with its peculiarities demonstrated through a real case study involving the engine room of a large pleasure yacht that allowed highlighting the greatest benefits coming from adopting such a solution.

2. Maintenance in shipbuilding

2.1. Definition and basic principles of maintenance

The term "maintenance" refers to all the operations necessary to keep a system, apparatus, or component in good condition, ensuring its functionality and efficiency while addressing any faults that may occur [12]. Over time, the concept of maintenance has evolved notably to not only preserve usability and economic value over time but also to potentially enhance these attributes, thus requiring careful design and planning.

The basic principles of maintenance are universal for all systems and technologies. As a common process, maintenance includes actions such as inspection, testing, fault detection, measurements and adjustments of operating parameters, component replacement and repair, and system tuning. Maintenance is categorised as either ordinary or extraordinary [13]: ordinary maintenance involves planned routine operations and fault prevention, including preventive and corrective/improving maintenance, whereas extraordinary maintenance involves unplanned action due to sudden breakdown or malfunctions, often requiring major repairs or replacements. As shown in Fig. 1, preventive maintenance can be further subdivided into fixed and predictive, with the latter being preferable as it is based on the so-called "condition-based maintenance". This approach involves constant monitoring and diagnostics of the entity's functioning and status over its lifetime, thereby avoiding unnecessary and expensive interventions [14].

At a more structured level, maintenance is expressed differently across industrial sectors, depending on the product design, technical and economic analysis and portfolio, policies, and working methods. For shipbuilding, maintenance practices have evolved over time to specifically address the unique characteristics of ships, as discussed below.

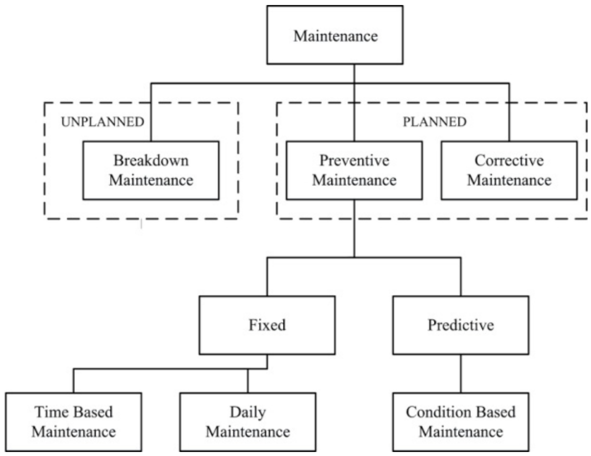


Fig. 1. Types of maintenance activities [13].

2.2. Peculiarities and evolution of maintenance in shipbuilding

Most of the time, ships are not mass-produced but are characterised by differences and distinctive traits based on both the shipbuilder's and shipowner's choices and requirements. As a result, machinery and equipment that require maintenance may vary even on ships belonging to the same series. This has necessitated an advanced development of maintenance process, which for years was based on activities undertaken as needed and relied heavily on the knowledge and experience of the on-board engineer. In fact, maintenance initially aimed to reduce sudden failures and keep the ship operational, serving as a simple repair operation to which limited economic resources were devoted.

In recent years, however, the shipbuilding industry has begun to recognise the importance of establishing a maintenance plan as the set of activities aimed at qualitatively improving ship performances, reducing waste of time and money on equipment repairs, and increasing economic profits [15, 16]. In response, maritime regulatory bodies have adapted existing standards from the industrial world to meet these new requirements. Specifically, regulations have evolved from initially covering only procedures for corrective maintenance to also encompassing preventive maintenance based on planned periodic surveys [17].

The introduction of preventive maintenance has been deemed necessary due to several critical aspects unique to ships that make maintenance activities more challenging compared to those in land-based industries. For instance, procuring replacement components can be complex and time-consuming if the vessel is sailing in remote areas [18]. Additionally, performing accurate interventions can be further complicated by the limited spaces characteristic of ship technical rooms where equipment is allocated. Although the position of each specific piece of equipment is decided during the design stage with potential maintenance needs in mind, there can be situations in which a component is not easily accessible, limiting the freedom of movement for technical personnel in charge of restoring measures. Finally, in the most serious cases, maintenance on ships may need to be carried out in dry dock, with the consequence of leading to a halt in operability and revenues, coupled with high expenses for the necessary interventions. For these reasons, constant monitoring of equipment status to prevent sudden failures and to allow for part replacement only when absolutely necessary has become increasingly important, driving the evolution of ship preventive maintenance into predictive maintenance [7]. In this framework, the shipbuilding industry will need to increasingly rely on condition-monitoring techniques and the most advanced technologies associated to Industry 4.0, as explained in the following sections.

3. Industry 4.0 technologies to support maintenance on board ships

To enable a fast and effective transition to predictive maintenance in the maritime sector and on board ships, devices capable of systematically monitoring the status of machinery and systems and collecting real-time data regarding their operating conditions are essential. Additionally, other technologies developed within Industry 4.0 and related to the evolution of IT equipment may be integrated as key tools to exploit predictive maintenance's huge potential [19–22]. Specifically, attention should be focused on advanced sensors, Virtual and Augmented Realities, and Block Chain technology to facilitate the instant transfer and exchange of information and technical data, as detailed below.

3.1. Real-time monitoring of equipment

Within the shipbuilding framework, the possibility of installing a dense network of sensors to detect performance data from equipment has already been studied by the authors with specific reference to in-live monitoring of main engines [23]. Still, the previous research was not focused on enabling predictive maintenance but rather on adjusting operating conditions to reduce fuel consumption and pollutant emissions. Starting from the assumptions made in this earlier work, the importance of establishing precise mathematical models that accurately reproduce the exact functioning of components becomes apparent [24]. As a further step, these virtual replicas could support the accurate determination of equipment degradation and its remaining useful life [25].

To effectively apply this approach, the signals deriving from instrumental diagnostics must be correctly interpreted and integrated with the software designed for maintenance management. In this regard, artificial intelligence and machine-learning techniques are particularly useful, as they enable the accurate interpretation of the collected data necessary for modelling the complex non-linear systems that characterise equipment functioning. As a result, an extensive network infrastructure involving sensors and information storage is required. The latest technological innovations, including Internet of Things (IoTs), Cloud Computing, and Big Data, must be integrated on board ships to create an advanced predictive maintenance system based on cloud platforms. To this end, ensuring extremely fast communication systems between sensors and data storage is essential. Since this process involves the transmission of large amounts of data, enhancing the efficiency of the ship's on-board network is required. As ships are *de facto* isolated steel structures, they present unique challenges that can cause connectivity issues during navigation in remote areas and signal disturbances. To overcome these challenges, modern ships are equipped with advanced connection solutions that guarantee stable connectivity and deploy signal repeaters strategically. For example, beacons are small electronic sensors that use low-power Bluetooth technology or radio waves of different frequencies that can facilitate data transmission to and from other electronic devices. These beacons, which can be powered either by their internal batteries or the ship's electrical power, communicate within their range based on GPS positioning. A network of beacons covering the entire ship can significantly enhance maintenance activities by providing precise spatial mapping of the various spaces and integration with advanced sensors. In such a way, when an anomaly is detected, the relevant beacon can notify the technical personnel, assisting in the rapid tracking and resolution of the issue.

Equally important is ensuring that the network of sensors is placed to cover every interested component and maintains continuous reliability. As often ships are not rapidly reachable to replace any damaged device, the network architecture must be based on the redundancy of each fundamental part of the system, including sensors, connectivity tools, hardware, and data management software. This approach ensures the functionality of the entire network even in the event of a localised malfunction. Finally, as machinery and equipment can be supplied by various manufacturers, another challenge in implementing IoT technologies on ships is connecting all the monitored components with the web platform and the data management software used, which in turn must convert data into a format understandable by technical personnel and provide all the necessary information to ensure the correct maintenance procedure.

3.2. Virtual and Augmented Realities and QR-coding technology for data collection and exchange

Virtual and Augmented Realities allow users to interact with the digital world at a highly enhanced level. Specifically, with Virtual Reality (VR), a digital simulation of physical objects can be created and explored, while Augmented Reality (AR) enables the introduction and superimposition of digital models onto the physical world.

As published by the authors in [26], the level of realism reached by virtual models today makes them excellent tools for managing both quality and maintenance on a ship. Indeed, each individual piece of equipment within the virtual model carries all the technical and operational information provided by the manufacturer [27, 28]. Even before construction begins, virtual models allow exploration of the vessel, equipped with all its components and structures, and enable assessing system positioning. Interferences, lack of space for crew passage in restricted areas, and insufficient space for dismantling and repairing parts during maintenance can be instantly checked, reported to the design engineer, and corrected. Specifically concerning maintenance operations, a virtual and interactive model of the ship can be used in conjunction with specific devices (i.e., VR visors such as smart glasses) to train the crew before the ship is actually built. This allow them to familiarise with the room and machinery layout and to learn how to operate on the various pieces of equipment following maintenance procedures [29].

As for AR, this technology can be exploited to ensure the immediate access to real-time data regarding equipment position and health status, transmitted by the aforementioned network of sensors and beacons. In fact, by means of smart glasses and tablets, the virtual model developed during design phases can be partially superimposed onto reality, allowing technical personnel to rely on an interactive map of all the ship's systems to identify their actual on-board positions. If a piece of equipment shows signs of malfunction or anomalous data, the relevant manager will receive a notification signal while the position of the component will appear on smart glasses and tablets, allowing the identification of the fastest path to reach it. Thanks to the information stored in the virtual model, technical personnel can rely on a complete documentation package necessary to carry out normal operations and urgent interventions.

Access to such data can also be facilitated by the presence of specific QR-coded targets positioned on each machine or component, which could provide relevant information even in case of the absence of an actual network of antennas and transmitters [30]. In fact, QR-code matrices developed for systems, machinery, or elements present on board can allow the immediate opening of maintenance-related documentation, which can be read both through smart glasses and tablets. Furthermore, 3D models could be visualised and be queried to ease recognising the various parts of the machinery, while virtual animations could serve as a guide to perform repairing and replacing components.

4. Novel methodology for enhancing predictive maintenance of ship systems

As seen in the previous Section, Industry 4.0 paradigm offers valuable technologies to support the transition to predictive maintenance on board ships. In the following, a novel approach developed by the authors, which integrates Augmented Reality and QR-coding techniques, is presented and commented by means of a real case study.

4.1. Case study description

A large pleasure yacht was used as a case study by the authors, with specific reference to its engine room. This space, along with all the machinery and equipment arranged within it, was modelled using some of the most advanced 3D CAD tools currently available on the market. The final result is a highly detailed model that accurately represent the layout of both structures and systems. Within the model, all present objects can be shown or hidden according to the designer's necessities. This allows the possibility to isolate individual machinery or equipment to focus on that part and verify that everything is coherently arranged. The ultimate goal is to detect any potential interferences and resolve related issues already during design phase. From a maintenance perspective, the model provides the necessary level of detail for technical personnel to begin virtually exploring the ship, getting used to the spaces, learning the positions of the main and auxiliary machinery, and memorising the routes and actions required in the event of an urgent repair. In fact, as walkable areas were defined during the model implementation, the ship's engine room can be accessed using virtual visors, allowing crew members to move inside it just as they were actually on board. It is also possible to point to any machine and receive information about it, increasing the level of integration between real and virtual world. Figure 2 show some images from the model and highlights the high accuracy of both structures and system equipment.

4.2. Digital application based on Augmented Reality and QR-coding

To assist shipowners in managing ship maintenance and to facilitate the performance of these tasks by the technical personnel, the authors propose leveraging Augmented Reality to address potential issues that may arise during scheduled activities or in the event of breakdowns. In fact, despite their training, on-board technical staff must rely on the manuals provided by the suppliers of each piece of machinery and equipment to carry out all the individual steps required for maintenance and restoring operations, especially during long and complex procedures. Up to now, instruction manuals have only been available in paper form on board ships, necessitating the storage of these documents in safe and accessible spaces that can be quickly reached when necessary.

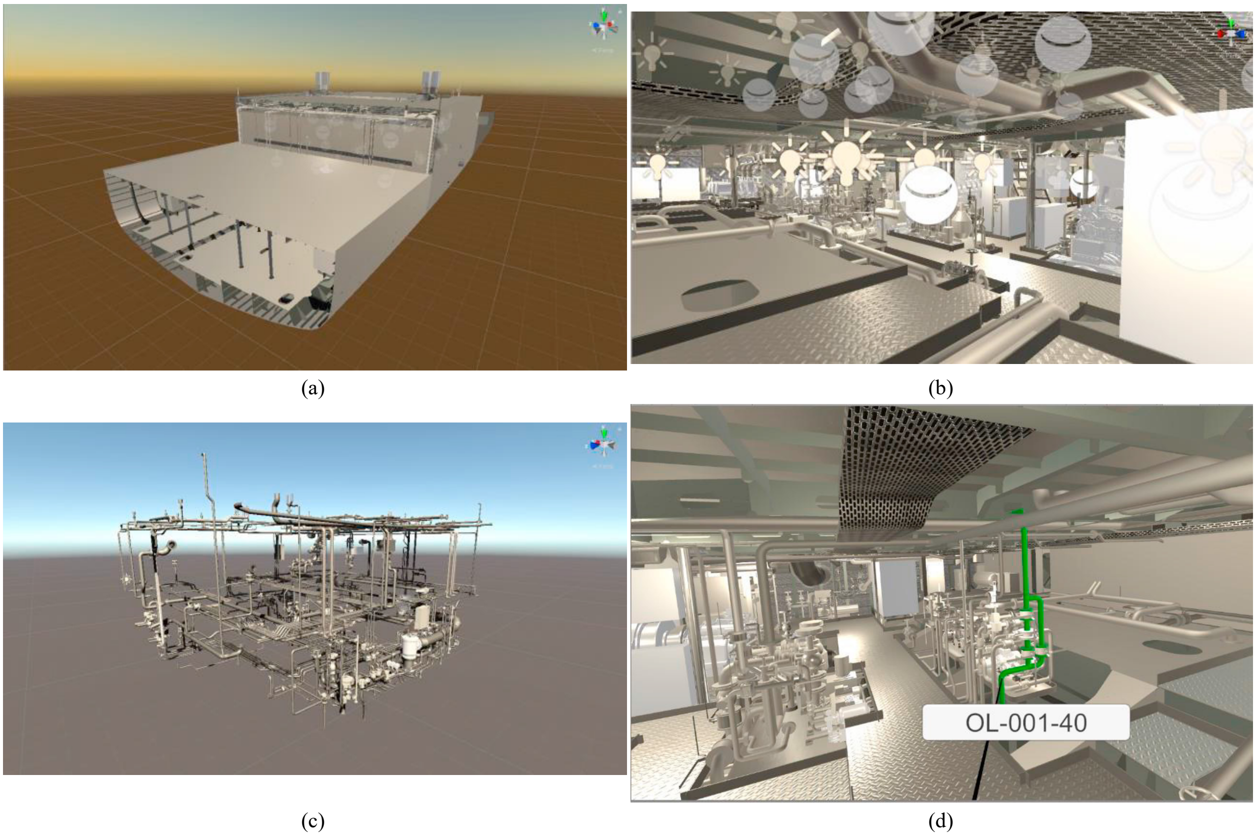


Fig. 2. Virtual model of the engine room: (a) Model view from the outside; (b) Inside view of the engine room with light spots and reflection probes to allow a realistic lighting of the space; (c) View of the engine room systems; (d) Inside view of the engine room as seen through virtual visors.

For these reasons, starting from the virtual model described in the previous section, the authors developed a digital application that could facilitate access to and readability of technical manuals using tablets – already part of the equipment available to technical staff – and virtual visors, which could be integrated into this equipment in the near future. To create a useful and functional application for maintenance purposes, this shall not only display a static view of the component and its manuals but also provide further information, such as supplier contacts, maintenance videos, exploded views, general plans, interfaces with other systems, and more. The virtual model shown above supports this functionality, as it includes a complete data package for every component, encompassing all construction, technical, operational, and commercial information. This information set will be utilised by the technical personnel throughout the ship's operative life, accessed as needed via the proposed digital application. Furthermore, the digital application must run in a relative short time, as emergency interventions could be required in case of sudden failures, and it should provide a user-friendly interface for all the personnel involved in maintenance tasks.

To allow the connection between real world and virtual reality, each piece of machinery and equipment present on board the completed ship shall be equipped with specific image targets that can be scanned by tablets or virtual visors enabling access to the virtually data stored. In the proposed methodology, QR codes were adopted as image targets due to their ease of use and representation. As shown in Fig. 3, when a QR code is framed, the corresponding component (e.g., the ship's sewage unit) will be virtually displayed as a perfect reproduction on the device screen or as an augmented reality object that can be rotated and examined in all its parts. For ease of representation, the application shows scaled models, but for maintenance purposes, the user can set to visualize the real dimensions.

For each component equipped with its own QR code, the user will see an interface called Main Menu as soon as he frames an image target using the digital application (Fig. 4a). Through this Main Menu, he will have access to all the available documents, which are listed and briefly described below.

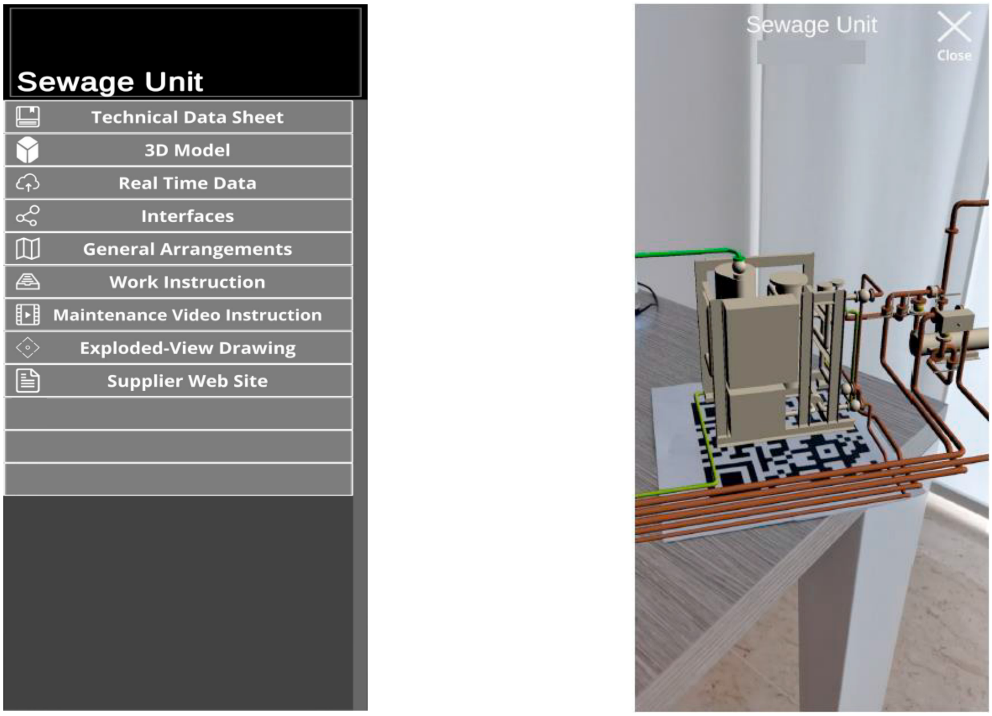
- Technical Data Sheet in .pdf form;
- 3D Model: the three-dimensional representation of the requested component will be shown, allowing the user to investigate, scale and rotate it as he prefers;
- Real-Time Data: if advanced sensors have been installed on the element, real-time data recorded can be received by the application and shown to the user to check information regarding, for example, current working temperature and pressure and continuous hours of operation. If real-time data are synchronised also with the relevant Ship Classification Society, details regarding the next maintenance to be carried out can be displayed and recorded;
- Interfaces: the 3D representation of the selected model and the systems connected to it will be shown, allowing the user to investigate, scale and rotate it as he prefers (Fig. 4b). By pressing the various elements, the user could follow the pipe route and highlight the components connected to it, activate or deactivate ship structures in order to better check the positioning of the systems, and superimpose the visualisation onto the ship's general plan;
- General Arrangements in .pdf form;
- Work Instruction: assembly and disassembly instructions of the requested component will be shown;
- Maintenance Video Instruction: the application will show a video on how maintenance is carried out and, through the use of virtual visors, the technical personnel could be guided during the procedure;
- Exploded-View Drawing: the schematic drawing of the object will be shown, along with the order of assembly of the various parts of the component and three-dimensional exploded views;
- Supplier Web Site: the user will be redirected to the supplier's website in order to establish a direct communication in case of necessities.

The developed digital application can be extensively used not only to explore individual pieces of machinery and system components, but also to have an overall representation of the engine room. In fact, a global target containing the ship's structures and systems – such as pipes and equipment – can be placed, for example, at the centre of the space. Once scanned, this target can provide the user with a complete view of the space layout. Components and structural members can be hidden to isolate each individual system, allowing for a clear understanding of where all the accessories are located. This is demonstrated in Fig. 5, where the engine room model is shown with a specific focus on pipes and accessories (Fig. 5a) and machinery (Fig. 5b).

As can be inferred, the application developed by the authors offers significant benefits in performing maintenance tasks, as it facilitates crew's work by reducing human errors and enabling prompt and safe actions. The potential integration of this technology with advanced artificial intelligence models could lead to the development of more structured data storage and management platforms, paving the way for other applications that require constant data sharing, such as the implementation of ship digital twins for instance.

(a) (b)

Fig. 3. Virtual reproduction of the ship sewage unit: (a) component with the relevant QR code; (b) rotation tool of the digital application.



(a) (b)

Fig. 4. (a) Main Menu window; (b) Interface tool showing pipes and elements connected to the sewage unit.

(a) (b)

Fig. 5. Overall view of the engine room model: (a) Details of pipes route and connections; (b) Details of machinery.

5. Conclusions

The shipbuilding industry has always been crucial to the global economy and, to maintain its relevance, it must embrace the advancements of Industry 4.0 by adopting its key principles.

As presented in the paper, Virtual and Augmented Realities are among the most transformative technologies currently available, offering potential uses in different fields. In particular, virtual models that digitally represent ship components and rooms can enhance maintenance processes, enabling predictive actions. Indeed, by deploying network of sensors and specific image targets on machinery and equipment, a comprehensive system able to collect real-time data can be created, allowing for continuous monitoring of component state of health and parameters.

The digital application developed by the authors was tested with ship system designers and on-board personnel, demonstrating concrete advantages. Specifically, it reduced human errors and shortened execution times of ship's maintenance operations, resulting in less downtime for machinery. In fact, a significant 25%-time saving was noted by the technical maintenance staff. This gain is linked to the shorter time taken to identify the component to be serviced and its location, as well as to the possibility of reaching this object without first having to search for the relevant technical manual. This time reduction can be further increased by implementing a training program based on the use of virtual reality models and by further training personnel in the correct use of the technology described. In addition, the availability of interactive maintenance instructions made it possible to reduce the errors committed during trials, ensuring perfect execution of the operations planned in the test scenarios.

This technology delivers high-value, effective and improved service with reduced overall costs, even when accounting for the initial capital expenditure required to implement the system. In fact, the digital application is compatible with standard devices like tablets and smartphones, while ship and system virtual models can be created using widely available 3D CAD software. Of course, the level of detail of the model depends on the necessity of the shipowner, impacting the time needed for its elaboration. However, as 3D modelling has become increasingly common in ship design, the availability of virtual models will certainly grow. As for QR codes, the related technology does not imply relevant costs: QR-code plates can be installed on pieces of machinery without additional costs during ship construction, and in the future, suppliers may directly provide these codes in order to speed up operations and ensure the most complete documentation package.

Despite all the benefits outlined so far, two crucial aspects might compromise the reliability of predictive maintenance approaches. Specifically, the potential collection of data anomalies as regards health and operational parameters of components and the correct set up of prognostic models to properly evaluate system behaviours must be carefully monitored. Human intervention is essential to avoid these two problems. If an unrealistic data is detected by a sensor, only the experience of the technical staff can allow its identification and subsequent isolation from the data set useful for monitoring the component's operating state. Moreover, also the validity of predictive models and the results produced by them must be checked and validated basing on previous knowledge and expertise regarding machinery parameters during routine operations. Regarding the adoption of the proposed technology, the most significant challenge lies in incorporating the necessary training for its use into the current programs for technical personnel, as it may require considerable increases in practice time.

As for future developments, integrating the digital application with smart glasses technology can further enhance facilitating maintenance processes by providing videos and step-by-step visual instructions. Though the digital application proposed will continue to evolve, it has already proven to be a valuable tool in integrating Industry 4.0 technologies in shipbuilding. This innovation paves the way for a new generation of ships that are more efficiently managed and maintained, improving reliability and safety for passengers, cargo and crew.

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