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Development of a Waterproof Virtual Reality Head-Mounted Display: An Iterative Design Approach

Hiromu Otsubo[1), Johannes Schirm[1), Daniel Bachmann[2), Alexander Marquardt[2), Felix Dollack[1), Monica Perusquía-Hernández[1), Hideaki Uchiyama[1), Ernst Kruijff[2), and Kiyoshi Kiyokawa[1)

1) 奈良先端科学技術大学院大学 （〒 630-0192 奈良県生駒市高山町 8916 番地-5,
{otsubo.hiromu.oj1, schirm.johannes.sh6, felix.d, m.perusquia, hideaki.uchiyama, kiyo}@is.naist.jp）

2) University of Applied Sciences Bonn-Rhein-Sieg (Grantham-Allee 20, 53757 Sankt Augustin, Germany,
{daniel.bachmann, alexander.marquardt, ernst.kruijff}@h-brs.de）

概要:
In an iterative design process, we developed a waterproof virtual reality (VR) head-mounted display (HMD) for underwater use. In an underwater environment, we can modulate proprioception to enhance immersion and engagement in VR. We target eliciting complex emotions, such as awe, during VR experiences. We detail the iterative development phases of a low-cost, underwater VR HMD prototype, showing how each development cycle introduces, tests, and refines different aspects of the system. The final prototype increased comfort and image quality. Future work should seek to add a mechanism to adjust Interpupillary Distance.

キーワード： Virtual reality, Head-mounted display, Awe, Underwater, Overview effect

1. Introduction

Virtual Reality (VR) offers immersive experiences that can evoke strong emotions [1]. Multisensory cues such as visual, auditory, and haptic feedback are commonly used to enhance user experience. However, the role of proprioceptive cues, related to the perception of body position and movement are less explored [2]. We propose manipulating proprioceptive cues to match the specific VR scenarios by immersing users in a pool while experiencing VR. We present an underwater VR head-mounted display (HMD) prototype developed through an iterative design process. We aim to create immersive underwater experiences that can evoke feelings of awe. The unique sensory stimuli of the underwater environmentcan potentially enhance the emotional impact of VR and support the elicitation of emotional responses [3].

2. Related Work

2.1 Emotional Evocation and Awe in VR

Emotion is an essential factor in VR experiences. Awe stands out as an emotion that evokes wonder and amazement, often triggered by encounters with the grand or sublime [4]. Typically, awe has two main components: perceived vastness and the need for adaptation [5, 6]. In the context of VR, the "overview effect" – a cognitive change experienced by astronauts when viewing the Earth from space – is a compelling example for feelings of awe, connectedness, and a sense of vastness [7]. Previous VR research has successfully simulated the overview effect to induce awe, resulting in shifts in perception [8, 1]. However, most previous work focused on delivering audiovisual stimuli without other modalities.

2.2 Underwater VR Head-Mounted Displays

HMDs that enable underwater VR experiences are helpful for underwater training and entertainment. Zhang et al. developed a low-cost, safe, underwater HMD [9]. Osone et al. developed an underwater HMD that could be filled with water to reduce buoyancy. They adjusted the distance and angle between the lens and display to ensure a wide viewing angle even when water penetrates the HMD's internal structure [10]. Building on this, Hatsushika et al. designed a wired underwater VR system for scuba training to simulate various underwater conditions and scenarios [11]. Nagata et al. proposed a virtual scuba diving system that leverages the sense of weightlessness underwater. Their system allows users to swim freely in a virtual undersea world, using a head tracking sensor and controller [12]. Finally, Sinnott et al. created an HMD incorporating a smartphone and lenses into a full-face scuba mask. This design considered the fit and

図 1: Comparison of underwater VR HMD prototypes: (a) Prototype 1, (b) Prototype 2, and (c) Prototype 3, showcasing water-permeable and waterproof design ideas. *Note: Prototype 3, initially designed as waterproof, experienced minor leakage with a small amount of water entering the HMD, but without impacting the visual quality of the VR experience.*

buoyancy of the mask and face, enabling users to experience VR in a state of neutral buoyancy underwater [13]. Although their study observed increased symptoms related to nausea, it was unclear whether this was due to the use of VR or the unique sensory environment underwater.

3. System Design

We developed and tested an underwater VR HMD prototype iteratively. The tests were done in a pool with a simulated space scene.

3.1 Simulating the Overview Effect

The VR environment was created using Unity 2021.3.6f1. A 360° video of a space flight was used for the visual representation, giving users an unobstructed view of the earth and solar system. Users can freely explore the scene by turning their heads underwater. For auditory stimuli, we incorporated sound waves of the sun, obtained from NASA[1] to create a natural soundscape that supports the visual experience of the space scene.

3.2 Prototype 1

Our first prototype was based on the work of Osone et al. [10]. Their approach assumes that the space between the display and the lenses is filled with water. Regular swimming goggles with attached lenses facilitated underwater viewing. The image distortion caused by the water layers was corrected using plano-convex lenses with a diameter of 25 mm and a focal length of 25 mm. Our prototype utilized a plastic VR headset frame for smartphones, a waterproof case to hold a Xiaomi 11T Pro smartphone, and a custom 3D-printed holder for secure attachment, see Figure 1a. The VR experiencewas delivered via a Unity application on the smartphone and bone-conducting headphones. A snorkel was used to let the user breathe.

User Evaluation Three participants (one female, aged 33 to 37 years old) tested our HMD prototype and a commercial underwater HMD[2] in a public swimming pool[3]. Our HMD prototype presented the custom overview effect scene, while the commercial HMD offered three experiences, “Space Odyssey”, “Deep Sea Dive”, and “Atlantis Exploration”, designed by the commercial HMD vendor. The order of headset use was counterbalanced among participants. Users were equipped with a floating belt to keep their position fixed in the water while still allowing free movement. Additionally, a nose clip was used during the testing of prototype 1. Each experience lasted between three and five minutes.

Feedback and Discussion. Feedback indicated that the commercial HMD had a clear image and no need to wear headphones (P1, P2), but its weight was noticeable, and using the snorkel was tiring for those unaccustomed to it (P2). One participant anticipated motion sickness, but the floating sensation in the water helped to mitigate the effect and improved the match between physical sensations and the VR experience (P3).

For Prototype 1, all the participants found the visuals clear but with a slight blurriness in the periphery. They also expressed discomfort with the goggles and the nec-

[1] https://www.nasa.gov/feature/goddard/2018/sounds-of-the-sun

[2] https://www.ballastvr.com/divr

[3] https://www.stadtwerke-osnabrueck.de/nettebad

essary nose clip. This combination was less preferred than the commercial HMD, whose goggles included a nose cover. Overall, the quality of stimuli and usability aspects of the first prototype did not match the standards set by the commercial system, indicating potential areas for improvement. Furthermore, the Interpupillary Distance (IPD) was fixed at about 6.5 cm because the lenses were glued to the swimming goggles. The reported blurriness may be attributed to differences in participants' individual IPD. Based on the discomfort reported with the goggles, we decided to explore a different type of goggles for the next prototype.

3.3 Prototype 2

Prototype 2 improved usability by utilizing diving goggles with an integrated nose cover (Figure 1b). The same lenses as in Prototype 1 were used to address image distortion caused by water. The headset remained unchanged.

User Evaluation Four participants (one female, aged 23 to 53 years old), including one who had tested the first prototype, tested the improved HMD in a research pool. Participants wore a floating belt to maintain their position on the water surface while experiencing the same simulated overview effect scene as in Prototype 1.

Feedback and Discussion. Participants were more optimistic about the visual quality. Although not quite achieving the clarity of the commercial underwater VR device, Prototype 2 performed adequately for underwater use (P1, P2). Users with corrected vision reported seeing fine details in the simulated space scene even though they had to remove their glasses to put on the headset (P3). While some participants experienced sufficient stereo perception despite incorrect IPD settings (P3, P4), this was not the case for others (P1). The headset's form factor was rated more comfortable than the first prototype (P1, P4), which was improved by the nose cover (P2). Finally, concerns were expressed about the need for interactive navigation (P3), and the fear of colliding with the pool walls or panicking because of losing contact with the ground (P2, P4). Similar to its predecessor, Prototype 2 used plano-convex lenses with a short focal length and a fixed IPD, causing geometric distortions and affecting the stereo effect (Figure 3 - left). Chromatic aberrations from the lenses slightly blurred the view. These issues were noted for future improvements.

3.4 Prototype 3

This iteration addressed visual artifacts caused by the plano-convex lenses when water filled the space between the lenses and the display. To mitigate these issues, the headset frame was made waterproof to prevent water from entering this space, which allowed the omission of particular lenses, as shown in Figure 1c. As a result, standard biconvex VR lenses (42 mm diameter) were used in this version. Instead of using average IPDs, an optimal IPD was determined based on a collective assessment from a group of experts ($n = 4$), using the HMD's built-in IPD adjustment. The waterproof isolation of the headset was achieved by attaching a 2 mm thick acrylic glass to the headset frame and taping the connection to the diving goggles. While the remaining air inside the device could affect buoyancy, full underwater dive was not required.

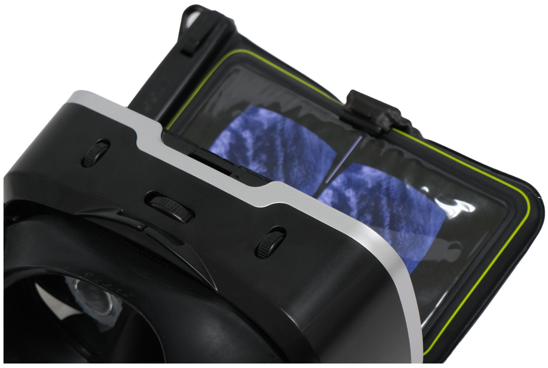

図 2: Immersive view of earth from space in Prototype 2, showcasing the overview effect on the integrated smartphone.

User evaluation Two participants (one female, aged 23 to 37 years old), including one who had tested the second but not the first prototype, tested Prototype 3 in a research pool.Participants were equipped with a floating belt with two elastic ropes at the back, preventing them from drifting toward the sides of the pool. They experienced various custom-made awe-inspiring virtual scenarios (high mountain, waterfall, polar lights) as well as the space scene with an overview effect. Scene switching was enabled by touching the smartphone in the HMD frame with an NFC tag.

Feedback and Discussion. Despite waterproofing efforts, participants reported minor water leaks in the headset frame. However, image quality remained unaffected, ensuring a mostly clear visual experience. The device also felt lighter due to higher buoyancy (P2). Users noticed a mismatch between body posture and the virtual scene orientation, particularly noticeable in camera motion scenarios. While one participant found the floating belt uncomfortable to wear (P1), the other participant did not pay attention the traction force of the elastic ropes (P2). Among the virtual scenes, the mountain scene received positive feedback due to its animated locomotion path (P1), and the space scene harmonized well with the sensation of floating in the water.

The third prototype introduced improvements to mitigate visual artifacts caused by lens-related issues and variations in IPD, as shown in Figure 3 (right). However, efforts should be made to improve isolation and prevent water leaks in the third prototype. Nevertheless, alternative approaches that allow water to enter the headset may be worth investigating in the case of deep dives when buoyancy might be problematic. In this case, adjusting the IPD of the lenses used would be critical to maintaining visual acuity.

図 3: Comparing underwater image quality between Prototype 2 (left) and Prototype 3 (right) using a checkerboard pattern to evaluate sharpness, chromatic aberration, and optical distortion effects. *Note: The headset in Prototype 3 was filled with air.*

4. Limitations

Our study shows some limitations that should be considered. First, we used a small sample size of participants, which may limit the generalizability of our findings. Second, we could not address the issue of water entering the HMD frame, which may affect the visual quality and comfort of the images, such as blurriness. Third, we did not control for environmental factors that may influence the user's perception and mood, such as the position and temperature of the water in the pool.

5. Conclusions and Future Work

We described the design and development of a prototype underwater VR HMD that aims to induce complex emotions, such as awe, when using an experimental pool facility. We conducted three iterations of prototyping and testing. We improved the device's usability and functionality based on the participants' qualitative feedback. Our results show that our prototype provided a novel and appealing experience for most users but also revealed some challenges and issues regarding the device's visual quality and comfort.

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