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Enhancing Maritime Training: The Role of VR in Ship Bridge Simulators - The CAL-TEK Case Study

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Abstract

This study examines the integration of Virtual Reality (VR) into Maritime Education and Training (MET), specifically through the application of the CAL-TEK Ship Bridge Simulator. The research evaluates how VR technology enhances seafarer training by providing immersive, realistic, and interactive experiences. It focuses on the dual aspects of utilizing the CAL-TEK simulator—its capabilities as a standalone training tool, and its enhancement through VR technology. This approach allows trainees to engage with complex maritime operations in a safe, controlled environment, thereby significantly improving their technical skills, decision-making capabilities, situational awareness, and teamwork. The adaptability of the CAL-TEK simulator to different training needs, through customized scenarios, equips trainees for a broad spectrum of real-world maritime challenges. The findings emphasize the transformative potential of integrating VR into MET and advocate for continued research and investment to maximize its educational benefits. In conclusion, VR-enhanced simulators like those developed by CAL-TEK represent a substantial advancement in maritime training, promoting safety, efficiency, and operational readiness across the global maritime industry.

Keywords: Virtual Reality; Maritime Education and Training; Ship Bridge Simulator; Immersive Technologies; Seafarer Training

1. Introduction

The maritime industry is increasingly embracing advanced technologies to enhance the quality of education and training provided to seafarers (Kumar & Rajini, 2024). Among these technologies, Virtual Reality (VR) simulators have emerged as a powerful tool for Maritime Education and Training (MET) (Wu et al., 2024). VR simulators offer a unique blend of realism and interactivity, allowing trainees to experience and practice complex maritime operations in a controlled, risk-free environment. This innovation addresses the limitations of traditional training methods by providing a highly immersive experience that closely replicates real-world scenarios, from ship handling in adverse weather conditions to emergency response situations.

One of the key advantages of VR simulators is their ability to recreate the dynamic and often unpredictable nature of the maritime environment (Gernez et al., 2023). Trainees can be exposed to a variety of scenarios, such as navigating through congested waterways, managing equipment failures, or coordinating search and rescue operations, all while receiving immediate feedback on their actions. This hands-on approach not only improves the trainees' technical skills but also enhances their decision-making abilities, situational awareness, and teamwork, which are important for safe and efficient ship operations (Liu et al., 2021).

Furthermore, VR simulators offer significant flexibility and scalability in maritime training. They can be customized to simulate different types of vessels, operating conditions, and specific maritime procedures, making them suitable for a wide range of training needs (Garza Espinosa et al., 2023). This adaptability ensures that the training programs can be tailored to the specific requirements of different shipping companies, vessel types, and regulatory standards. Additionally, the ability to repeat exercises under varying conditions allows trainees to build confidence and competence, preparing them for the challenges of real-life maritime operations.

The adoption of VR simulators in MET is not just a technological advancement but a significant step forward in improving the safety, efficiency, and effectiveness of maritime operations (Abid et al., 2024). As the industry continues to evolve, the role of VR in training seafarers will undoubtedly expand, offering new opportunities to enhance learning outcomes and operational preparedness across the global maritime sector.

The main objectives of this study are to evaluate the effectiveness of Virtual Reality simulators in enhancing Maritime Education and Training and to position the case study of CAL-TEK srl as a leading example of successful implementation in this field. This article specifically aims to provide a comprehensive presentation of the application of VR within the CAL-TEK simulator, highlighting how it enhances training outcomes and how the different parts are integrated. Through a detailed analysis of CAL-TEK's approach, the study examines the practical benefits, challenges, and overall impact of VR technology on trainee performance and operational readiness.

The study is structured as follows: Section 2 reviews the State of the Art, providing a comprehensive overview of current technologies and methodologies in maritime simulation training. Section 3 presents the Case Study of CAL-TEK srl, including a full presentation of the VR application in the ship bridge simulator. Section 4 covers the Discussion, where the outcomes of the CAL-TEK case study are analyzed and discussed in detail. Finally, Section 5 offers Conclusions, summarizing the key findings and their implications for the future of maritime education and training.

2. State of the art

To better understand the significance of ongoing research and to identify existing gaps in the literature, the authors conducted a search on Scopus using the following query: (TITLE-ABS-KEY ("ship bridge simulator" OR "maritime simulator" OR "maritime training" OR "maritime education") AND TITLE-ABS-KEY ("vr" OR "virtual reality")). This search initially yielded 48 results.

The graph in Figure 1 shows a significant increase in the number of documents published on the topic of MET and the adoption of VR from 2002 to 2024. In the early years, publications were sporadic and limited, likely reflecting a nascent interest and an initial exploration phase of VR technologies in the sector. However, starting around 2015, there is a steady and progressive growth, culminating in an exponential increase from 2019 onwards. This sharp rise in publications indicates a growing recognition of the importance of VR in maritime training, with increasingly widespread adoption and significant academic attention. The peak observed in 2024 suggests that the field has become a mature area of research, with continuous development and implementation of VR technologies in the maritime industry.

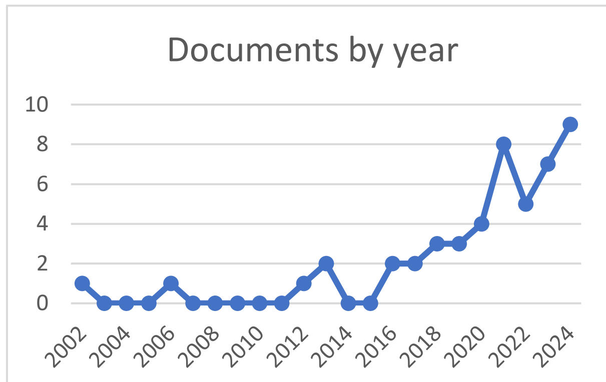

Figure 1. Documents by year.

To refine the selection, only open access articles were considered, reducing the number to 21. Further filtering was applied by selecting only those studies categorized as "Article" and "Final," resulting in a final selection of 12 studies for this review of literature.

The integration of immersive technologies, such as VR and AR, in MET is quickly becoming a key factor in addressing the complexities of an increasingly digitalized and automated maritime sector. These technologies are transforming traditional educational approaches by offering innovative tools that not only improve the safety and effectiveness of training but also enhance the practical preparation of maritime operators, allowing for a more immersive and engaging learning experience.

Kumar & Rajini (2024) highlight the urgent need to update the MET system, which has long been tied to outdated STCW conventions that are no longer adequate for preparing seafarers for current and future challenges in the sector. The authors propose a blended learning approach that integrates AR and VR to fill the gaps in traditional methods, which are insufficient for training in a rapidly evolving maritime context. However, while recognizing the tangible benefits of these technologies, they warn that large-scale implementation requires significant investments and infrastructure changes, posing a challenge for many educational institutions that may not have the necessary resources to fully adopt them. In line with this urgent need for modernization, Cao (2016) introduces an advanced teaching system based on VR, developed at Dalian Maritime University. This system not only provides high-fidelity simulations but also overcomes the limitations of traditional simulators by offering a more accessible and economically sustainable alternative. While it may not match the visual quality of large-scale simulators, this solution represents significant progress, making maritime training more inclusive and widespread, especially in contexts where resources are limited.

The application of immersive technologies goes beyond practical training and extends to the area of maritime safety. In this context, was presented the "Immersive Safe Oceans Technology" (Markopoulos & Luimula, 2020), an innovative VR system designed to simulate emergency scenarios such as onboard incidents. This technology, which is highly portable and easy to implement, offers an unprecedented opportunity to improve crew preparedness, providing realistic and immersive training that could become the standard for safety practices at sea, revolutionizing the way maritime safety is managed globally.

The COVID-19 pandemic significantly underscored the importance of immersive technologies and acted as a catalyst for the rapid adoption of advanced digital solutions in maritime education. As traditional training methods were disrupted, the maritime industry increasingly turned to VR and cloud-based simulators to support distance learning. Both Kim et al. (2021) and Renganayagalu et al. (2022) provide critical reflections on this shift, highlighting how the global health crisis accelerated the use of these tools. Their analyses emphasize that the integration of VR and cloud-based simulators, driven by necessity during the pandemic, could lead to a radical transformation of MET. These emerging technologies have the potential to foster a more resilient, flexible, and high-quality maritime education, which is essential for meeting the needs of a rapidly evolving sector, even in a post-pandemic context where adaptability will be fundamental for the continuity and effectiveness of training programs.

Furthermore, in the field of safety training, the effectiveness of VR has been particularly evident, especially in non-Western, Educated, Industrialized, Rich, and Democratic (WEIRD) cultural contexts (Makransky & Klingenberg, 2022). This suggests that VR could become a valuable tool in global maritime safety training, improving operator preparedness across diverse cultural and technological environments.

Similarly, research conducted at the National University Odessa Maritime Academy emphasizes the importance of VR in addressing human resource shortages by significantly improving learning quality and preparing seafarers to meet the challenges of an evolving labor market (Miyusov et al., 2022). The use of VR in navigator cadet training has led to a 25.93% increase in learning effectiveness, particularly when combined with traditional teaching methods. This research emphasizes that VR should complement, not replace, traditional instruction, leveraging its immersive capabilities to produce new, positive learning effects. These advancements not only help bridge the skills gap in the maritime sector but also enhance overall safety on marine vessels. Further research is needed to develop universal methods for effectively integrating VR into maritime education.

In a systematic review of maritime training, it was found that immersive simulators offer significantly greater engagement compared to traditional methods. However, challenges related to the costs and complexity of integrating these technologies into standard curricula were also identified, emphasizing the need for further research and optimization (Dewan et al., 2023). Despite these challenges, VR has proven particularly effective in practical training scenarios where precision and immersive experiences are a basilar point. For instance, a study on passenger ship evacuation training showed that VR not only improved knowledge retention but also increased participant satisfaction (Chae et al., 2021). These findings suggest that VR has the potential to become the superior training method in critical situations, offering a level of safety and preparedness that traditional methods may not fully achieve.

The purpose of VR extends beyond just improving training processes; it also plays a fundamental role in the design of maritime interfaces. Using operational scenarios reconstructed in VR facilitates more effective collaboration among various stakeholders, promoting a user-centered design approach (Aylward et al., 2021). This advanced use of VR technology enables a deeper understanding of the operational context, leading to better interface design and enhancing the overall efficiency and safety of maritime operations. By integrating these findings, it becomes evident that VR is very useful for both enhancing the quality of maritime training and improving the overall preparedness of the workforce. Its flexibility and effectiveness make it an essential component of modern MET, addressing both training and operational needs in a comprehensive manner.

Building on this, Pruyn (2024) explores the integration of digital games with VR in maritime education, demonstrating that this combination can significantly improve both knowledge retention and student motivation. However, he cautions that these tools must be carefully designed to avoid cognitive overload, ensuring that learning remains effective and sustainable in the long term. In a broader context, Tusher et al. (2024) further examine the effectiveness of various maritime simulators using a multi-criteria decision-making approach. Their study highlights that while full-mission simulators are still preferred, VR and cloud-based simulators offer valid and more accessible alternatives, especially in resource-limited environments. The ability to choose from different training tools, depending on specific needs and resources, contributes to an overall improvement in the effectiveness of maritime training, underscoring the importance of flexibility and adaptability in modern educational practices.

In summary, the literature indicates that the integration of immersive technologies in MET is revolutionizing maritime education, opening new opportunities to improve training effectiveness, safety, and practical preparation for seafarers. However, it is still necessary to address the challenges related to costs, usability, and integration into existing programs through further research and targeted investments.

3. Case study: CAL-TEK srl

The Ship Bridge Simulator developed by CAL-TEK srl (Figure 2) is designed to provide realistic and effective training that meets the Standards of Training, Certification, and Watchkeeping for Seafarers (STCW) Convention. This simulator includes all the essential instruments found on a real ship's bridge, set up in a way that closely matches how they are arranged on an actual ship. This setup allows trainees to practice in a realistic environment, preparing them for the situations they will encounter at sea.

The simulator can recreate complex, real-world scenarios, giving trainees the chance to assess situations, evaluate risks, and work together with others in a coordinated way. Using VR the simulator offers a highly engaging experience where trainees can respond to various emergencies, such as engine failures or fires, in a safe and controlled environment.

Figure 2. Ship Bridge Simulator

The Ship Bridge Simulator comes with a detailed database of geographic areas, including major international ports and inland waterways, ensuring that training scenarios are as close to reality as possible. The system is designed to be flexible and modular, allowing it to be customized to meet specific training needs, whether for different types of ships or propulsion systems. Key features of the simulator include:

- **Advanced Visualization System:** this system provides a realistic view and sound to make the bridge environment feel real.
- **Complete Navigation Tools:** it includes several tools and, all meeting international standards to support comprehensive navigation training.
- **Scalability and Flexibility:** the simulator can be set up for basic desktop training or expanded to add more student stations—where trainees interact directly with simulated scenarios using tools to learn navigation and vessel operation, as well as more scenarios and software as needed.
- **Interoperability:** the system works well with other existing training solutions, thanks to IEEE 1516 HLA standards for interoperable simulation.
- **Instructor Workstation:** it serves as control centers where instructors manage, monitor, and customize these training scenarios. They adjust simulation conditions, track performance, and provide feedback, ensuring that the training is effective and meets educational goals.

3.1. Integration of Virtual Reality and Advanced Technologies

The Ship Bridge Simulator makes extensive use of VR to create a more realistic and effective training environment. VR is a key feature that transforms traditional training by placing trainees in a fully immersive, interactive virtual bridge, where they can experience the complexities of ship operations as if they were on a real ship.

In this virtual setting, trainees wear VR headsets that allow them to interact with the ship's controls and instruments in real-time (Figures 3 and 4). They can practice navigating through challenging scenarios, such as docking in a busy port or handling the ship in rough weather, all within a safe, controlled environment. This level of immersion helps trainees to better understand and react to real-world situations.

Figure 3. Detail of the VR headset used for navigation simulation

Figure 4. VR enabling technologies of the Ship Bridge Simulator

VR also enables real-time interaction and feedback. Trainees can move around the virtual bridge, operate the controls, and respond to changing conditions just as they would on an actual ship. The system provides immediate feedback on their actions, helping them to quickly learn from their mistakes and improve their decision-making skills. Moreover, the VR system is highly adaptable. Training scenarios can be customized to meet specific needs, whether it is simulating different types of ships like tankers or passenger vessels, or adjusting conditions like fog, night operations, or stormy seas. This flexibility allows for realistic and varied training that prepares trainees for the wide range of situations they may encounter at sea. VR also enhances situational awareness and teamwork. Trainees can work together in the virtual environment, practicing communication and coordination as they would in real life. This helps ensure that all team members are prepared to handle complex operations smoothly and efficiently.

The simulator is designed to incorporate the latest developments in VR technology, ensuring that it continues to provide state-of-the-art training experiences as technology evolves.

3.2. Virtual Reality Components

The CAL-TEK Ship Bridge Simulator incorporates several VR components, in order to enhance the training process. This section lists the key VR tools used: the VR headset, navigational interfaces such as ECDIS, RADAR, and TOUCH Interface, and supporting technologies like the MCS and SRS. Details on SocketChannel, APIs and FFmpeg, which facilitate seamless interaction and media streaming, will also be briefly introduced. All the specific interactions of these components will be explored in depth in the next section.

3.2.1. VR Headset

The VR headset serves as the central interface for trainees, immersing them into the virtual environment of the ship's bridge. It provides a 360-degree view, allowing trainees to interact with the simulated world in a highly realistic manner. This direct interaction is very important for effective learning and skill development, as it mimics real-life conditions and responses.

3.2.2. ECDIS (Electronic Chart Display and Information System)

This instrument provides trainees with advanced chart display and route planning tools. Key features include multi-chart loading, chart content management, and route monitoring. The system allows for detailed route planning, checking, and monitoring, with integrated AIS and ARPA target data, ensuring that trainees are fully prepared for real-world navigation tasks.

3.2.3. RADAR ARPA (Automatic Radar Plotting Aids)

This application is designed to simulate radar operations, providing the essential functionalities required for maritime navigation training. Trainees can practice radar-based navigation, including relative motion and true motion displays, manual and automatic target plotting, and the use of guard zones. The RADAR ARPA can also simulates radar-specific challenges such as radar interference, false echoes, and shadow effects, providing a comprehensive radar training experience.

3.2.4. TOUCH Interface

This system likely refers to a touch-based method for managing various ship operations, providing a more intuitive and interactive way for trainees to engage with the simulator's features.

3.2.5. MCS (Mouse Controller Server)

The MCS is a specialized server designed to handle the translation of user inputs from one interface, such as a VR environment, into mouse actions on a traditional computer system. Essentially, the MCS interprets gestures or movements made in VR—like pointing or clicking—and translates these into standard mouse commands that interact with software running on a computer. This server is useful in training simulators or other applications where users need to interact with virtual elements as if they were manipulating physical controls on a computer interface, enabling seamless integration between different input modalities and enhancing the interactive experience. In summary, the MCS is a component that interprets actions taken by trainees in the VR environment and translates them into real commands that affect the simulator's systems. This server ensures that every maneuver in the virtual world has an appropriate and realistic impact on the simulation, mirroring actions that would be taken on a real ship.

3.2.6. Instructor Workstation

The Instructor Workstation (Figure 5) is a fundamental component of the Ship Bridge Simulator. It provides instructors with complete control over training exercises, allowing them to create, manage, and analyze scenarios in real-time. Instructors can easily start, stop, and adjust exercises, manage ship movements, and modify environmental conditions. The workstation also allows for the creation, editing, and replay of exercises, with a dedicated map for precise visualization. During exercises, the system continuously displays key ship parameters and environmental conditions, enabling real-time monitoring and control of both own and target ships. The Instructor Workstation is designed to track trainee performance, ensuring that all aspects of the training process are effectively managed and optimized.

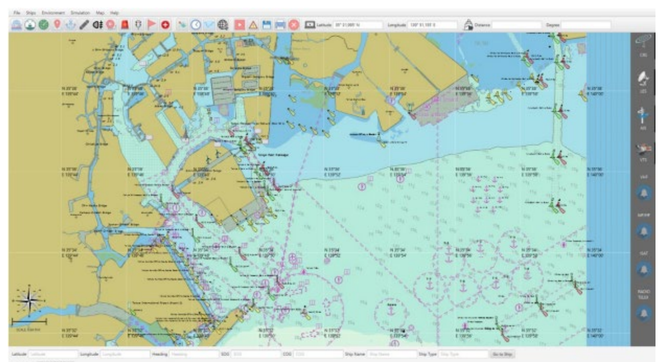

Figure 5. Instructor Workstation, overall view

The Instructor Workstation also offers advanced functionalities such as the ability to customize training scenarios to specific needs, generate detailed performance reports, and provide instant feedback to trainees. Instructors can simulate various emergencies, adjust difficulty levels, and seamlessly integrate new training modes.

3.2.7. SRS (Streaming Relay Server)

It is a specialized server designed to handle the transmission and management of audio and video streams over a network. It captures live media from different sources, processes it for optimal delivery, and relays it to end users in real-time. The SRS is extremely useful in environments like virtual reality simulations, where it ensures that the streamed content is synchronized, maintains high quality, and provides an immersive experience with minimal latency. The SRS plays an important role in enhancing the realism of the simulation by streaming video from the simulator's systems back to the VR headset. This allows trainees to see the effects of their actions, such as changes in the navigation path or adjustments in the radar screen, in real time.

3.2.8. SocketChannel

A SocketChannel is a component of Java's New I/O (NIO) library, which provides a way to handle network communications more efficiently. Essentially, a SocketChannel is used to establish a connection between software applications over a network, allowing them to send and receive data. It operates in either blocking mode, where a call to read or write data blocks until data is transferred, or non-blocking mode, which allows an application to perform other tasks while waiting for data to be transferred. This flexibility makes SocketChannels particularly useful in environments where managing real-time data flow is needed, such as in the CAL-TEK Ship Bridge Simulator, where timely and efficient data transmission between different systems enhances the overall simulation experience. SocketChannels are highly effective for continuous data exchange, ensuring that interactive elements like RADAR, ECDIS, and other are synchronized and responsive to user inputs in the virtual environment.

3.2.9. APIs

Application Programming Interfaces (APIs) are utilized within the system to facilitate the integration and communication between different software components, such as streaming video content to the VR headset. APIs are sets of protocols and tools that allow different software applications to interact with each other. They enable developers to create applications that can request services from an operating system, software library, or another service, and receive responses in a standardized format.

3.2.10. FFmpeg

FFmpeg is a free and open-source software project that consists of a vast library of tools and programs capable of handling video, audio, and other multimedia files and streams. At its core, FFmpeg is designed for command-line-based processing of video and audio files, which makes it highly flexible and widely used in software development for media applications. This tool is used for processing and streaming video, ensuring that the visual content trainees see in the VR headset is up-to-date and synchronized with the simulator's operations.

3.3. Component Interactions in the CAL-TEK Ship Bridge Simulator

The CAL-TEK Ship Bridge Simulator employs a network of interactive components that work together to deliver a highly immersive and realistic training environment. Below, is detailed how these components—ranging from VR headsets to navigational tools and supporting servers—interact with each other to enhance the simulation experience. These interactions are shown in Figure 6.

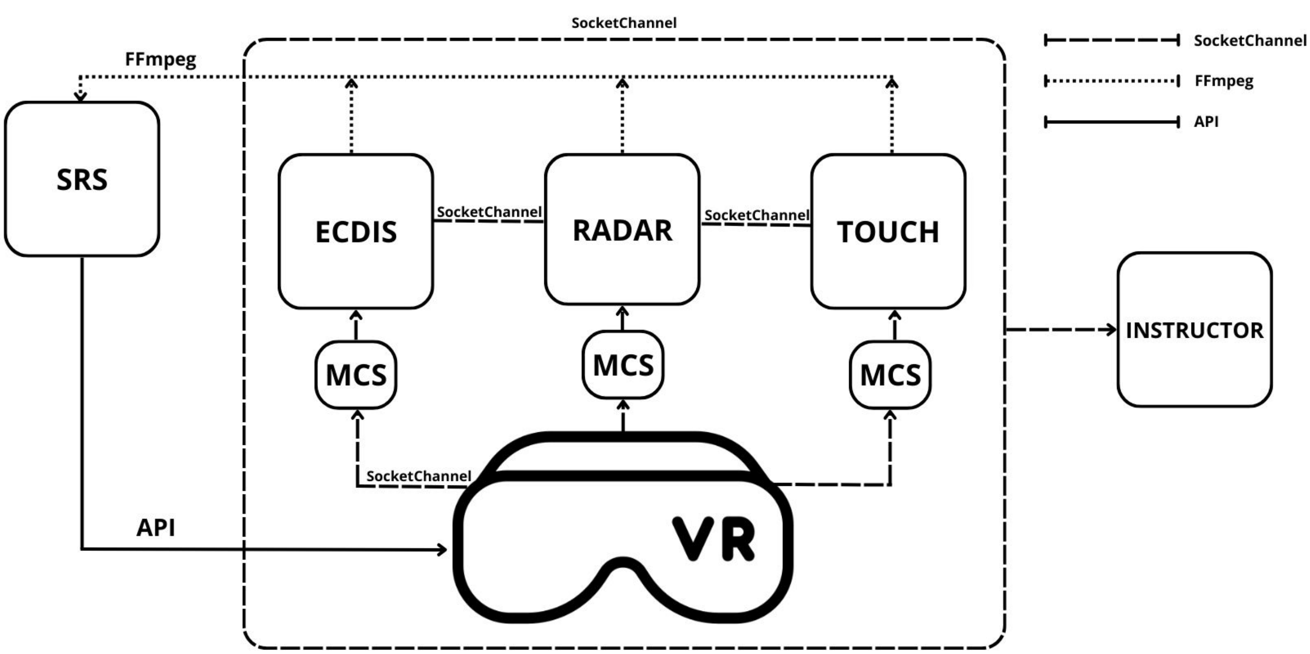

Figure 6. Architectural Diagram of the CAL-TEK VR Maritime Training Simulator

As stated earlier, simulation system uses SocketChannels to manage communication and data exchange between tools and applications such as RADAR, ECDIS, and Touch. In fact, these devices are supported by real computers that interface with each other through SocketChannels. At the same time, VR is integrated and interacts with these physical instruments to provide a complete simulation experience.

In the VR environment, it is possible not only to view data but also to control the ship and navigate through a virtually replicated dashboard. For example, changing the power in VR causes the ship simulator to react accordingly. These changes are immediately transmitted to navigation tools like RADAR and ECDIS through SocketChannels, updating their displays based on the ship's movements.

Additionally, an external supporting server, called SRS, is used to project images from RADAR, ECDIS, and Touch directly into the VR environment. This is made possible by FFmpeg, a software that manages the streaming of images to the SRS server. The images are then transmitted to VR through APIs.

Each tool has its own MCS, which allows for advanced interactions in VR. For example, if a user in VR "clicks" on a computer icon, it opens a window showing what is happening on the ECDIS in real-time. The VR interface is designed to allow users to "touch" specific points on a screen virtually, simulating mouse movements in the physical system, thanks to the MCS.

It is important to note that the system allows the connection of multiple VR headsets simultaneously. In fact, each headset can be configured to manage different aspects of navigation: one can pilot the ship, another monitor the RADAR, and a third manage the ECDIS. During maneuvers, users can also "look" virtually out of the ship's side wings, similar to side mirrors, to assist in docking. Although the simulation is "single player" (only one ship is driven at a time), multiple people can collaborate using different tools, both in VR and on real devices, just be mindful not to use the same tool simultaneously. Indeed, it is feasible to work on the actual simulator or through VR, for instance, by assigning one student to the RADAR and another to the ECDIS. However, both should not operate the ECDIS at the same time, as they would interfere with each other's commands.

Finally, the instructor's workstation is connected to all elements of the system, except for the SRS server. This allows the instructor to control and modify simulation scenarios, monitor operations, and provide real-time feedback, optimizing the learning and training of navigators.

As evidenced from the detailed interactions and configurations within the CAL-TEK Ship Bridge Simulator, this system embodies flexibility and interoperability. The ability to support multiple VR headsets concurrently, allowing trainees to manage different navigation tools independently, showcases the simulator's adaptability. This feature enables tailored training for individual roles, ensuring effective multitasking without command interference. Furthermore, the use of SocketChannels for real-time data exchange exemplifies the system's interoperability, integrating various components, and the integration of APIs facilitates enhanced communication between the simulator's components and external data services. This capability allows for real-time updates and interactions across the system, seamlessly incorporating changes and maintaining the integrity of the training environment. This setup not only maintains the continuity and accuracy of the simulation but also adapts dynamically to a range of educational objectives, enhancing the overall effectiveness of maritime training.

4. Discussion

The use of VR simulators in MET is changing how seafarers are trained, as shown by the case of the CAL-TEK Ship Bridge Simulator. VR technology significantly improves training by overcoming the limitations of traditional methods, which often involve physical simulators and classroom lessons. These traditional methods can be expensive, limited in availability, and unable to fully recreate real-world maritime scenarios. The CAL-TEK simulator, with its immersive VR environment, allows trainees to experience complex situations, which are difficult to simulate with traditional approaches. However, implementing VR widely comes with challenges, particularly the high costs of purchasing the devices and upgrading infrastructure, which can be a barrier for smaller institutions. Moreover, while VR offers a realistic experience, it may not fully replicate the physical sensations of actual maritime operations, such as ship movement or physical tasks, suggesting that VR should be used alongside physical training for well-rounded preparation. The study supports the continued use of VR in MET but also highlights the need for further research to make VR simulations even more realistic and to reduce costs, making the technology accessible to more institutions. Overall, the CAL-TEK case study demonstrates how VR can significantly improve maritime training, making it safer, more effective, and better suited to preparing seafarers for real-world challenges.

5. Conclusions

The integration of VR simulators in MET marks a significant advancement in the way seafarers are trained, offering numerous benefits that address the limitations of traditional training methods. The CAL-TEK srl Ship Bridge Simulator serves as a prime example of how immersive technologies can be integrated and how can enhance the realism, engagement, and effectiveness of maritime training programs. Through the ability to recreate complex and dynamic maritime scenarios, VR simulators enable trainees to develop technical and soft skills, such as decision-making, situational awareness, and teamwork, in a controlled and safe environment. This not only improves their preparedness for real-world operations but also builds confidence and competence that are essential for effective maritime operations.

The flexibility and scalability of VR simulators, as demonstrated by the CAL-TEK system, allow for the customization of training programs to meet the specific needs of different maritime operations and regulatory requirements. This adaptability ensures that trainees receive relevant and comprehensive training that prepares them for the diverse challenges they may encounter at sea. Furthermore, the immediate feedback provided by VR simulators enhances the learning process, enabling trainees to quickly learn from mistakes and refine their skills.

However, the widespread adoption of VR simulators in MET also presents challenges, particularly in terms of the significant financial and infrastructural investments required (Wu et al., 2024). These challenges may limit the accessibility of such advanced training technologies, particularly for smaller institutions or those in developing regions (Jakubakynov et al., 2024). Additionally, while VR provides a highly immersive training experience, it may not fully replicate the physical conditions of real-world maritime environments, which could be a limitation in certain training scenarios (Thach & Hung, 2024).

Despite these challenges, the benefits of VR simulators in enhancing maritime training are clear. As the maritime industry continues to evolve, the role of immersive technologies like VR will likely become increasingly important, offering new opportunities to improve safety, efficiency, and overall operational readiness. Continued research and investment in this field are essential to fully realize the potential of VR in MET and to ensure that seafarers are equipped with the skills needed to navigate the complexities of modern maritime operations.

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