Virtual Reality Scuba Diving Simulator: Supplementing Real-World Training while addressing HCI Challenges

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***Abstract*—In a number of domains, including diving, virtual reality (VR) has become a revolutionary training and simulation tool. The potential of a virtual reality underwater environment simulation for diving instruction is investigated in this study. The study intends to improve training effectiveness, safety, and user experience through the use of immersive technology. It examines current VR-based training materials, identifies limitations, and offers a methodical approach to creating and evaluating the proposed VR simulation. According to preliminary research, VR-based training provides aspiring divers with a safe and controlled environment while also enhancing spatial awareness, reaction times, and procedure recall. These findings demonstrate VR's potential as a valuable supplement to conventional diving instruction techniques. This work contributes a prototype of a low-cost, immersive VR underwater simulator that integrates motion feedback and realistic environmental modeling. It further introduces a quantitative and qualitative evaluation framework to assess training effectiveness, comfort, and feasibility, thereby establishing the feasibility of VR as a tool for diver training.**

Index Terms*—*Virtual Reality, Diving Training, Underwater Simulation, Immersive Learning, Feasibility Study

I. Introduction

Traditional scuba diving training, while effective, faces challenges such as high costs, limited access, environmental impact, and safety risks. With advancements in digital technology, Virtual Reality (VR) emerges as a promising solution, offering a safe, immersive, and repeatable environment for skill development and emergency preparedness.

VR enables simulation of underwater physics, buoyancy, and marine settings, helping learners build confidence before real-world dives. However, its effectiveness depends on factors like realism, user engagement, physiological impact, and cost-efficiency.

Early research highlights VR's ability to enhance procedural memory and spatial awareness, while minimizing physical risk. Despite progress in haptics and motion tracking, concerns such as hardware limitations and motion sickness persist.

This study explores the viability and limitations of VR-based underwater training to inform the development of safer and more accessible alternatives to conventional methods.

A. Problem Statement

Although virtual reality has demonstrated promise in skill-based training, accurately replicating underwater conditions presents substantial technical challenges. Most existing VR diving simulations fail to reproduce realistic water resistance, buoyancy effects, and multi-sensory feedback, resulting in limited immersion and reduced training value. Furthermore, issues such as motion sickness, hardware limitations, and high development costs hinder adoption in real-world diving instruction. This study aims to address these challenges by proposing and evaluating a technically feasible, cost-effective VR scuba diving simulator capable of delivering a realistic and safe underwater training experience.

B. Research Contribution

The key contributions of this study are summarized as follows:

- Development of a Prototype: A low-cost and immersive virtual reality (VR) underwater simulator was developed, integrating motion tracking, haptic feedback, and realistic environmental modeling to replicate diving conditions safely and effectively.
- Evaluation Framework: A combined quantitative and qualitative evaluation framework was introduced to assess user immersion, comfort, and training effectiveness through participant testing.
- Feasibility Validation: The study empirically validates the feasibility of VR as a supplementary tool for scuba diving education, demonstrating its potential to enhance accessibility, safety, and learner engagement compared to traditional training methods.

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These contributions collectively position the study as a foundational effort toward establishing virtual reality as an effective medium for underwater training and skill development.

II. Background And Literature Survey

Scuba diving is a physically and mentally challenging sport requiring rigorous training for safety and performance. Traditional methods include classroom sessions, pool practice, and supervised open-water training, often following standards like PADI or NAUI [1]. While effective, these are limited by high costs, restricted facilities, and environmental risks [2], [3]. VR offers a controlled, immersive alternative addressing these challenges [4], [5].

A. *Traditional Methods to Diving Training*

Scuba courses typically combine theory, skill practice, and real dives. Research like that of Biersner and Hall [2] and Mekjavic et al. [3] highlight the benefits of real- world scenarios, but repeating emergency simulations is expensive and impractical.

B. *Virtual Reality for Skill Development and Training*

VR is widely applied in fields like military, medical, and industrial safety training [6], [7], enabling repeated prac- tice and real-time feedback. In diving, VR can simulate buoyancy, pressure, depth perception, and emergencies [8], improving spatial skills and muscle memory though it cannot yet reproduce physiological conditions like water pressure and breathing resistance [8].

C. *Virtual Reality in Underwater Simulations*

VR underwater environments are used in education, tourism, and marine science [5]. High-fidelity rendering of underwater light, refraction, and motion is essential. Haptic devices improve immersion, though accurate sen- sory replication like temperature and resistance remains difficult [9], [10]. Research supports multi-sensory inter- faces to better mimic real diving [10], [11].

D. *Effectiveness of VR-Based Training for Diving*

Studies show VR improves situational awareness and recall more than traditional training alone [8], [7]. Novices especially benefit in navigation skills. However, VR cannot fully replace in-water experience for adapting to real pressure and buoyancy [8].

E. *Challenges and Future Directions in VR-Based Diving Training*

Accurately simulating underwater phenomena like temperature and pressure is still hard. Wearables and ad- vanced tracking may help [10]. Cybersickness due to dis- orientation is another issue, addressable through motion and display optimizations [12], [11]. High equipment cost also limits adoption, but cheaper devices and cloud-based systems may help [5], [13].

F. *Summary of Literature Review*

VR shows promise for safer, cost-effective, immersive diving training [4], [8], [7], but still lacks full sensory realism, physiological simulation, and comfort at high usage durations. Future research should enhance sensory feedback, underwater physics accuracy, and hybrid models combining VR with real dives [10], [11], [13].

This study evaluates the feasibility of VR in underwater training, highlighting its potential and limitations.

III. Research Objectives

This research aims to design, develop, and evaluate a feasible VR underwater simulation system that supports scuba diving training through immersive environments and real-time feedback. The objectives address both technical and educational dimensions related to safety, accessibility, and system efficiency.

1) Enhance Training Safety and Accessibility: Develop a VR simulator for practicing core diving skills such as buoyancy control, emergency handling, and navigation in a safe, repeatable, and cost-efficient environment to improve readiness before real dives.
2) System Architecture Design: Create a modular VR architecture integrating Unity, Meta Quest, and Arduino-based haptics to simulate underwater physics and feedback in real time with minimal latency.
3) Optimize Rendering and Physics: Implement accu- rate buoyancy, drag, and current models. Use optimized shaders for underwater lighting and visibility while maintaining smooth performance.
4) Add Motion and Haptic Feedback: Integrate motion tracking and tactile responses (e.g., resistance, vibration) to enhance immersion and support realistic skill practice.
5) Evaluate Skill Development: Measure the simulator's impact on users' skill retention, spatial awareness, and task performance using data like reaction time, navigation accuracy, and procedural recall. Compare results with traditional training.
6) Implement Data Logging and Analytics: Develop a module to record metrics such as task time, movement accuracy, and error rates, enabling personalized feedback and adaptive learning.
7) Reduce Motion Sickness, Improve Comfort: Apply techniques like adjustable field of view, motion smoothing, and frame rate control to minimize cybersickness and support prolonged use.
8) Enable Integration with Existing Courses: Explore embedding the simulator into current diving certification programs (e.g., PADI, NAUI) to support blended learning.
9) Evaluation of System Performance and User Experience: Conduct empirical testing to assess both technical and experiential performance. Measure system latency, frame-rate stability, and interaction accuracy alongside user satisfaction, realism, and immersion levels.

By achieving these objectives, this study bridges the gap between immersive learning theory and practical VR system engineering, establishing the technical and educational feasibility of VR as a complementary tool for scuba diving training.

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IV. Methodology

This section outlines the technical approach used to design, implement, and evaluate the proposed VR scuba diving simulator. The methodology is structured around five major technical components: system architecture design, environmental rendering, motion and haptic feedback integration, data analytics, and evaluation. It describes the process of building an interactive, realistic, and immersive virtual underwater environment that replicates diving conditions to enhance diver training.

A. *System Architecture Design and Integration*

By using VR technologies, the VR underwater simulation system is intended to provide lifelike underwater experi- ences. A variety of underwater conditions, such as water depth, lighting, visibility, and interactions with aquatic life, will be replicated in the system design. To enable complete immersion, VR hardware (such as headsets and motion sensors) and software (such as game engines and 3D modelling tools) must be integrated.

The Meta Quest VR headset is the primary piece of hardware, tracking the user's hand, leg, and head movements to enable real-time control of the underwater simulation. To improve both visual and physical immersion, the user dons a specially made mask. To add realism and simulate the feeling of breathing underwater, a mounted oxygen (O_2) sensor monitors airflow and breathing patterns.

The Unity game engine powers the simulation, control- ling everything from the underwater environment to the user interface. Gesture recognition, ambient animations, and training modules that lead the user through safety procedures and targeted diving tasks are all handled by Unity. The (O_2) sensor and VR headset continuously stream real-time data to Unity, enabling the simulation to respond to the user's movements and physiological input. An Arduino microcontroller is connected with an external motor (M) to provide haptic effects. The motor generates physical sensations such as water currents or equipment vibrations corresponding to virtual world events. The Arduino serves as a communication interface between the hardware and Unity, actuating the motor according to simulation changes.

Overall, the system creates a responsive loop where the user's actions affect the virtual environment, with the system reacting with appropriate visual, auditory, and physical feedback. This makes the training procedure highly interactive, realistic, and effective for learning scuba diving skills in a safe, virtual environment.

B. *Scenario Modeling and Content Generation*

To generate realistic training scenarios, we use crowd-sourcing to gather information from real divers, instruc- tors, and subject matter experts. We get feedback from online surveys, interviews, and forums about the types of diving environments, issues, and conditions that divers generally face. This feedback helps us determine the most critical scenarios to simulate in the VR world, enabling the training to be practical and relevant.

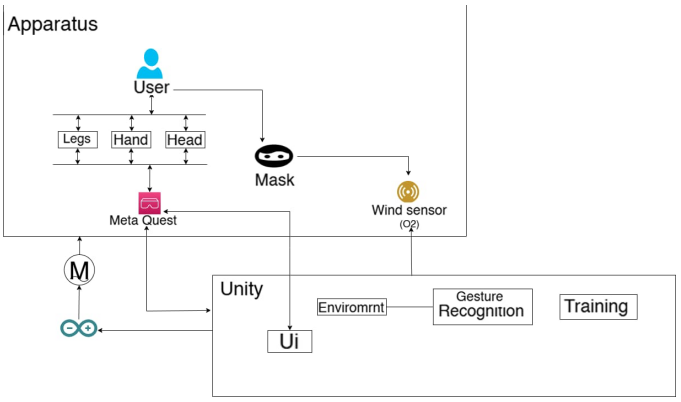


Fig. 1. System overview diagram of the VR underwater simulator

C. *Optimization of Environmental Rendering and Physics Simulation*

The following aspects need to be realistically modeled and simulated for an underwater environment to feel realistic:

- Water Physics: We simulate water currents, buoyancy, and motion resistance to create realistic diving experiences. This is done using fluid dynamics simulations in the VR engine.
- Lighting and Visibility: Different lighting effects (e.g., light diffusion, refraction) are used to create a realistic underwater lighting environment, with variable visibility at different depths.
- Marine Life Simulation**:** To create a realistic underwater environment, a variety of marine life and plants are modelled using 3D modelling techniques.



Fig. 2. Environment view from the simulated underwater scene

D. *User Interaction and Control Module Design*

Focused on developing interactions to allow users to engage with the world, objects, and sea creatures in a manner that can provide the best training experience and immersion. Test sessions are used to collect user feedback on a regular basis, where divers inspect training effective- ness, engagement levels, and usability. The simulation is then tuned based on the feedback to improve both the user experience and the effectiveness as a trainer.

E. *Machine Learning and Data Analytics*

Machine learning algorithms are used to monitor and evaluate user performance to further develop the training experience. This information contains:

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- Dive Timing: The amount of time spent on particular tasks, such as object location or arriving at an exact depth.
- Error Tracking: Errors made by the user, such as improper techniques or unsafe diving procedures.
- Performance Metrics: Performance metrics such as air usage, buoyancy control, and navigation efficiency.

Machine learning algorithms are used on this data to provide real-time feedback as well as personalize training recommendations to the users.

F. *Hardware Integration and Sensor Communication*

VR simulation utilizes a variety of hardware components in combination to facilitate total immersion:

- VR Headset: A high-end VR headset (e.g., Oculus Rift, HTC Vive) is used to immerse the users in the underwater environment.
- Motion Tracking: Motion controllers or full-body tracking systems are integrated to mimic the movements of users, e.g., swimming or using diving equipment.
- Haptic Feedback: To simulate underwater sensations (e.g., resistance of water), haptic feedback devices are integrated to provide tactile feedback based on user actions.

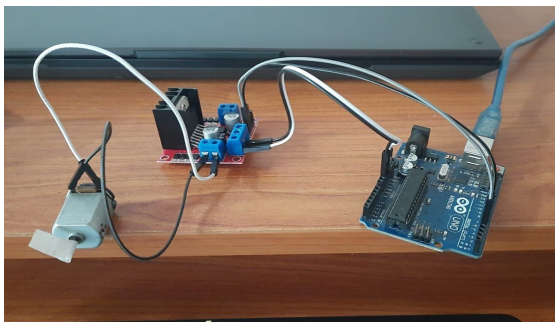


Fig. 3. Testing a DC motor with Arduino for haptic feedback

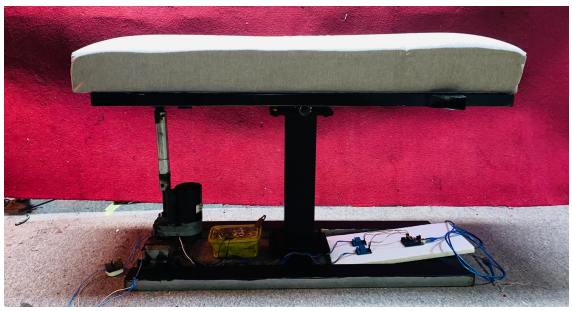


Fig. 4. Experimental apparatus used in the VR underwater simulation setup

Users can only move forward and backward for a total of 40 seconds in the VR swimming simulation system. This restriction mimics the natural swimming distance limit, ensuring balanced gameplay and preventing excessive motion in one direction.

Let:

- T_f: Total time the user has moved forward (in seconds)
- T_b: Total time the user has moved backward (in seconds)
- $T_{\max}$: Maximum allowed total movement time (set to 40 seconds)
- T_r: Remaining allowable movement time

The following equation represents the constraint:

$$T_f + T_b \leq T_{\max} \tag{1}$$

To determine how much more movement time is allowed:

$$T_r = T_{\max} - (T_f + T_b) \tag{2}$$

This guarantees that the total amount of time spent moving forward and backward will never be greater than the maximum permitted movement time. After the user crosses this threshold, they are unable to move further until a completion or reset event takes place.

For example, if the user has already moved forward for 10 seconds ($T_f = 10$) and backward for 15 seconds ($T_b = 15$), the system calculates the remaining movement time as:

$$T_r = 40 - (10 + 15) = 15 \text{ seconds} \tag{3}$$

As a result, the system stops allowing the user to move for another 15 seconds in either direction. This method improves the simulation's realism and control while enforcing a constant movement budget.

G. *Testing and Evaluation*

The testing phase was conducted to evaluate both the technical performance and user experience of the de- veloped VR underwater simulator. Twenty participants were selected, representing a mix of novice and expe- rienced VR users. The evaluation followed two main dimensions: system-level measurements and user-level experience metrics.

1) System-Level Measurements: System performance was benchmarked using the Unity Profiler and Meta Quest performance overlay. The following quantitative metrics were recorded:

- Frame Rate (FPS): Average and minimum frames per second were measured to ensure stable real-time rendering, with a target of maintaining above 72 FPS.
- System Latency: The time delay between user movement input and on-screen visual response was measured using the Unity `Time.deltaTime` function and hardware logs, targeting under 30 ms latency.
- Haptic Response Time: Signal delay between Unity command execution and Arduino motor actuation was captured using serial timestamp comparison to verify synchronous feedback.
- Hardware Utilization: CPU and GPU usage percentages were monitored to confirm optimization under typical operation loads.

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2) User Experience Measurements: User experience was evaluated using a structured questionnaire based on standardized scales:

- Immersion and Presence: Measured using a five-point Likert scale adapted from the Presence Questionnaire (PQ), assessing realism, attention focus, and sense of control.
- Usability: Measured using the System Usability Scale (SUS), capturing user perceptions of interface simplicity, responsiveness, and ease of navigation.
- Motion Sickness: Evaluated using the Simulator Sickness Questionnaire (SSQ), recording symptoms such as dizziness, nausea, and disorientation.
- Comfort and Training Usefulness: Measured via custom Likert-scale items focused on comfort during use and perceived value for skill improvement.

The combination of quantitative system metrics and user perception data enabled a comprehensive evaluation of the simulator's technical performance, stability, and effectiveness for diving-related skill training.

H. *Deployment of VR Software and Tools*

To create the underwater simulation, we use several tools and software:

- Game Engine: A powerful game engine (e.g., Unity or Unreal Engine) is used for real-time 3D rendering and physics simulation.
- 3D Modeling: 3D modeling tools like Blender or Autodesk Maya are used in designing detailed 3D models of the underwater environment and sea life.
- Machine Learning Tools: Python, TensorFlow, and other machine learning libraries are used for analyzing user performance data and providing personalized feedback.

I. *Data Collection and Analytics*

User interaction information (e.g., movements, dive actions, and performance data) is collected and stored in a secure database. The data is analysed to improve the system and give users customised feedback. The simulation is also optimised using data analytics in response to user input and real-world circumstances.

V. Results And Discussion

The following is the outcome of the user testing phase of the Sea Quest VR underwater simulator. Twenty participants were involved in the sample, spanning a range of knowledge about VR and diving experience. The feedback was collected on a standard questionnaire, noting usability, realism, immersion, and effectiveness of the actual tilting device.

A. Quantitative Results

Table I summarizes the mean response percentages obtained from twenty participants. To ensure reliability, descriptive statistics were computed for each item, including mean values and standard deviations. Where applicable, paired-sample t-tests were conducted to determine whether differences in user ratings across key factors (e.g., immersion vs. comfort) were statistically significant at the 95% confidence level ($p < 0.05$). The overall results showed low variance (standard deviation < 8%) among participants, indicating consistent feedback across the group.

TABLE I. Summary of Participant Responses (N = 20)

Question	Common Response	Percentage
Ease of navigation in the VR environment	Easy	85%
Motion sickness or discomfort	No	90%
Perceived realism of underwater environment	Realistic	75%
Water effects quality	Very Good	80%
Marine life realism	Good	67%
Sound design realism	Good	73%
Usefulness for training, education, or tourism	Training	82%
Increased interest in underwater exploration	Strongly Agreed	78%
Natural feeling of tilting	Very Natural	68%
Tilting enhanced realism	Strongly Agreed	75%
Discomfort from tilting device	No	98%

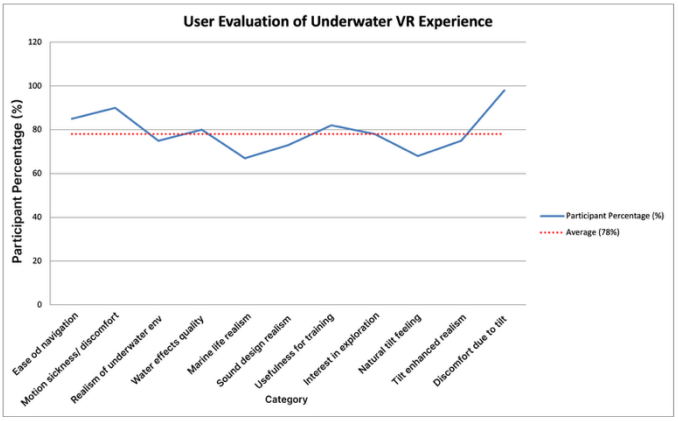


Fig. 5. Summary of participant responses across immersion, realism, comfort, and perceived training value

B. Qualitative Feedback Summary

Unrestricted comments from participants provided valuable insights into the benefits and problems of the Sea Quest VR experience.

What users liked the most (Q17): The users particularly appreciated the underwater visuals, the tilting mechanism's natural movement, and the calming sound design. Several users described the experience as "peaceful," "engaging," and "very close to real diving." The gamified elements, such as physical interaction, were also highlighted as motivating and enjoyable.

Dislikes and improvement suggestions (Q18): Some participants recommended that the marine life be more interactive or varied to increase realism. Furthermore, some users mentioned that they occasionally had problems getting used to the tilting mechanism at the start of the session, suggesting that a brief tutorial or calibration phase could be beneficial. Better lighting in deeper scenes and more audio cues related to motion or depth were also recommended.

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Enhancement ideas (Q19): Several users proposed future enhancements such as:

- Integration of hand-tracking or gesture recognition for object interaction.
- More complex tasks for gamification, such as treasure hunts or underwater missions.
- Haptic feedback for touch simulation with marine objects or environmental changes (e.g., pressure variation).
- Voice guidance or educational narration to explain marine biodiversity and safety practices.

These recommendations provide a path forward for the project's subsequent iterations, especially if training or commercial applications are sought.

Overall, the qualitative responses supported the quantitative results, demonstrating that the system offers opportunities for further development and improvement while simultaneously providing a realistic, entertaining, and captivating VR diving experience.

C. Discussion

The Sea Quest VR simulation demonstrated high user satisfaction across multiple metrics. 85% of participants found navigation easy, indicating effective UI/UX design, while 80% reported a strong sense of presence, supported by positive feedback on visual and audio effects.

The tilting device significantly enhanced realism for 75% of users, with 65% noting natural movement and 80% reporting improved immersion. Only 15% experienced discomfort, reflecting the system's overall ergonomic design.

Users also highlighted the educational and recreational value, with 90% recognizing practical applications such as diving instruction and tourism. 70% expressed increased interest in underwater exploration, suggesting the simulation's positive emotional and behavioral impact.

Overall, the results affirm the system's effectiveness in balancing realism, usability, and engagement. Minor improvements in marine life detail and motion comfort could further enhance the experience.

VI. Limitations And Future Works

While the VR underwater training system demonstrates strong potential, several challenges persist. Motion sickness, caused by mismatched physical and virtual cues, still affects user comfort and session length. Future versions should include adjustable comfort settings, adaptive frame rates, and smoother transitions.

Current hardware limitations also restrict realism. Devices like the Meta Quest lack advanced haptic and physiological tracking. Future improvements may require higher-end VR systems and custom hardware.

Sensory feedback is currently basic. Adding multi-sensory effects like temperature change, water pressure, and resistance could further enhance immersion.

More user testing and comparisons with traditional methods are needed to confirm long-term skill retention and safety benefits. Planned updates include expanding scenarios, integrating AI-based content adaptation, and simulating advanced emergency situations.

VII. Conclusion

The study indicates that virtual reality (VR) can be used to train diving, providing a more effective and safer option compared to traditional methods. Promising though it is, software and hardware developments are still to arrive to further optimize VR simulation performance. In order for VR to become more widely used in diving training, more studies must quantify its cost-effectiveness and long-term performance in learning.

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