Exploring Gesture Interaction in Underwater Virtual Reality

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Figure 1: Participants used gestures with a waterproof head-mounted display to interact with a virtual underwater environment while submerged: grab for navigation (left), pinch for single actions (center), and point for continuous actions (right).

ABSTRACT

An underwater virtual reality (UVR) system with gesture-based controls was developed to facilitate navigation and interaction while submerged. The system uses a waterproof head-mounted display and camera-based gesture recognition, originally trained for above-water conditions, employing three gestures: grab for navigation, pinch for single interactions, and point for continuous interactions. In an experimental study, we tested gesture recognition both above and underwater, and evaluated participant interaction within an immersive underwater scene. Results showed that underwater conditions slightly affected gesture accuracy, but the system maintained high performance. Participants reported a strong sense of presence and found the gestures intuitive while highlighting the need for further refinement to address usability challenges.

CCS CONCEPTS

• **Human-centered computing** → **Gestural input**; **Mobile devices**; *Virtual reality*; *User centered design*; *Interface design prototyping*; Interaction design theory, concepts and paradigms.

KEYWORDS

Virtual Reality, Underwater, Submerged, Gesture-Based Interaction

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1 INTRODUCTION

Using virtual reality (VR) in underwater environments offers unique opportunities by enabling the exploration of otherwise inaccessible areas. However, implementing underwater VR (UVR) presents challenges due to water dynamics that affect user interaction. Previous approaches have focused on adapting traditional interaction devices to function underwater [1, 2]. However, gesture-based controls offer more natural and intuitive interactions, which can enhance user experience and immersion in UVR environments.

2 SYSTEM DESIGN

Building on previous work with underwater head-mounted displays (HMD) [3], we enhanced the design using a full-face mask with an integrated snorkel for better comfort and a custom 3D-printed housing (Figure 2). The housing, filled with water for neutral buoyancy, contained a Xiaomi 11T Pro smartphone. We used the Manomotion Hand Tracking SDK[1] in Unity, originally trained for above-water conditions, utilizing the smartphone's main camera stream. This setup facilitated real-time recognition of three gestures: **grab** for navigation, allowing users to move in head gaze direction; **pinch** for single interactions; and **point** for continuous interactions. A hand skeleton visualization indicated the user's hand movements.

[1] https://www.manomotion.com

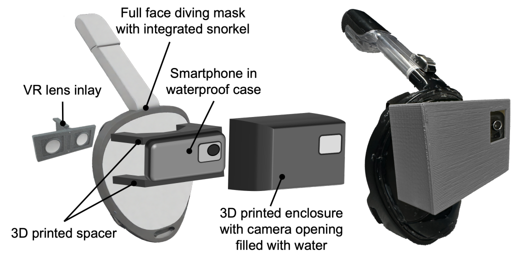

Figure 2: System design of the underwater HMD (left) and assembled prototype (right).

3 EXPLORATORY STUDY

The study examined the impact of underwater conditions on gesture recognition (Part 1) and user experience of gesture-based interaction in UVR (Part 2). Ten participants (two females, eight males, aged 22 to 43) completed the study in a controlled pool (4m x 2m x 1.5m), wearing floating belts and secured by elastic ropes to stay partially submerged. One participant's data was excluded from Part 1 due to technical issues. Subjective experience in Part 2 was assessed using the Igroup Presence Questionnaire (IPQ) [5] for presence (four subscales on a 7-point Likert scale) and the short User Experience Questionnaire (UEQ-S) [4] for pragmatic and hedonic quality (from -3 to +3). Open-ended questions provided additional insights.

Study Part 1. This part validated hand gesture recognition accuracy above and underwater. Participants performed grab gestures with both hands, and pinch and point gestures with one hand, each five times in random order. Above water, participants were seated wearing the HMD; underwater, they assumed a swimming position. Results between conditions were compared to assess underwater gesture accuracy using above-water performance as a control.

Study Part 2. Participants experienced an immersive UVR scene while submerged using the underwater HMD. Using the grab gesture, participants navigated the path and encountered interactive objects highlighted by colored sparkles: yellow for one-time interactions (e.g., opening a crate with a pinch gesture) and purple for continuous interactions (e.g., making a squid follow the user's gaze with a pointing gesture). These interactions are shown in Figure 1.

4 RESULTS AND CONCLUSION

Results of Study Part 1. The study investigated a 3-class gesture recognition system for grab, pinch, and point gestures in a UVR environment. A total of 198 interactions were performed above water and 202 underwater. The results suggest that underwater conditions affect gesture recognition accuracy (Table 1). The pinch gesture performance remained consistent underwater with a marginal improvement, while point and grab gestures showed minor reductions in performance. Overall, the system maintained high accuracy, indicating robustness despite underwater challenges.

Table 1: Gesture recognition accuracy above and underwater.

Gesture	Condition	TP	FP	FN	Precision	Recall	F1 Score
Pinch	Above Water	42	3	7	0.93	0.86	0.89
	Underwater	43	2	6	0.96	0.88	0.91
Point	Above Water	43	2	2	0.96	0.96	0.96
	Underwater	42	3	4	0.93	0.91	0.92
Grab	Above Water	84	6	9	0.93	0.90	0.92
	Underwater	81	9	12	0.90	0.87	0.89

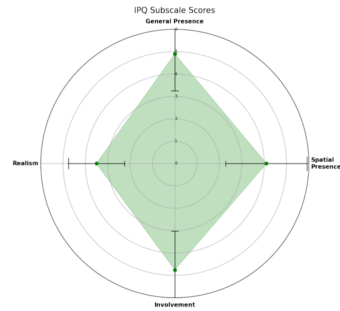

Figure 3: IPQ presence ratings.

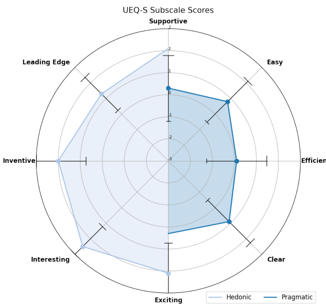

Figure 4: UEQ-S user experience ratings.

Results of Study Part 2. The IPQ results indicated a relatively high sense of presence, with high ratings for *General Presence* and *Involvement*, moderate ratings for *Spatial Presence*, and somewhat lower ratings for *Realness* (Figure 3). UEQ-S ratings reflected high stimulation and novelty, with *Interesting* and *Exciting* as the highest rated items. *Leading Edge*, *Easy*, *Clear*, and *Inventive* received positive ratings, while *Supportive* and *Efficient* were rated neutrally, indicating lower satisfaction with pragmatic qualities (Figure 4). Open-ended survey responses highlighted the engaging and novel gestures but also noted issues, such as controlling direction and speed, problems with camera view when hands were out of sight, and physical discomfort. Participants suggested improvements like more intuitive gestures, incorporating swimming-like motions, and gestures that allow speed adjustments.

Conclusion. We explored gesture-based interaction in UVR environments using methods trained for above-water conditions. Our results show that the gesture recognition system maintained robust performance underwater, with only minor reductions in accuracy for some gestures. Participants reported a strong sense of presence and found the experience interesting and exciting, although they noted some difficulties in controlling gestures and experienced physical discomfort during interactions. These findings suggest that future work should focus on improving control precision, enhancing physical comfort, and refining gestures based on user feedback.

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