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Condition-based Maintenance and Digital Maintenance of Ship Systems

Abstract

Ship maintenance is one of the most important processes for preserving the vessel's functionality and prolonging its operational life, and the approach to maintenance has evolved throughout history. With the development of information technology, a new approach to maintenance has emerged.
The authors analyze modern approaches to ship systems maintenance based on digital technologies, with a particular emphasis on condition-based maintenance. The paper examines the application of the monitoring device systems, digital twins, and augmented and virtual reality technologies. The implementation of these technologies enables timely fault detection, reduced downtime, and enhances the safety of ship operations. Although digital maintenance offers significant technical and economic advantages, its implementation is challenging due to high initial costs and the need for additional crew training.
The aim of this research is to present the advantages, limitations, and prospects of condition-based maintenance and digital maintenance and to highlight their impact on the safety and efficiency of ship operations.
The authors emphasize that predictive and digital maintenance will become a standard approach to ship systems maintenance in the future.

Keywords: condition-based maintenance, monitoring device system, digital twins, virtual and augmented reality

1. Introduction

In recent years, maintenance activities have gained critical importance for manufacturing enterprises, especially due to growing complexity of interactions among production activities within increasingly extended manufacturing ecosystems [24]. The rapid advancement of technology, and particularly information technology, has led to the development of new methods of ship maintenance. One of the first major innovations was the development of a new and different maintenance method, called predictive maintenance. In comparison with classical maintenance approaches, which remain the predominant techniques in industrial practice, condition-based maintenance (CBM) promises to reduce the increasing number of failures caused by the inability to accurately estimate component failure times [8]. Unlike traditional maintenance approaches, which are based on planning and experience or passage of time, CBM relies on modern technologies and data analysis. It requires interdisciplinary knowledge, making it a broad field [20]. Data is fundamental to generating information that can anticipate or collaborate in making predictive decisions [32]. CBM has become a promising approach, providing solutions for estimating the remaining life of equipment through the prediction of data collected by various sensors on equipment [26]. This innovative approach enables companies to address the challenges of an increasingly dynamic environment [1]. Moreover, CBM has the potential to improve operational efficiency and reduce vessel downtime [14].

Alongside the development of predictive maintenance, the Internet of Things technology has also advanced significantly. The Internet of Things is an emerging technology now present in most processes and devices, improving quality of life and facilitating access to specific information and services [28]. In the near future, the number of connected devices is expected to be tens or even hundreds of times greater than the number of connected people [7]. Within a monitoring device system (MDS), devices can exchange data and if necessary, process it according to predefined protocols [16]. This technology is applied in numerous fields, including the maritime industry. CBM and the Internet of Things are closely interconnected concepts that have significantly influenced each other.

Another modern technology developed for technical systems maintenance, of which ships are a specific example, is digital twin technology. In strict terms, a digital twin is a mirror image of a physical process, operating alongside it, typically replicating the operation of the physical process in real time [2]. Although this technology is not yet widely implemented, it is the subject of ongoing research and is expected to have significant applications in the future [29, 30]. In addition, technologies of augmented and virtual reality are also being applied in digital ship maintenance to support crews in facilitating maintenance processes. Over time, the concept of maintenance has evolved from merely preserving usability and economic value to potentially enhancing these attributes, thus requiring careful design and planning [3]. CBM is also recognized as an indispensable component of Industry 4.0 [21].

2. Condition-based maintenance

Together with advances in sensor and computer technology, a new approach to technical systems maintenance has emerged: condition-based maintenance (CBM). CBM is a modern maintenance strategy that relies heavily on information technology. For this reason, the literature often distinguishes it from traditional maintenance approaches (preventive and corrective). CBM is founded on the use of sensors that record various physical phenomena and changes related to a system's technical components. Temperature, vibrations and similar conditions are measured so the computer can then use the results of constant measurements and changes in results of measurements to calculate the probability of malfunction and estimate the expected life expectancy of components. Through regular (or continuous) condition monitoring of system components, CBM determines the status of equipment, predicts future trends in equipment status, and develops maintenance plans based on these trends and potential failure modes. For example, a condition indicator (e.g., vibration RMS, exhaust valve temperature, bearing wear) can be modeled as:

$$\mathbf{x(t)=x_0+kt} \tag{1}$$

Where:
x(t) = condition indicator at time t
x_0 = initial value of the indicator
k = degradation rate (e.g., increase in vibration per hour/day)
t = operating time

At present, the specific content of CBM typically includes equipment condition monitoring, fault diagnosis, remaining life prediction and maintenance decision-making [31]. The importance of CBM lies in its ability to reduce maintenance costs, improve resource efficiency, avoid unnecessary replacement of still-functional components, and minimize downtime, ultimately lowering overall operational expenses. A significant contribution to the practical application of this approach has been made by Monitoring Device Systems (MDS). In addition, advances in Artificial Intelligence (AI) and Machine Learning (ML) have further supported the development and effectiveness of CBM. CBM relies on measuring and analyzing various operating conditions, including vibrations and sounds (i.e., their frequency and intensity), infrared radiation analysis (heat), analysis of different fluids, etc. In predictive maintenance, this is achieved through sensors that continuously monitor the state of various parts and, based on changes in certain characteristics, determine whether replacement is necessary. It moves beyond breakdown or corrective maintenance, maintenance performed on equipment that has broken down, to time-based or preventive maintenance; maintenance performed according to a fixed schedule [4]. The assessment of component condition is performed using complex mathematical algorithms that incorporate the physical quantities measured and relate them to the actual condition of the system's components. In this way, replacement is carried out at the optimal time, neither too early nor too late, while downtime is also reduced since maintenance is performed less frequently and in a more targeted manner. Reported benefits include up to a 15% reduction in downtime, a 20% increase in labor productivity, and a 30% reduction in inventory levels with less need to stock just-in-case parts [23]. The main advantages of introducing CBM include lower maintenance costs, shorter maintenance durations, more productive usage of time for the shipper, reduced need for spare parts, extended component life expectancy, improved spare parts management and overall more efficient management of the maintenance process. CBM also enhances safety on board. Automated data analysis enables operators to quickly identify potential risks, such as engine or generator failures, which could lead to serious incidents at sea. Additionally, reducing manual inspections decreases the risk of human error, contributing to overall navigational safety [6]. On the other hand, CBM also has some disadvantages that may discourage shipowners from adopting it. The primary drawback is the high initial investment cost, which includes investment in sensors, software production and its installation together with training crew to operate the system, which all present significant expense for the company, and there is no guarantee that it will be profitable through future maintenance cost savings. Additionally, this type of maintenance is very complex, both due to the volume of the data collected and to all of sensors that have to be placed, whose position has to be carefully planned and maintained after installation. Another disadvantage of this maintenance approach is the fact that with the flow of time crew becomes too reliant on the technology and stops verifying data received from the system. Technology can also make mistakes, so data or calculations can be wrong, regardless of whether the fault is on the sensor or in the software. As illustrated in Figure 1, maintenance strategies have evolved throughout history in response to technological progress, becoming increasingly efficient as new technologies have emerged.

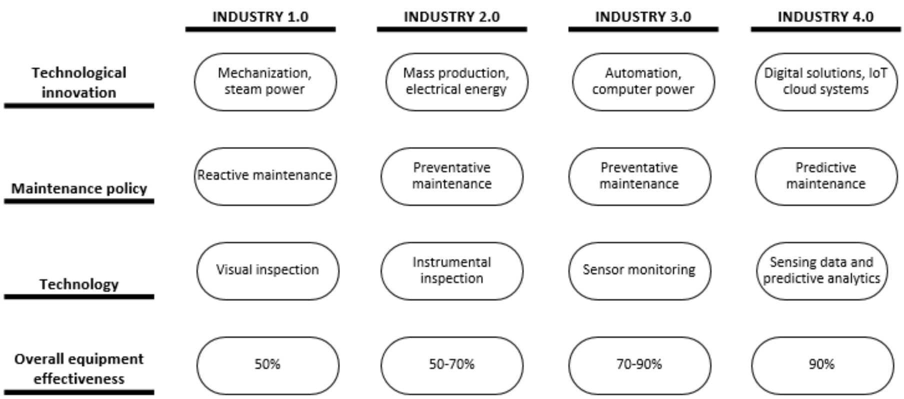

Figure 1. Impact of technology progress on maintenance approach and gear efficiency
Source: Authors according to [23]

In the beginning, it was reactive, and its efficiency was about 50%. With the emergence of advanced technology and the introduction of preventive maintenance, its efficiency grew up to 70%, while with the introduction of digital solutions that enable the use of preventive maintenance, the efficiency reached a rate of 90%.

3. Monitoring Device System

Monitoring Device System (MDS) is a technology that connects physical devices, vehicles and other objects that collect, share and process data via the internet. Connections may be wired or wireless, enabling devices to communicate with one another and with users with the aim of making life and jobs easier. MDS represents a computer concept which describes the idea that everyday physical objects are connected to the Internet and that they can be identified with other devices. Additionally, it presents a global infrastructure for an information society, which enables advanced services by the mutual connection of physical and virtual things on the basis of existing and developing interoperable information technologies [15]. MDS is one of the fastest-growing technologies and plays a central role in modern innovative industries, particularly within the framework of Industry 4.0. Although its application brings both advantages and disadvantages, it is evident that this technology will continue to expand and become increasingly significant in the future. Projections of its impact on the Internet and economy are impressive, with some estimates predicting up to 100 billion connected MDS and a global economic impact exceeding $11 trillion by 2025 [22].

A key characteristic of MDS technology is its ability to interconnect devices and enable coordinated operation with minimal human intervention. Devices receive information from their surroundings, exchange it with other devices and act accordingly. The most important component responsible for data acquisition is the sensor. Sensors must be small enough not to interfere with the device's primary function, as well as durable and energy-efficient to ensure long-term, reliable operation with minimal maintenance. Another essential feature of MDS is autonomy: after initial configuration, devices can operate independently in performing their tasks.

MDS devices work on the principle of collecting data using sensors and then sending it via the Internet to a server where the data are processed. Based on the results of this processing, appropriate commands are generated and executed. The entire process is highly automated, minimizing the need for human supervision. According to their operating principles, MDS devices can be categorized into three groups: devices that collect data (sensors), devices that process data, and devices that perform both functions. As is mentioned in the previous section, the main characteristic of sensors is their size and durability. Also, they are very cheap and available, which means that the final price of the product will not be too high. The Internet enables data transmission, after which data are commonly stored in the cloud. Processing devices then access the stored data, analyze them, and send commands to other connected devices. The communication and data-transfer process is illustrated in Figure 2. These features have significantly simplified and accelerated the adoption of MDS technology across numerous fields of human activity.

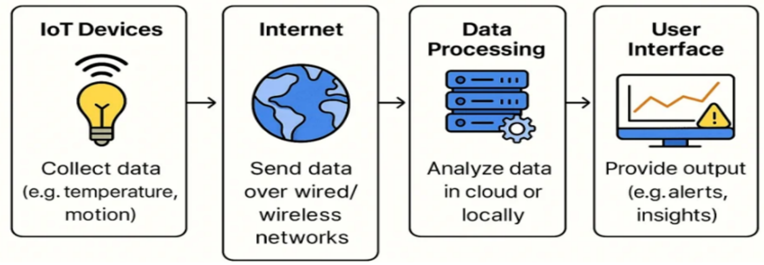

Figure 1. MDS principles of work
Source: [13]

In everyday life, there are numerous devices that operate based on MDS technology. Common examples of MDS applications that can be encountered daily include point-of-sale (POS) terminals, automated teller machine (ATMs), and various devices in automobiles (such as navigation systems, in-car audio systems, etc.). Regarding vehicles, a particularly practical example is the traffic congestion monitoring system, which uses specialized cameras to detect the potential formation of traffic jams on specific road sections and then informs drivers by recommending alternative routes. Furthermore, in recent years, smart benches, refrigerators, intelligent lighting systems, and many other examples have emerged, while in the field of medicine, MDS technology has long been applied in various diagnostic devices. Like any technology, MDS also has its advantages and disadvantages. The most obvious advantage is the speed and simplicity of data collection, which leads to savings in both time and money. Other advantages include the automation of tasks, which improves service quality and can reduce the need for human labor. The main disadvantage is the lack of security in certain situations. This is caused by the fact that the system transmits information via the Internet. That information is then exposed to potential hacking attacks. In some cases, this information may be sensitive or confidential, and unauthorized access could have serious consequences.

As in many other industries and areas of life, the MDS technology has also found its application in the maritime industry. The maritime industry can be viewed as a complex system of systems, in which various criteria and operational functions are modeled and analyzed through simulation [11].

The possibilities of its application are extensive. They include monitoring ship movements for route optimization, improving safety on board, reducing environmental impact, enabling automation, and ultimately optimizing ship maintenance processes.

As mentioned earlier, this technology supports the implementation of a maintenance approach known as CBM maintenance. Two notable examples of its application in ship maintenance are hull maintenance and main ballast pump maintenance. MDS sensors continuously collect data on various equipment parameters. This data is transmitted in real-time to a central monitoring system, often located onshore, where it is analyzed for any signs of abnormality or degradation [9]. The condition of the hull is determined by sensors installed along the structure, which record various stresses or detect certain chemical changes that may indicate the onset of corrosion. In this way, deterioration of the hull or the occurrence of structural damage (which could endanger the vessel and result in costly repairs) is prevented. Similarly, this technology can be used to monitor the condition of the ballast pump.

$$Ci\ BP\ vib\ (t) = \frac{V\ BP(t) - V\ BP\ ref}{V\ BP\ limit - V\ BP\ ref} \tag{2}$$

Ci nor BP vib (t) – vibration indicator of the ballast pump at time t
V BP(t) – measured vibration of the ballast pump at time t
V BP ref – reference (normal) vibration level
V BP limit – limit (maximum allowable) vibration level

Ci nor BP vib – normalized condition indicator in the range 0–1. Sensors record the vibrations of different pump components helping to identify the occurrence of potential faults at an early stage when their elimination is easier and less expensive. There are also other cost savings brought by the implementation of this technology, and they can be seen in Figure 3 where it is noticeable that two years are required for cost savings to cover the initial investment of USD 300 000 and that after five years, total cost savings amounted USD 450 000.

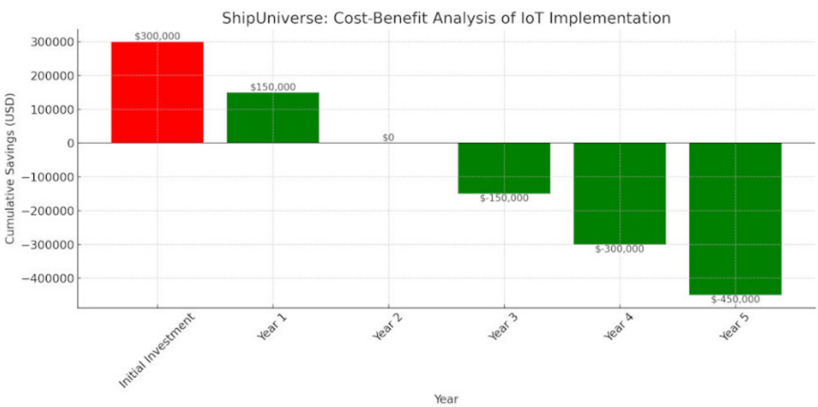

Figure 3. Relationship between initial cost and savings over the years following MDS implementation on board a ship
Source: [25]

This image is supported by a citation from the internet website Ship Universe: "Fuel savings: A study by the European Maritime Safety Agency (EMSA) indicates that by applying MDS technology and data analysis, it is possible to achieve fuel savings between 10% and 20%. Reduction of maintenance costs: Companies that implement CBM solutions often report a reduction in maintenance costs ranging from 20% to 30%. Reduction of downtime: Real-time monitoring and CBM can reduce operational downtime by 30% to 50%" [25].

4. Digital twin technology

The rapid development of digital technologies has provided maintenance engineers with countless opportunities to assist them in their work. One of the most significant innovations in this context is Digital Twin technology. This technology enables a shift from traditional, reactive maintenance approaches to intelligent and data-driven management of technical systems. A digital twin is a virtual representation of a physical object or system that uses real-time data to accurately reflect its real-world counterpart's behavior, performance and conditions. It enables continuous monitoring, simulation and a behaviour analysis of an object, product or system over the course of its lifecycle. They can also incorporate external processes and critical variables that affect an asset's performance [12]. The concept originated at NASA in the 1960s, when it was developed to support spacecraft design and mission operations. The goal was to enable precise monitoring and simulation of system behavior in real time – even when physical objects (such as capsules in space) were beyond reach. Nowadays, this technology is applied in many technical fields, primarily in manufacturing, but also in construction and various industries that involve the repair or maintenance of technical systems. This includes the maintenance of ship systems. In the context of ship maintenance, digital twins' technology represents a revolutionary advancement, as it allows surveyors and marine engineers to gain insight into the actual condition of systems without the need for physical inspection.

In the construction of a digital twin (Figure 4), three main components are generally distinguished:

- An information model of the physical entity
- A communication mechanism between the digital and physical entity
- A data processing module capable of extracting information from heterogeneous and multiple data sources and constructing a real-time representation of the physical entity [31].

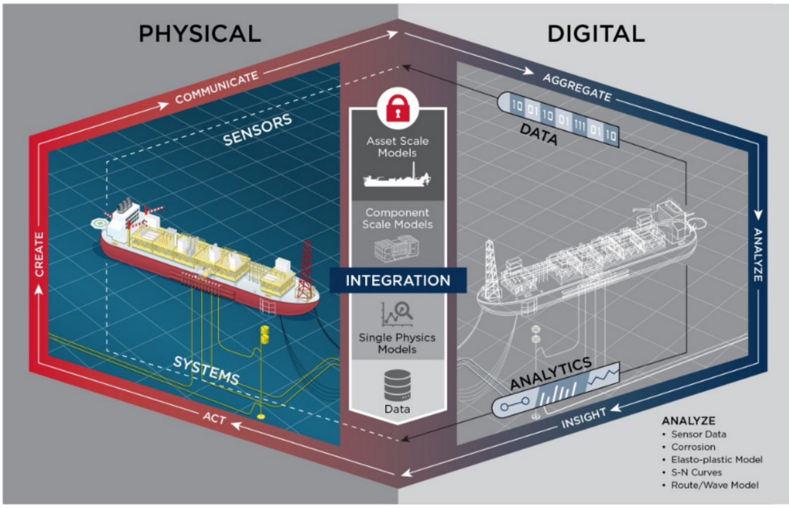

Figure 4. Digital twins illustration
Source: [17]

The operation of digital twins is fundamentally based on reliable and accurate data collected from sensors installed at various points within the ship system. That data is not processed manually but is automatically fed into previously developed mathematical models and algorithms specifically adjusted for each type of system. Those models calculate the potential effects of certain events (such as increased friction, propeller damage, or improper fuel combustion) on the ship's performance, thereby enabling timely decision-making and planning of interventions before an actual failure occurs. For the creation of digital twins, the data collected by sensors is of crucial importance. It is then fed into predefined algorithms tailored to each specific case, allowing the computation of potential impacts of a given event on the vessel. Digital twin technology adopts a proactive approach to fleet maintenance by providing a real-time representation of the actual condition of each vessel. Through continuous monitoring of key ship systems, such as engines, navigation equipment, and fuel systems – digital twins can detect signs of wear and damage before they develop into serious problems. This enables fleet operators to plan maintenance based on the actual condition of the vessel rather than relying on predefined intervals. In addition to facilitating technical maintenance, digital twins also contribute to the economic efficiency of operations, reducing operational costs, improving environmental performance (through decreased exhaust gas emissions), and enhancing the organisation of the crew and logistics.

In the future, it could be expected that almost every new ship will be projected with the integration of a digital twin as an integral part of its digital architecture. That will help maintenance to become automatically supervised and highly optimised.

5. Application of augmented and virtual reality in maintenance

The development of augmented reality (AR) technology and virtual reality (VR) technology has significantly changed the way in which maintenance of the technical systems is performed in different industries, including the maritime industry. These technologies enable a new level of interaction between human and machine, providing a visually rich and intuitive approach to diagnostics, repairs and education of technical personnel.

Augmented reality enables all users to see digital information in the real environment. Some instances of those are technical instructions, 3D models of the system and real-time data from sensors. While using AR glasses or smartphones, marine engineers can access digital manuals or interactive guidebooks without the need to leave their working position. In ship maintenance, this technology can make it easier to identify the ship engine's components, monitor working conditions, and provide a warning about some potential problems before serious faults occur. On the other hand, virtual reality enables complete immersion of the user into a simulated digital environment. VR is mostly used for training and education of crew in maintenance, especially in complex or dangerous interventions. Through VR simulation, it is possible to practice dismantling an engine, detect faults or to conduct emergent interventions without any risk and without real gear wear.

A combination of AR and VR creates a base for so-called mixed reality (MR), where users can operate with the physical systems and their digital duplicates at the same time. This integration is especially useful in systems that already use digital systems and MDS devices, because it enables maintenance based on real-time data. Although these technologies are not yet widely used in the maritime industry, pilot projects already show that their usage in maintenance brings significant advantages: reduced downtime, increased work safety, fault reduction and an increase in education efficiency. Future of maintenance will without any doubt be influenced by digital technology, whose prominent parts will be AR and VR.

Augmented Reality is one of the key technologies that is changing the approach to technical systems' maintenance, including the maritime industry. AR enables the display of digital information, such as data from sensors or 3D models, directly in the user's real surroundings. This technology does not replace physical reality but complements it by making a powerful tool for fast, safe and effective maintenance on the ship.

The main advantage of AR is the fact that it enables marine engineers to work with both hands at the same time while receiving the information necessary for performing. Crew members are able to see important information while using AR glasses (e.g., Microsoft HoloLens), tablets or smartphones. That information includes animated displays of inner engine components, warnings of defects in the system's work or visual steps for components decomposition or replacement. In that way time needed for diagnostics and repair is significantly reduced, and the ship's operational efficiency is increased. This approach is useful in complex ship systems like the main engine, ballast system or electrical system.

One of the key applications of AR on board ships is its integration with existing MDS systems. Sensors installed on equipment transmit real-time data, which AR devices display directly on the corresponding physical components. For example, an engineer standing in front of the main engine can use AR glasses and see the current temperature of bearings or oil pressure. This enables informed decision-making without the need to visit the control room or manually read instruments. Maintenance and repair operations are another area where AR has proven to be highly effective. Technicians can use AR glasses or tablets to access real-time information on ship components, including interactive 3D models, schematics, and procedural guides. This allows for faster and more accurate repairs, reducing downtime and the need for specialised training [18]. Testing also shows that the implementation of AR technology can reduce repair time by up to 50% [27]. Such integration enables rapid responses to potential faults, which in the end reduces the risk of accidents and extends the gear's lifetime.

Another important application of VR technology is remote maintenance. AR can also connect remote experts with on-site technicians, enabling real-time support and troubleshooting [18]. Experts located on shore can use the AR system to connect with seamen on the ship and literally "see through their eyes". In that case expert can draw arrows, mark the system's components, or give verbal instructions to seamen and guide them through the process. This type of cooperation enables real-time high-quality decision-making, even if the crew is not highly specialised for some problem. Consequently, decision-making time is shortened and the need to deploy additional personnel to the vessel is reduced.

Augmented reality is also used in training and crew education. AR applications enable simulations of different scenarios in which users learn through interactive guides, gear visualisations or learning of correct procedures. This type of learning increases learning efficiency and enables faster learning, particularly among younger personnel. Furthermore, it is possible to create personalised learning programs which are adjusted for user's experience and position in the hierarchy. That feature additionally increases safety and reduces the number of mistakes in real work.

From the perspective of fleet management, AR enables centralised work supervision through standardised maintenance protocols. By data visualisation through AR, technical team leaders can have better insight into the gear condition on every unit and schedule service activities in time. This supports better resource allocation and reduces implementation challenges. Although the advantages of AR technology are clear, there are also some challenges to its implementation on the ship. High-quality, durable equipment is needed, which should be resistant to water and vibrations as well. Also, the cost of this system's implementation can be high, particularly for smaller shipowners. Further, user training is needed, and software solutions should be adapted for a specific type of ships and systems. When integrated with digital twins, MDS and CBM systems, AR enables comprehensive digitalisation of technical maintenance with greater precision, lower risk and improved efficiency. Despite these challenges, trends suggest that augmented reality will become a standard tool in ship maintenance.

On the other hand, virtual reality represents technology that enables full immersion in a computer-generated environment. In comparison to augmented reality, which enriches the real world with digital overlays, this technology completely separates users from physical reality and places them in a simulated world. In the context of the maritime industry and ship maintenance, this technology is gaining importance, particularly in areas of education, intervention simulation and testing of operational scenarios. *Encyclopaedia Britannica* defines VR as "the use of computer modelling and simulation that enables a person to interact with an artificial three-dimensional (3-D) visual or other sensory environment. VR applications immerse the user in a computer-generated environment that simulates reality through the use of interactive devices, which send and receive information and are worn as goggles, headsets, gloves, or body suits" [5].

VR technology enables the recreation of real working situations in digital space, which makes the preparation of personnel for work in complex conditions like those in the engine room significantly easier. Likewise, this technology enables performing training in every moment and from every location, which is especially useful for companies that operate with international fleets. One of the paramount benefits of using VR in maritime training is the ability to simulate hazardous or critical situations in a safe and controlled environment. Traditional training methods have limitations in preparing maritime professionals for unpredictable and potentially dangerous conditions at sea. In contrast, VR can simulate complex emergency scenarios, such as fires, equipment failures, or severe weather, without exposing trainees to actual risk. This risk-free environment enables trainees to practice emergency responses, refine problem-solving skills, and make critical decisions under pressure [19]. VR systems can also record user performance, facilitating knowledge assessment and identifying areas requiring further training.

A common application of VR simulators in ship maintenance is technical personnel training and education. VR simulators are able to show detailed 3D models of ship systems, including all of their functional and mechanical characteristics. Crew members can walk through the virtual ship environment, identify equipment location, perform diagnostics, and practice assembly and disassembly procedures. Each step can be accompanied by instructions, sound signals or an automatic test of correctness, ensuring standardised and repeatable training. Besides technical practice, VR is used for practicing safety procedures and handling dangerous substances, ensuring that all crew members know how to respond in uncommon situations without exposure to real danger.

Besides practising, VR can also be used for testing and evaluation of technical solutions. Before preforming complex system maintenance, the crew can look at the simulation of intervention in VR surroundings [13], test different approaches and optimise procedural steps. This approach is particularly useful in cases when the approach to gear is complex, for instance, in the engine room. An additional advantage of this approach is the possibility of standardisation of maintenance procedures in the company's fleet. Regardless of experience level or workplace, all crew members undergo identical VR simulations, improving uniformity and safety in performing interventions. In that, knowledge differences and human mistake risk are both reduced. The second important aspect of VR implementation in ship maintenance is cooperation between different teams. Onshore engineers and onboard crew can jointly take part in virtual workshops, system analyses, discuss solutions and coordinate maintenance plans. This results in greater efficiency, reduces the possibility of misunderstandings, and accelerates decision-making. This cooperation enables the creation of a joint virtual environment in which knowledge can be shared in real time, regardless of geographical distance. Maritime simulator training reduces fuel consumption and emissions by replacing real-world training exercises. The controlled environment is optimal for trainees to practice ship handling, navigation, and emergency response without the risks associated with actual operations. This ensures the safety of trainees and eliminates potential environmental hazards [10]. Special attention should be given to connecting the VR system with digital twins and MDS devices. In combination with real data collected from ship sensors, it is possible to create dynamic VR that accurately represents the actual condition of the ship and enables performance analysis in real time. In that way, maintenance is not limited to reaction after the fault occurs but becomes predictive and planned with the support of simulation analysis.

However, there are still some challenges in VR technology implementation on board. First of all, high-performance computer equipment is required together with the appropriate training of users. Besides that, for full VR implementation, it is necessary to develop quality and precise 3D ship system models, which can require additional investments in scanning and modelling. Also, it is necessary to adapt work protocols and safety procedures for new digital tools. Although initial implementation costs are high, long-term benefits include reduced errors, faster diagnostics and more efficient training.

In conclusion, given the increasing complexity of ship systems and stricter safety and efficiency requirements, virtual reality represents a powerful tool capable of enhancing maintenance at all levels, from training to operational execution.

6. Conclusion

Ship system maintenance presents one of the crucial factors of safety, and cost-effectiveness in maritime operations. Ship maintenance practices have developed in parallel with the technology advancement, from simple corrective interventions to sophisticated preventive systems, and today also condition-based maintenance and digital maintenance.

The rapid development of information technology has enabled the creation and implementation of new technologies, including condition-based maintenance, digital twins, Internet of Things augmented, and virtual reality. These technologies allow detailed observation of the actual condition of ship systems and support decision-making based on real-time data.

Despite their significant potential, the full implementation of these technologies in the maritime sector still faces considerable challenges. The industry has traditionally been relatively slow in adopting modern technological innovations, primarily due to high implementation costs and the need for additional crew training.

To conclude, it is possible to state that the development and implementation of new technologies lead to new maintenance approaches. Technologies described in this paper do not yet have widespread application on all ships, however, over time, they will experience full affirmation, and an increasing number of shipowners will decide to implement them, because it is the only way to increase maintenance efficiency and consequently business performance.

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