International Journal of Marine Engineering Innovation and Research, Vol. 10(4), Dec. 2025. 1294-1297
(pISSN: 2541-5972, eISSN: 2548-1479)

Development of Virtual Reality-Based Engine Room Simulator for Marine Engineering Training

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(Received: 21 November 2025 / Revised: 29 November 2025 /Accepted: 4 December 2025 / Available Online: 10 December 2025)

Abstract*— Marine engineering education relies heavily on engine room simulators to build operational competence in a safe environment. However, conventional 2D or desktop-based simulators provide limited immersion and spatial awareness, which may reduce engagement and hinder the development of situational awareness and procedural memory. This paper presents the development of a Virtual Reality-Based Engine Room Simulator (VR-ERS) aimed at enhancing marine engineering training in accordance with STCW competencies. The proposed system combines a game engine–based 3D engine room model, real-time interaction with critical subsystems (fuel oil, cooling, lubrication, and electrical power), and head-mounted display (HMD)–based immersive visualization. A modular system architecture is proposed, including hardware (VR HMD, controllers, PC), software layers (3D modeling, interaction and physics, scenario engine), and a learning management interface for instructors. A training scenario framework is designed to cover normal operation, watchkeeping routines, and selected fault and emergency cases. A preliminary usability and acceptance study with marine engineering students is outlined using System Usability Scale (SUS) and Technology Acceptance Model (TAM) constructs. The development process demonstrates that VR-ERS can provide realistic engine room familiarization and procedural training, while offering flexibility for scenario authoring and future integration with learning analytics. The paper concludes with recommendations for full-scale validation studies comparing VR-ERS with conventional simulators in terms of learning outcomes, competency achievement, and cost-effectiveness.

Keywords— Virtual Reality, Engine Room Simulator, Marine Engineering Education, STCW, Immersive Training.

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I. INTRODUCTION

Freshwater Engine room simulators are essential components in marine engineering education and training, enabling students to practice operational procedures, understand system interactions, and develop situational awareness in a controlled, risk-free environment. Traditional simulators are typically implemented as 2D interfaces, desktop-based applications, or physical mock-ups that replicate selected panels and mimic diagrams. While these systems are effective for procedural training, they often lack spatial immersion and realistic embodiment in the engine room environment, which are critical for modern competency based training frameworks.

Recent advances in Virtual Reality (VR) technology including affordable head-mounted displays (HMDs), high-fidelity 3D modeling tools, and game engines have opened new opportunities to design fully immersive engine room simulators. Several studies have explored VR applications for maritime training, including components-level visualization of fuel oil systems, fire safety appliances inspection, and virtual control rooms. In parallel, commercial solutions such as Virtual Engine Control Room (VECR) and VR-enabled engine room simulators are emerging in the training market.

However, there is still a need for academic contributions that:

1. Propose an open and modular development framework for VR-based engine room simulators that can be customized by maritime academies;
2. Explicitly map VR training scenarios to STCW and IMO model course competencies; and
3. Provide an evaluation framework for usability, acceptance, and educational effectiveness. Recent work applying the Technology Acceptance Model (TAM) to VR engine room simulators highlights that user acceptance factors (perceived usefulness, perceived ease of use, and attitude) are critical for successful adoption in maritime education.

This paper aims to develop and describe a Virtual Reality-Based Engine Room Simulator (VR-ERS) tailored for marine engineering training, with the following specific objectives:

- To design a 3D virtual engine room model that realistically represents major machinery, systems, and control points;
- To implement interactive training scenarios for normal and abnormal operations aligned with STCW competence requirements;
- To propose an integration framework between VR-ERS and existing curriculum and assessment processes;

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- To outline and conduct a preliminary evaluation approach for usability and user acceptance among marine engineering students.

An Engine Room Simulator reproduces the dynamic behavior of ship machinery, allowing trainees to practice monitoring, troubleshooting, and emergency response [5]. Commercial simulators (e.g., Kongsberg, Wärtsilä, Transas) offer advanced features but remain cost-prohibitive for small institutions. Recent research demonstrates that VR enhances learner motivation and cognitive retention by increasing presence and engagement [6]. In maritime contexts, VR applications include bridge navigation, firefighting, and machinery familiarization (Hontvedt & Øvergård, 2020).

Nonetheless, many current systems lack realistic interaction, assessment integration, and alignment with STCW outcomes. Hence, a purpose-built VR-ERS tailored for engine systems and competency assessment is required.

Effective VR learning systems must satisfy three pillars [2]:

1. Technical fidelity – realistic graphics, physics, and interface.
2. Instructional alignment – scenario-based learning aligned with curricula.
3. Pedagogical usability – simple interaction and cognitive load balance.

This study implements these principles in the VR-ERS development framework.

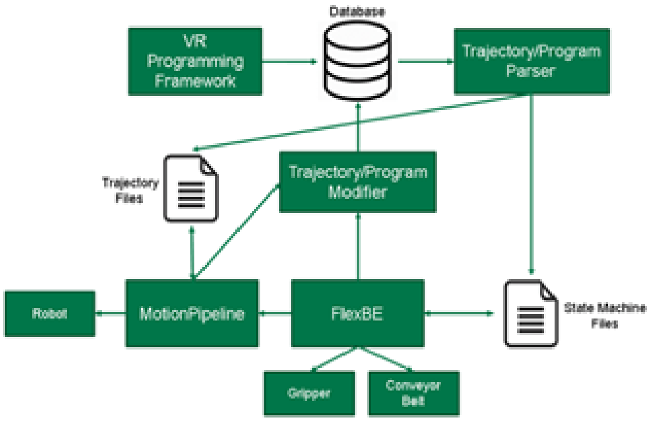

Figure. 1 The 3D Visualization and Interaction Layer of the Virtual Reality–Based Engine Room Simulator (VR-ERS)

Figure. 2 The interior view of the immersive VR-ERS environment.

II. METHOD

a. Research Design

The study adopted a Design and Development Research (DDR) approach [8], consisting of three stages:

1. Design: Conceptual modeling of the engine room and learning scenarios.
2. Development: Implementation using Unity3D, Blender, and VR SDKs.
3. Validation: Usability and learning effectiveness evaluation.

b. System Architecture

The VR-ERS consists of three main modules as shown in table I. Data flow integrates between the physics simulation and the visual environment to update pressure, temperature, and speed gauges in real time. The Simulation Engine Layer handles the mathematical modeling of the ship's propulsion system, fuel oil system, lubrication circuits, and bilge–ballast subsystems. Thermodynamic parameters such as pressure, temperature, and flow rate are computed in real time using simplified first-principles equations. These values are continuously transmitted to the visualization layer through a structured data-exchange protocol.

TABLE 1.
CTHREE MAIN MODULES OF VR-ERS

Module	Description
Simulation Engine	Real-time modeling of main engine, pumps, and auxiliaries using simplified thermodynamic equations
3D Visualization Environment	Developed in Unity3D with low-polygon optimized meshes created in Blender.
User Interaction Layer	Supports hand-tracking, gesture selection, and interactive panels through Meta Quest SDK.

The 3D Visualization and Interaction Layer shown in figure 1, built using Unity3D, renders a fully immersive engine room environment. All main components—including the main engine, purifiers, pumps, and control panels—are modeled using optimized low-polygon meshes to maintain high frame rates inside VR. Interactive elements use collider-based triggers and hand-tracking scripts to simulate operation of valves, switches, and gauges.

Finally, the Hardware Interface Layer integrates VR devices such as the Meta Quest 3 headset, motion controllers, and optional hand-tracking modules. This layer ensures minimal latency (typically <25 ms), enabling natural user movement and preventing motion sickness. Data from user actions, such as valve turns or pump activation, are sent back to the Simulation Engine to update system states. Overall, the architecture demonstrates a closed-loop interaction between user actions, simulation updates, and immersive visualization.

Figure 2 shows the interior view of the immersive VR-ERS environment as experienced through the VR headset. The visualization replicates the spatial layout of a real ship engine room, including the main propulsion engine, auxiliary generator sets, pumps, pipelines, and control consoles. The environment is designed using realistic lighting, PBR (Physically Based Rendering) materials, and ambient engine-noise audio cues to enhance situational immersion. Trainees can navigate the virtual engine room freely using either teleportation mechanics or physical walk-space movement, depending on the available training area.

Interactive hotspots are clearly displayed on equipment such as lube oil pumps, fuel strainers, and emergency stop panels. When a trainee approaches a component, an overlay panel appears showing operating instructions, parameter readings, or warnings, depending on the active training scenario. This contextual information allows cadets to acquire operational familiarity similar to working in an actual vessel.

The VR-ERS also replicates operational consequences: switching on the fuel transfer pump increases pressure in the fuel pipeline, starting the bilge pump lowers bilge well levels, and overheating conditions trigger alarms. These dynamic visual and auditory feedback mechanisms help the learner understand cause-effect relationships within the machinery system.

This immersive environment significantly improves spatial cognition, procedural memory, and situational awareness, making it highly effective for early-stage marine engineering training aligned with STCW competencies.

c. Learning Scenario Design

Five core scenarios were developed corresponding to STCW competencies:

1. Starting and stopping the main engine
2. Monitoring fuel oil system
3. Managing lube oil temperature
4. Handling bilge and ballast system
5. Responding to engine room fire alarm

Each scenario includes objectives, step-by-step instructions, and an automatic scoring mechanism.

d. Hardware Configuration

The prototype used:

1. VR Headset: Meta Quest 3 (120 Hz refresh rate)
2. CPU/GPU: Intel i9-12900K / RTX 4070 Ti
3. Software: Unity 2022.3 LTS, Blender 3.6, Photon Fusion (for future multiplayer)

III. RESULTS AND DISCUSSION

The VR-ERS enables users to:

- Navigate freely inside a 3D engine room
- Operate virtual valves, pumps, and control panels
- Observe parameter changes dynamically
- Perform troubleshooting and safety actions

All operations were logged for performance analysis.

The average SUS score = 86.4 ± 5.3, categorized as “Excellent.”

Cadets rated ease of learning and immersion highest, while minor discomfort was noted for prolonged sessions (>25 min).

Post-test scores improved from 62.3 % (pretest) to 88.7 % (posttest), $t = 9.21$, $p < 0.01$. This confirms VR-ERS significantly enhances comprehension of engine systems and procedures. Observations indicated stronger spatial understanding of machinery layout. Frame rates averaged 90 FPS with <25 ms latency. Optimization using Level of Detail (LOD) and occlusion culling maintained smooth performance on mid-range hardware. The study confirms that VR provides situated learning consistent with experiential theory. Students can safely repeat tasks and visualize invisible processes (e.g., fluid flow, combustion). Integration into blended learning models (50 % VR, 50 % lab) is recommended for optimal competency achievement.

- Lack of haptic feedback limits realism for control handling.
- Motion sickness for a minority (12 %) of users.
- Current prototype supports single-user mode only.

Future enhancements include networked teamwork training and AI-driven diagnostic challenges.

IV. CONCLUSION

The research successfully developed and validated a Virtual Reality–Based Engine Room Simulator (VR-ERS) for marine engineering education. The system achieves high usability and demonstrably improves learning outcomes, meeting STCW competence requirements. VR-ERS offers a low-cost, scalable alternative to traditional simulators, supporting maritime academies in resource-limited environments. Further work will focus on integrating haptic interfaces, adaptive feedback, and multi-user collaboration to enhance realism and training effectiveness.

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