Usability Verification of Virtual-Reality Simulators for Maritime Education and Training

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Abstract. The shortage of seafarers in the maritime industry persists until fully autonomous maritime transportation is achieved. To address this challenge, improving the efficiency and effectiveness of knowledge delivery in maritime education and training (MET) is crucial. Currently, MET relies on expensive scale maritime ship-bridge simulators to provide immersive training experiences for apprentices. While effective, these simulators come with high costs and safety concerns. Lower-cost alternatives are needed, and virtual-reality simulators (VRS) are considered viable options. This study investigates the usability of VRS in MET through qualitative experiments involving bachelor students in nautical science and experienced seafarers. The suitability of VRS is evaluated in comparison to traditional scale maritime ship-bridge simulators. By exploring the potential of VRS, this research aims to address the need for cost-effective solutions in MET, particularly in less developed countries and institutions with limited resources.

Keywords: virtual reality; maritime education and training; simulator-based training.

1 INTRODUCTION

Although the advancement of maritime autonomous surface ships (MASS) in the industry is underway, the shortage of skilled seafarers will persist until fully autonomous maritime transportation is achieved and demonstrated to be capable of operating without human intervention. Therefore, improving the efficiency and effectiveness of knowledge delivery in the maritime education and training (MET) sector to maritime navigators and operators is a pressing issue, given the rising demand for marine and other waterborne transportation [1]. Currently, the predominant pedagogical approach employs scale maritime ship-bridge simulators (SBS) to provide apprentices with a realistic experience for acquiring occupational skills on board before they can navigate an actual ship.

This state-of-the-art technology has proven effective in MET, as it eliminates the need to take apprentices on board, thereby reducing expenses and preventing any safety issues or potential accidents that may arise from inexperienced operational techniques. However, certain issues remain, such as the relatively high cost associated with scale maritime ship-bridge simulators, which includes construction, licensing, technical support, maintenance, and service. This issue is particularly prevalent in less developed countries and institutions with limited funding. A more cost-effective solution is required to meet the MET requirements, and virtual reality simulators (VRS) are considered viable alternatives [2]. Practitioners have developed VRS, integrating various ship-bridge configurations and types of ships, as well as multiple navigational marine environments and water areas. VR is also used to promote the navigation environment with more information display and decision support [3].

On the other hand, modeling and analyzing the operational behavior of mariners (including apprentices and experienced captains) remains crucial for the traffic safety. Considering that MASS at human-in-the-loop levels (HITL) will continue to dominate maritime transportation for the next few decades, whether the operator is on board, at a shore-based remote operation center, or intervening in the autonomous navigation system (ANS) of the vessel, it is essential to address the issue of avoiding errors and accidents caused by human factors. Modeling their behavior can be approached from two perspectives. Firstly, by analyzing log data of ship maneuvering control and considering factors such as current environmental conditions and vessel response to model specific maneuvering patterns [4]. However, the limitation of this approach lies in its retrospective modeling, as it overlooks the operator's pre-action behaviors, including perception of the environment and the interaction with auxiliary systems (ECDIS, ARPA) leading to corresponding actions. Modeling this process is particularly challenging as it involves capturing a range of biological signals, such as EEG, eye movements, and body motions. This necessitates additional monitoring devices and sensors, which may introduce interference as mariners operate under different physical conditions compared to normal operations [5]. Furthermore, these devices often require significant preparation and calibration time, which is unfavorable for extensive data collection.

However, Virtual Reality Simulators have the potential to address this issue. In the case of traditional scale simulators, the main challenge lies in the fact that having operators wear wearable devices fundamentally creates a scenario different from normal maritime operations. Analyzing the impact of these wearable devices on operations is difficult. VRS, on the other hand, does not have this issue. As the biological signal sensors (such as EEG, eye movements, and motion signals) are directly integrated into the VRS system, mariners using VRS are required to wear these devices regardless. Therefore, the problems present in scale simulators are avoided. Additionally, the portability and low cost of VRS make it more accessible and easier to widely adopt, creating possibilities for extensive data collection.

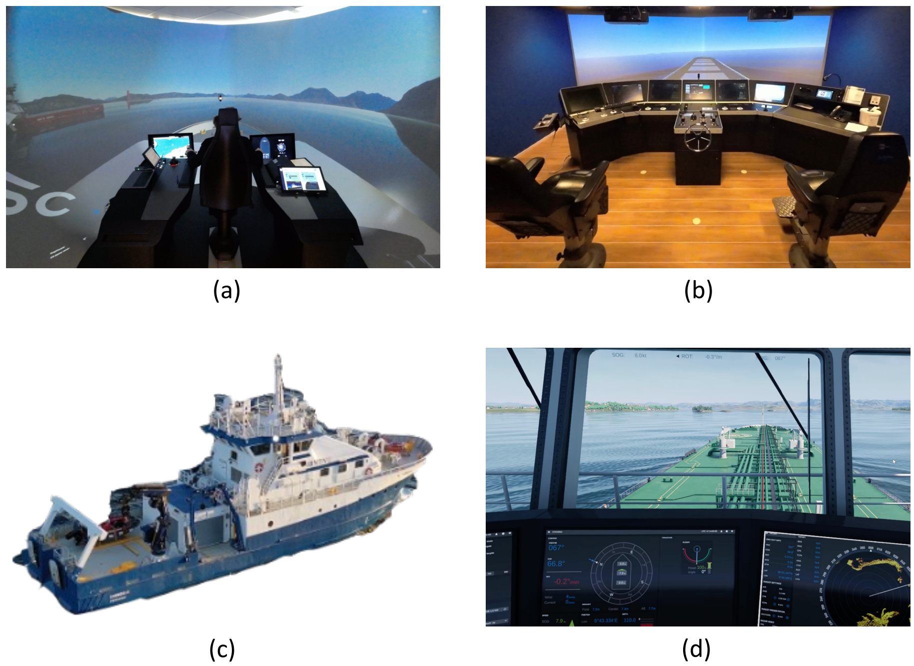

Fig. 1. Platforms used for MET (including (a) an immersive MET simulator; (b) standard scale martime simulator for MET; (c) developed VRS; (d) research vessel for practical training).

Scholars in related domains have started investigated how VR can benefit the MET and discuss its potentials, for instance, in maritime installation [6], safety education for ship engine training on maintenance and safety [7] [8], evacuation on passenger ships [9], crane operation [10], and specific navigation scenarios, including watch change and collision avoidance [11]. Besides these practical maritime applications, scholars also make efforts in enhance the user experience considering the feature of ocean environment, for instance, reduce seasickness through visual compensation of ship motions [12]. Apart from the interests from researchers, students from the nautical science are also attracted by learning enabling technologies to promote their skills and careers in the future [13].

This paper investigates the usability of VRS in MET, employing qualitative method by conducting experiments with experienced seafarers. The eligibility of VRS is discussed in comparison to the traditional scale maritime SBS. Through this study, our main aim is to verify the usability of VRS in MET, which is of great significance for the future promotion of VRS replacing traditional SBS, and/or as a complementary option to the current simulator facilities (as shown in Fig. 1) [14]. Firstly, we need to verify that the basic requirements and conditions for seafarer training in MET can be achieved on VRS with no less effectiveness than SBS. This includes basic operations such as navigation, ship handling, remote traffic control, construction of maritime traffic scenes, and other related ship operations (such as lifting operations), which are the most basic requirements for the widespread use of VRS in MET. Secondly, we need to compare the similarities and differences between MET and SBS as well as real ship bridges in terms of operational logic. This requires an intuitive comparison of the operational interface of the two methods, as well as subjective evaluations from trainees and experienced seafarers after actual experience. Finally, we need to identify the shortcomings of VRS at the current stage and explore to what extent these shortcomings will affect training effectiveness and crew performance, as well as how to compensate for these shortcomings.

2 METHODOLOGY

The research methodology and technical approach of this study are illustrated in Fig. 2. The study requires apprentices/experienced seafarers to conduct comparative testing on both SBS and VRS. The experimental procedure includes the following steps:

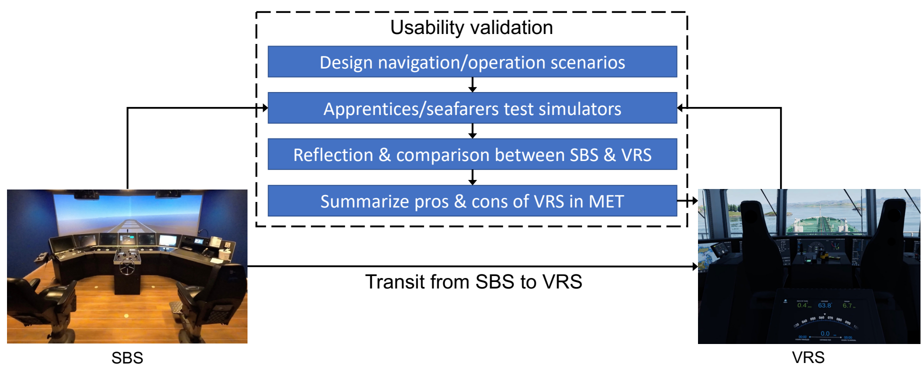

Fig. 2. Workflow of the study.

- Discuss and determine the navigation or operation scenarios and design with the Navigation course coordinator. The scenarios should include some challenging operational environments to better understand the interaction threshold between the navigator/operator and simulators.
- Participants are required to conduct tests on both simulators simultaneously.
- Collect participants' usage experience and comparative feedback on the two simulators to conduct a qualitative analysis of VRS usability.
- Meanwhile, record the participants' actual operating/navigating data, mainly ship log data.
- Summarize the advantages and disadvantages of VRS and provide feedback to the VRS development team to continuously improve the VRS performance, making it more suitable for MET requirements.

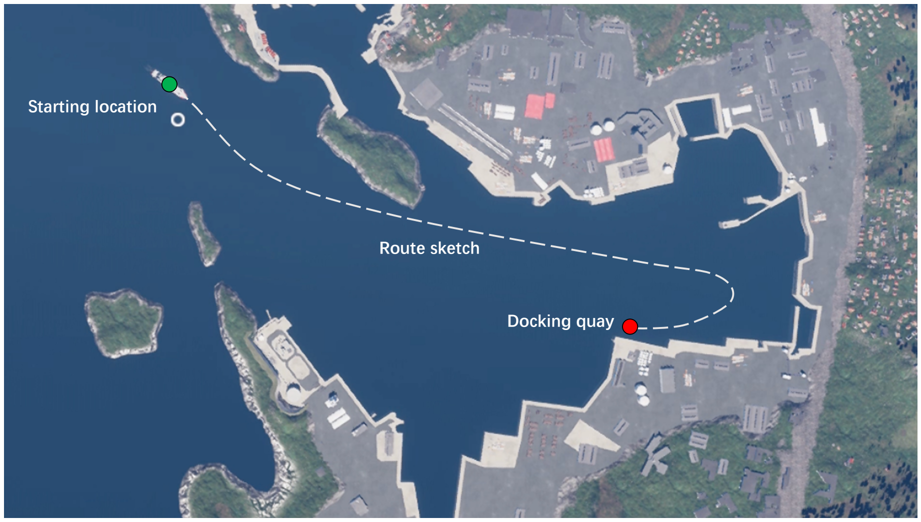

Fig. 3. Sketch of the proposed docking maneuvering operation.

In this study, the testing experiment scenario is set to docking operations. The simulated environment is a harbor in the western part of Stavanger, Norway. A sketch of the scene and route is illustrated in Fig. 3. The simulated navigational vessels are passenger ferries with a length of 170 meters and a beam of 27.5 meters, featuring the same ship bridge layout. The selection of docking operations as the test scenario is based on the requirement for a challenging routine operation, as mentioned earlier in the text. Docking represents a critical phase in general vessel navigation that requires a high level of overall navigation skills from the mariners, including environmental perception and vessel maneuvering. It is also a task that current Autonomous ANS cannot fully handle autonomously [15] [16]. Furthermore, since this study aims to assess the usability of VRS, the level of realism in the VRS scene construction (not limited to the marine environment but also including coastlines and harbor facilities) is an important evaluation factor regarding its suitability for MET.

The experiment is conducted with a group of bachelor students from nautical science in their third year (final year) and an experienced seafarer. Fig. 4 and 5 show that they are operating on different simulators. Prior to the formal commencement of the experiment, participants spent 60-90 minutes familiarizing themselves with and adapting to the use of the Virtual Reality Simulator (VRS).

3 RESULT & DISCUSSION

In this section, we will present the results of the experiments, briefing from participants, and the corresponding discussions.

Fig. 4. Navigator on the traditional SBS.

Fig. 5. Navigator using VRS.

3.1 Performance on different simulators

Table 1. Time to complete the task

No.	SBS (mm:ss)	VRS (mm:ss)	Difference (s)
1	12:56	13:55	59
2	12:15	11:46	-29
3	12:45	12:30	-15
4	13:04	13:05	1
Average	12:45	12:49	4
Standard Deviation	18.58	47.28	-

First, we assessed the overall performance of the experiments by primarily evaluating the completion time of the tasks by the participants. All participants successfully completed the designated tasks of docking the vessel into the specified berth using both the SBS and VRS. The completion times for each task are presented in Table 1.

From the average completion times, participants took an average of 12 minutes and 45 seconds to complete the task in SBS, slightly higher than the average completion time of 12 minutes and 49 seconds in VRS. However, it is worth noting that the standard deviation for completion times in SBS was 18.58, significantly lower than the standard deviation of 47.28 observed in VRS.

Given that the participants were experienced students or seafarers who were already proficient in using SBS, the smaller individual differences observed in SBS performance can be explained. On the other hand, the larger standard deviation in VRS can be attributed to differences in individual adaptability and acceptance of the new platform.

Since docking is a complex operation and all participants were deemed to have performed within operational standards and successfully completed the docking task, the observed differences, both at the individual and overall levels, are considered reasonable.

An important lesson for future experiment design is to incorporate an assessment of participants' proficiency in using VRS prior to the experiment. This would enhance the rigor of the formal experiment results.

3.2 Layout of ship bridges

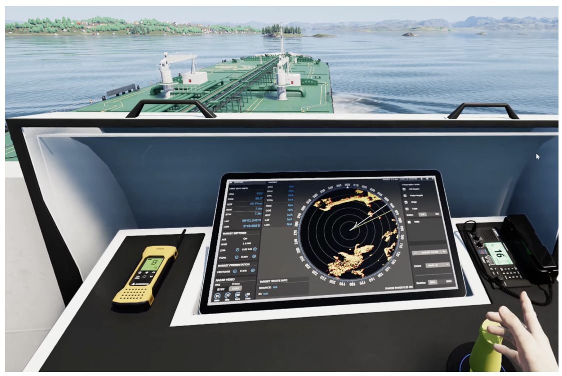

Fig. 6. Standing-out maneuvering panel at the starboard.

As mentioned in the Introduction, one of the most significant advantages of VRS is their cost-effectiveness. Traditional SBS are pre-designed, and the layout of an SBS space generally corresponds to only a few specific ship bridge configurations found in real vessels. However, various types of vessels such as commuter ships, ferries, cargo ships, cruise ships, tankers, and specialized vessels like research vessels may have different ship bridge layouts.

The limitation of traditional SBS lies in its ability to meet the layout requirements of specific vessel types, while only partially fulfilling the functionality for different layout requirements. This discrepancy between SBS and real vessels results in differences in the training experience provided. In contrast, VRS is not constrained by these limitations. Ship bridge scenes in VRS are created through software-based 3D modeling and projected onto VR headsets. This enables easy modifications or complete reconstruction of the ship bridge layout, accurately replicating the ship bridge layout found on real vessels.

For example, larger tankers or cruise ships often have separate conning panels on the port and starboard sides of the ship bridge, specifically used for operations like docking. However, due to factors such as limited space and equipment procurement, SBS may not include these separate conning panels. In contrast, VRS is not restricted by these factors, making it easy to implement features such as separate conning panels within the virtual environment (as shown in Fig. 6).

3.3 Feedback from participants

According to the accounts of the participants, they all found the experience on VRS to be highly engaging and enjoyable. However, they also noted distinct differences compared to SBS. Their negative feedback regarding VRS mainly centered around two aspects: the sensation of dizziness while wearing the VR headset and the lack of realistic tactile feedback during interactive operations, particularly when using the ECDIS and ARPA interfaces. Participants emphasized that the lack of tactile feedback from the control lever was particularly notable. This is important, especially during operations that require precise manipulation of course and thruster orders, such as docking.

Conversely, participants recognized that VRS primarily meets the needs of maritime students in terms of mastering the practical operation of ECDIS and ARPA. Additionally, VRS provides a fully immersive environment, surpassing the flat projection used in SBS, particularly in terms of modeling and displaying the external scene.

3.4 Summary

In this section, we presented the results of the experiments and the comparative evaluations of SBS and VRS from the participants. Overall, both in terms of experiment completion and participant feedback, VRS is capable of meeting some of the requirements for MET. As the participants mentioned, at least in lower-level maritime courses, VRS provides students with the opportunity to directly engage with practical ECDIS and ARPA systems. However, there are still deficiencies in human-computer interaction, whether it be specific methods of using ECDIS and ARPA or the feedback from control levers. These aspects are worth considering for developers, as the ultimate goal of MET remains to train crew members who can perform operations on actual vessels.

Due to the uncertainty surrounding whether VRS meets the requirements of MET, complies with existing regulations, and how to utilize it effectively, the framework for MET in relation to future technologies is still open for discussion. Regarding the repeated mention of tactile feedback by participants, if current VR devices are indeed unable to provide it, should Augmented Reality (AR) also be considered as a technological category for MET? Additionally, the application of VRS should not be limited to offline MET in the long run. Given that VRS inherently incorporates characteristics of the internet of things and the metaverse, it is worth exploring how to promote the widespread use of VRS in more MET institutions and increase user participation to establish a MET metaverse [17]. This would enhance communication between different MET institutions and improve the efficiency of MET. For example, in traditional collision avoidance exercises, either computer agents need to be programmed in SBS (lacking the communication abilities of real human navigators) or multiple interconnected local SBS systems are required. However, with the development of a MET metaverse, in response to such exercises, one could simply issue a request or proposal and await the cooperation of other online players to complete the task, enabling all participants to gain training in navigational skills to some extent. Furthermore, VRS itself has the potential to be used as an operational platform for remote control centers.

4 Conclusion

As introduced, VRS has its unique advantages in achieving educational equity and reducing costs, and there are more advantages worth exploring. Every evolution in educational technology is not accomplished overnight, just as before the emergence of SBS, seafarers could only train on real ships. Today, the emerging VRS technology is reshaping MET, and we explore the positive potential of VRS technology in this paper. It is unquestionable that the existing VRS can be used in simple navigational/operational tasks; however, we also discovered the urgent problems that need to be solved, including its incapability in providing necessary tactile feedback and dizziness under using. If VRS aims to replace SBS, further efforts are needed in this regard. Nevertheless, existing VRS systems may already be suitable for use by lower-level students and for maritime simulation training in regions or countries where acquiring SBS is not feasible. The application prospects of VRS in MET are promising, and further experiments will be conducted to validate its usability in various scenarios.

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References

1. B. Wu, G. Li, L. Zhao, H.-I. J. Aandahl, H. P. Hildre, H. Zhang, Navigating patterns analysis for onboard guidance support in crossing collision-avoidance operations, IEEE Intelligent Transportation Systems Magazine 14 (3) (2021) 62–77.
2. D. G. M. Vargas, K. K. Vijayan, O. J. Mork, Augmented reality for future research opportunities and challenges in the shipbuilding industry: a literature review, Procedia Manufacturing 45 (2020) 497–503.
3. T. Butkiewicz, Designing augmented reality marine navigation aids using virtual reality, in: OCEANS 2017-Anchorage, IEEE, 2017, pp. 1–9.
4. B. Wu, G. Li, T. Wang, H. P. Hildre, H. Zhang, Sailing status recognition to enhance safety awareness and path routing for a commuter ferry, Ships and Offshore Structures 16 (sup1) (2021) 1–12.
5. B. Wu, P. Han, M. Kanazawa, H. P. Hildre, L. Zhao, H. Zhang, G. Li, A camera-based deep-learning solution for visual attention zone recognition in maritime navigational operations, in: 2022 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), IEEE, 2022, pp. 699–706.
6. U. F. von Lukas, Virtual and augmented reality for the maritime sector–applications and requirements, IFAC Proceedings Volumes 43 (20) (2010) 196–200.

7. E. Markopoulos, M. Luimula, P. Porramo, T. Pisirici, A. Kirjonen, Virtual reality (vr) safety education for ship engine training on maintenance and safety (shipsevr), in: Advances in Creativity, Innovation, Entrepreneurship and Communication of Design: Proceedings of the AHFE 2020 Virtual Conferences on Creativity, Innovation and Entrepreneurship, and Human Factors in Communication of Design, July 16-20, 2020, USA, Springer, 2020, pp. 60–72.
8. E. Markopoulos, M. Luimula, W. Ravyse, J. Ahtiainen, V. Aro-Heinilä, Human computer interaction opportunities in hand tracking and finger recognition in ship engine room vr training, in: Advances in Creativity, Innovation, Entrepreneurship and Communication of Design: Proceedings of the AHFE 2021 Virtual Conferences on Creativity, Innovation and Entrepreneurship, and Human Factors in Communication of Design, July 25-29, 2021, USA, Springer, 2021, pp. 343–351.
9. C.-J. Chae, D. Kim, H.-T. Lee, A study on the analysis of the effects of passenger ship abandonment training using vr, Applied Sciences 11 (13) (2021) 5919.
10. E. Markopoulos, M. Luimula, Immersive safe oceans technology: Developing virtual onboard training episodes for maritime safety, Future Internet 12 (5) (2020) 80.
11. E. Markopoulos, J. Lauronen, M. Luimula, P. Lehto, S. Laukkanen, Maritime safety education with vr technology (marsevr), in: 2019 10th IEEE International Conference on Cognitive Infocommunications (CogInfoCom), IEEE, 2019, pp. 283–288.
12. A. H. Stevens, T. Butkiewicz, Reducing seasickness in onboard marine vr use through visual compensation of vessel motion, in: 2019 IEEE conference on virtual reality and 3D user interfaces (VR), IEEE, 2019, pp. 1872–1873.
13. B. Wu, H.-I. J. Aandahl, R. Bosneagu, M. L. Saeter, D. Cosofret, E.-R. Avram, H. Zhang, G. Li, Survey for interdisciplinary co-supervision on bachelor thesis in nautical science, in: 2023 IEEE Global Engineering Education Conference (EDUCON), IEEE, 2023, pp. 1–6.
14. B. Wu, M. L. Sæter, H. P. Hildre, H. Zhang, G. Li, Experiment design and implementation for human-in-the-loop study towards maritime autonomous surface ships, in: 2022 IEEE International Conference on Systems, Man, and Cybernetics (SMC), IEEE, 2022, pp. 1948–1953.
15. R. Skulstad, G. Li, T. I. Fossen, B. Vik, H. Zhang, A hybrid approach to motion prediction for ship docking—integration of a neural network model into the ship dynamic model, IEEE Transactions on Instrumentation and Measurement 70 (2020) 1–11.
16. L. Zhao, G. Li, K. Remøy, B. Wu, H. Zhang, Development of onboard decision supporting system for ship docking operations, in: 2020 15th IEEE Conference on Industrial Electronics and Applications (ICIEA), IEEE, 2020, pp. 1456–1462.
17. E. Markopoulos, A. D. Nordholm, S. Illiade, P. Markopoulos, J. Faraclas, M. Luimula, A certification framework for virtual reality and metaverse training scenarios in the maritime and shipping industry, in: Creativity, Innovation and Entrepreneurship, Vol. 31, AHFE International, 2022, pp. 36–47.