Optimized HMD System for Underwater VR Experience

Hiroyuki Osone[1], Takatoshi Yoshida[2], and Yoichi Ochiai[1]

[1] University of Tsukuba
[2] The University of Tokyo

Abstract. We designed a head mounted display (HMD) that is suited for underwater use. To reduce the buoyancy, we developed an internal optical design in which the viewing angle of the HMD remains wide even when the device is filled with water. Two types of HMD were prepared and tried in subject experiments. The first is an off-the-shelf HMD that was water-tightened with adhesive and vinyl tape. The second is a rectangular parallelepiped type HMD with a structure that can be filled with water. Subjects evaluated these HMDs in terms of clearness, wideness of view, ease of swimming, and feeling of immersion while watching 360° video in underwater. Until now, there had been no discussions regarding the optics of HMDs used in water. This research has established a method for the optical design of an HMD that can be used underwater and was first evaluated by subjects.

Keywords: Head-mounted display (HMD); virtual reality; wearable devices.

1 Introduction

Many people exercise in water. However, when swimming in a pool, they may get bored. Therefore, studies on virtual reality (VR) and augmented reality (AR) in water have been made. Yamashita et al. [10] made the AquqCAVE, which allows you to experience VR in an aquarium. Its associated payload is low but the cost of setting up the environment is high. Users cannot swim, over a wide area, and so this system cannot be used by many people simultaneously. Zhang, Tan, and Chen have created a head-mounted display (HMD) [1] that can be used underwater. However, air enters the device's structure, which greatly increases buoyancy and makes swimming uncomfortable. In another study carrid out by Quarles [7], water was present in the internal structure of the HMD. However, he does not address its properties from an optical point of view, and thus, the viewing angle is unknown. Therefore, we designed an optimal HMD for swimming. Because there is no air layer in the proposed HMD, we expected that buoyancy would not be an issue and that the HMD could be easily worn while swimming. Though swimming in a pool has low entertainment value, by wearing this HMD, one can enjoy VR while swimming comfortably. Our study is the first to evaluate underwater VR by subject experiments.

1.1 Contributions

- We designed the HMD with a sufficiently wide viewing angle even if water fills its internal structure. This ingenuity makes it comfortable to swim while wearing the HMD because buoyancy is greatly reduced.
- There was no discussion regarding optics in studies regarding conventional underwater HMDs. Our HMD, which can be used underwater, was designed optically properly and was evaluated by subjects for the first time by in this research.
- Subject experiments were conducted to evaluate VR experienced in water. The first evaluation of underwater VR was carried out in this study.

Fig. 1. We have designed, taking optics into account, an HMD that ensures a sufficient field of view even when its internal structure is filled with water. This reduces the buoyancy, so that the user can swim comfortably while enjoying VR

2 Related Works

2.1 Head-Mounted Displays

In this study, we propose an HMD best suited for use while swimming underwater. However, our main objective is to promote the use of head-mounted immersive VR. A historical investigation of HMDs has been presented by Rolland and Hua[13]. Recently, inventions regarding low-cost HMDs such as Google Glass and Oculus Rift [1] have gained attention. The former, proposed by Mann et al. [5], was developed commercially. The use of low-cost HMDs that uses a smartphone as a display, proposed by Olson et al.[6], is spreading. Among them, HMDs that

[1] https://www3.oculus.com/en-us/rift/

anyone can easily use to experience VR with cardboard and a smartphone, such as like Google Cardboard, are widely used.

We are not the first to propose a HMD that is usable in water. Zhang et al.[1], designed an waterproofed HMD, and Quarles et al. [7] developed an HMD that was designed with a structure that allowed it to be filled with water. However, buoyancy was a significant issue in the former study, which made it difficult to swim comfortably in water. The optics involved in the latter study were not discussed. Thus, we created an HMD that maintains the field view suitable for swimming underwater by using an optical design that allows water to fill in its internal structure, thereby reducing buoyancy.

2.2 Underwater VR/AR

Frohlich et al. [4] and Takala et al. [8] used a simulation system similat to a cave on which underwater environments are drawn. They surrounded the users in the room and projected 3D images of the ocean world onto the walls to create an enclosing simulation. Such environments are more comprehensive than PC games to completely enclose users in a virtual world. Thus, they can be used to target more human senses and make the simulation more extensive. However, the cost of setting up such an environment is high. Several systems immerse users in a pool or aquarium to simulate the experience of being in the ocean. For example, Blum et al. [9] visually enhanced a normal swimming pool with virtual marine objects displayed on mobile PC devices mounted in front of a submarine mask using augmented reality and a waterproof HMD. Bellarbi et al.[2] put tablets and sensors in a waterproof casing to display fish and submarines with AR markers that enabled underwater interactions. However, because the case has to be held in the hand, the user cannot swim. Likewise, Yamashita et al. [10] developed a computer-expanded aquarium with a rear projection on an acrylic wall surrounding swimmers and providing a stereoscopic environment with an immersive feel, like a cave. These systems are realistic because users are actually immersed in water, which is difficult to simulate on land. On the other hand, it is also costly to install these environments, and thus, it is difficult to spread the use of these systems to many people.

2.3 Position of This Study

By capitalizing on the portability of VR goggles as mentioned in the section titled "Head-Mounted Displays", we designed HMD that are comfortable for swimming in pools, an activity that could otherwise be boring. In order to prevent a significant increase in buoyancy, its internal optical design was developed so that the interior can be filled with water. Because the payload is low and environment settings are unnecessary, it is possible to play on the way home from work or to play with lots multiple people.

	Environmental cost	
	Low	High
User-friendly	This study Zahang[1] Quarles[7]	Yamashita[10] Torsten[4]
Not user-friendly	Abdelkader[2]	

Fig. 2. A chart of related works on (underwater VR/AR).

3 Designing the Underwater Head Mounted Display

In this section, we explain the configuration of our HMD, which uses smartphones, plano-convex lenses and underwater goggles designed in this research.

3.1 Optical design

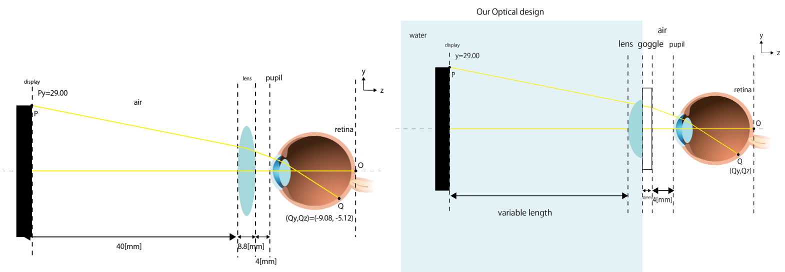

Fig. 3. Optical system of Google Cardboard (left) and Optical system of our HMD (right). The variable length is used to optimize focusing of the image.

First, as a prototype, we attached the lens of a Google Cardboard to underwater goggles and watched a video of Google Cardboard VR video underwater. However, the image fell to the center of the field of view and appeared triple. Then, we developed an optical design, using Zemax OpticStudio[3], that meant that the screen could be seen underwater with almost the same viewing field as that provided by Google Cardboard out of the water.

[3] http://www.zemax.com/opticstudio

Table 1. Parameters of the eye model

Part	Curvature radius [mm]	Thickness [mm]	Refractive index	Clear Semi-Diameter [mm]
Cournea	7.8	0.5	1.38	6.0
Aqueous	6.7	1.5	1.34	6.0
Aqueous	11.0	1.6	1.34	11.0
Iris	-	0.1	1.34	1.4
Lens	10.0	3.7	1.42	5.0
Vitreous	-6.0	16.6	1.34	5.0
Retina	-11.0	-	-	11.0

Optimization by numerical simulation The optical design system of the proposed system is the same as the one proposed by Osone et al. [11] Since the focus and the image are symmetrical, we only needed to consider the optical design for one eye. First, the optical system of Google Cardboard when used in the air was reproduced in OpticStudio, as shown in Fig. 3 (left). We used an iPhone 7 as display. Its height was 58.00 mm when laid sideways, so we set the ray from the top to 29.0 mm and the ray from the center to 0 mm. The wavelength of the ray was set to 0.59 μm, which is a general wavelength that defines the focal length of the lens. The eye model downloaded and used on the official site of Zemax was downloaded and used[4].
The center of the retina of the eyeball model was set as the origin of the coordinate system. When reproducing the optical system using Google Cardboard in the air, a ray coming from a height of y = 29.0 mm reached the retina at the coordinates shown in Fig. 3. This figure also shows the effects of the optical system for a ray coming from a height of y = 0 mm. Our HMD, shown in Fig. 3 (right), was designed so that the coordinates of the image formed by the retina are almost the same as those obtained when a Google Cardboard is used in the air. We tried each of the plano-convex lenses sold by Edmund Optics one by one, and repeated the optimization calculations for the image on the retina with the distance between the display and the lens as a variable. For each lens, the coordinates for a ray with y = 29 mm reaching the retina were examined, as shown in Table 1. We chose to use a lens with a diameter of 25 mm and a focal length of 25 mm, with which the coordinates obtained were the closest to the coordinates obtained when using a Google Cardboard.

We only needed to consider the optical design for one eye. First, as shown in the Fig. 3 (left), the optical system of Google Cardboard when used in the air was reproduced. The display had a height of 58.00 mm when laid sideways, so our calculations used a ray coming from a height of 29.0 mm and a ray coming from the center at a height of 0 mm. The wavelength of the light beam was set

[4] http://customers.zemax.com/os/resources/learn/knowledgebase/zemax-models-of-the-human-eye

to 0.59 μm. The eye model used on the official site of Zemax was downloaded and used. The optical system was set as shown in Fig. 3 (right). It was designed so that the coordinates of the image formed on the retina are almost the same as those obtained when a Google Cardboard is used in the air. We tried each of the plano-convex lenses sold by Edmund Optics one by one, and repeated the optimization calculations for the image on the retina with the distance between the display and the lens as a variable. For each lens, the coordinates on the retina obtained for a ray coming from a height of y = 29 mm reaching the retina were examined as shown in the Table 1. We chose to use a lens with a diameter of 25 mm and a focal length of 25 mm, with which the coordinates obtained were closest to the coordinates obtained when using a Google Cardboard.

Table 2. Lens data.

Diameter[mm]	Focal length[mm]	Variable length[mm]	Qy[mm]	Qz[mm]
Google cardboard	-	-	-9.08	-5.11
20	20	45.8	-10.13	-8.00
22.5	22.5	51.7	-9.77	-6.42
25	25	65.8	-8.38	-4.13
30	30	69.9	-8.02	-3.73

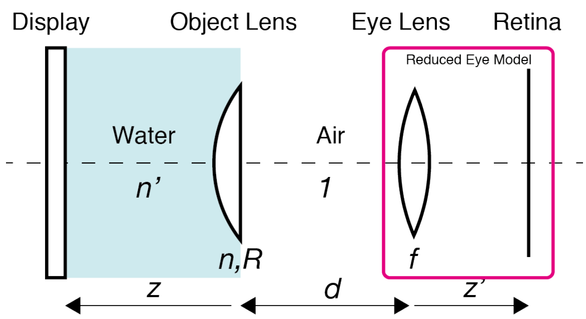

Fig. 4. Optical system of our HMD.

Gaussian optics In this section, we described the optimal optical design for our HMD, which is to be used in an underwater environment. The ray tracing diagram of the proposed system in an underwater environment is shown in Fig. 3 (right). Because there is water between the display and the lens, there is a difference in the distance between the object lens and the eye lens from what it

Table 3. Parameters in Figure 4 and their meaning

Parameter	Letter	Number
display-lens	z	68.9
Image distance of the reduced eye model	z'	17.0
Focal length of the reduced eye model	f	16.7
Distance between eye and lens	d	11.5
Curvature radius of lens	R	16.8
Refractive index of lens material	n	1.673
Refractive index of water	n'	1.33

would be without the water. When the focal length of the lens and the distance between the lens and the pupil are given, the goal is to find the distance between display and lens connecting the image without causing blurring on the retina. First, we rewrote the system presented in Fig. 3 into an equivalent optical system using a reduced eye model, as shown in Fig. 4. Let z be the distance between the display and the lens. See Table 3 for the meanings of the other parameters shown in Fig. 4. By doing ray tracing based on Gaussian optics, the following equation is obtained for ray matrix M to derive the convex lens of the reduced eye model from the plano-convex lens.

$$
\begin{aligned}
M &= \begin{pmatrix} A & B \\ C & D \end{pmatrix} && (1)\\
&= \begin{pmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{pmatrix} \begin{pmatrix} 1 & d \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & n \end{pmatrix} \begin{pmatrix} 1 & 0 \\ \frac{n-n'}{nR} & \frac{n'}{n} \end{pmatrix} && (2)\\
&= \begin{pmatrix} 1.235 & 15.30 \\ -0.0535 & 0.420 \end{pmatrix} && (3)
\end{aligned}
$$

The image conditions at this time satisfy the following expression.

$$z = \frac{B + Dz'}{A + Cz'}$$

Thus, the optimum distance between the display and the lens was calculated to be $z = 68.9\,\mathrm{mm}$. This value is close to the value of the variable length calculated in the previous chapter when using our lens.

3.2 Buoyancy and center of gravity evaluation

We designed the 3D model of the enclosure using Rhinoceros. For the sake of simplicity, the head was a ball with a diameter of 20 cm and a weight of 5 kg, and its center was set as the origin of the coordinates. For the other objects, their weight was measured and the volume was calculated from the model. The additional volume of tape and adhesives was ignored. The relationships between the center of gravity, weight, volume, and so on are shown in the Fig. 5. Considering these values, when a person puts on a watertight HMD, their head tends to float in the water, but, when the a person puts on our designed HMD, their head tends to sink in the water.

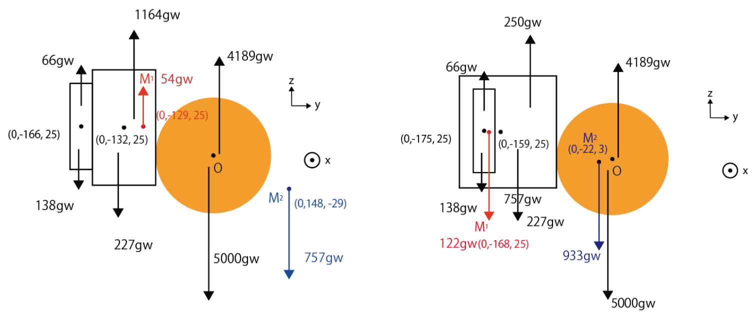

Fig. 5. Watertight HMD (left) and our proposed HMD (right). In each subfigure, M1 is the center of gravity of the corresponding HMD and M2 is the center of gravity of all objects.

3.3 External Design

The HMD was built by laser cutting on acrylic material. Because each person's vision is different, a mechanism was provided that allows focus adjustment by varying the distance between the display and the lens. More specifically, a vertical hole was made in the upper part of the HMD and a screw was passed through. In this way, after adjusting the position of the smartphone, the screw was tightened with a screwdriver so that its position would remain fixed.

4 Evaluation

In this section, the HMD experience was evaluated through subject experiments in terms of wide-view clearness, swimming comfort, and feeling of immersion.

4.1 Method

Participants Six male volunteers (ages 18-22) were recruited through social media. The participants average height and weight were 173.7 cm (SD=3.5, range 169–180) and 63.0 kg (SD = 8.4, range 51–79), respectively. All participants had normal or corrected vision. Each participant was briefly informed of the purpose of the study and told that they could abort the experiment and take a break at any time. Furthermore, they were provided with a consent form to complete and sign. No participant reported feeling any motion sickness.

System setup and performance Two types of HMD were prepared for the experiments. The first was an off-the-shelf HMD water-tightened with adhesive and vinyl tape. The second was the proposed HMD, which has a structure that allowed water to fill its inside.

Subjects swam freely while looking at a 360° video delivered as content for Google Cardboard from YouTube using an iPhone 7. The movie's display was automatically adjusted according to the subject's position by detecting movement using the accelerometer and the gyro sensor of the iPhone 7. When the subjects swam, they wore a snorkel, nose plugs, and earplugs according when disired.

4.2 Imagery assessment

Whether it was clearly visible in a wide field of view was evaluated by the subjects. Their average scores on a seven-point Likert scale (0 = negative, 6 = positive) were calculated. For the watertight HMD, the average was 3.2 out of 6 (SD = 1.0). For the HMD we made, the average was 4.2 out of 6 (SD = 0.7). This result proves that there was sufficiently large field of vision.

4.3 Feeling while swimming

We asked each subject to assess the ease of moving their head underwater on a seven-point Likert scale (0 = negative, 6 = positive), both for the watertight HMD with a higher buoyancy and for the proposed HMD with a lower buoyancy. For the watertight HMD, the average was 2.8 out of 6 (SD = 2.1). For the HMD we made, the average was 3.2 out of 6 (SD = 2.2). This result doesn't prove that users can swim comfortably by wearing an HMD subject to less buoyant force. However, all subjects could swim without push proposed HMD to water, and watertight HMD is needed to push in the water. It shows the HMD is useful.

4.4 Immersion into virtual reality

The factor analysis of an iGroup presence questionnaire (iPQ)[5] describes three factors that collectively affect presence on a seven-point Likert scale (0 = negative, 6 = positive). Spatial presence is related to the sense of operating in virtual space instead of operating something from outside. Involvement describes attention to the real and virtual environments during simulation, and realness is a comparison of the experience of the real world and the virtual world. The overall assessment of the presence is derived from the average of the ratings of these three factors and from the evaluation of another question about general existence. For the watertight HMD, the average overall presence of all reported participants was 2.78 out of 6 (SD = 1.72). Average spatial presence was M = 2.92 out of 6, (SD = 1.83), average involvement was M = 2.70 out of 6 (SD = 1.22), and average realness was M = 2.70 out of 6 (SD = 1.55). For our proposed

[5] http://www.igroup.org/pq/ipq/construction.php (last accessed October 21, 2017)

HMD, the average overall presence of all reported participants was 3.31 out of 6(SD=1.72). Average spatial presence, average involvement and average realness were M = 3.15 out of 6 (SD = 0.96), M = 3.52 out of 6, (SD = 1.70) and for M = 3.40 out of 6 (SD = 0.47), respectively. Through this result, we can infer that even though the participants were engaged and present in a virtual underwater world, they behaved as if they were scuba diving in real life. In other words, our HMD made it possible to experience the virtual world more naturally.

5 Discussion

Since players do not notice the surrounding walls or people, there is a need to implement a system to avoid obstacles. For example, Slawson et al.[12] showed that visible light tracking using an LED is possible even underwater. By expanding this system and using it three-dimensionally, it would be possible to specify the position of the players.

In addition, focus will be lost if a player uses this HMD in the air. By adding a mechanism that changes the position of the display so that the focal length is appropriate both in water and in air, swimmers would be able to see without interruption when taking their heads out of the water.

6 Conclusion

In this research, we have designed an HMD, taking optics into account, which ensures a sufficient field of view even when its internal structure is filled with water. This reduced buoyancy, and the evaluations by subjects proved that the proposed device is actually useful. Therefore, in this paper, we have described a device that allows users to enjoy VR comfortably in the water.

Acknowledgments. We would like to thank all contributors who supported our laboratory via the crowdfunding project.

7 The References Section

References

1. Zhang, W., Tan, Chek, T., Chen, T.: A safe low-cost HMD for underwater VR experiences. In SIGGRAPH ASIA 2016 Mobile Graphics and Interactive Applications. ACM, 12. (2016)
2. Abdelkader, B., Christophe, D., Samir, O., Samir, B., Alain D.: Augmented reality for underwater activities with the use of the dolphyn. In Networking, Sensing and Control (ICNSC), 2013 10th IEEE International Conference on. IEEE, 409412. (2013)
3. Jain, D. and Sra, M., Guo, J., Marques, R., Wu, R., Chiu, J., Schmandt, C.: Immersive Scuba Diving Simulator Using Virtual Reality. Proceedings of the 29th Annual Symposium on User Interface Software and Technology, 729–739. (2016)

4. Torsten, F.: The virtual oceanarium. Commun. ACM 43, 7 (2000), 94101. (2000)
5. Steve, M.: Through the glass, lightly [viewpoint]. IEEE Technology and Society Magazine 31, 3, 1014. (2012)
6. J, Logan, O., David, M, K., Evan, A, S., Mark, B.: A design for a smartphone-based head mounted display. In 2011 IEEE Virtual Reality Conference. IEEE, 233234. (2011)
7. Quarles, J.: Shark punch: A virtual reality game for aquatic rehabilitation. In 2015 IEEE Virtual Reality (VR). IEEE, 375375. (2015)
8. Tapio, T, Lauri, S., Tapio, L.: Swimming in a virtual aquarium. (2005).
9. Lisa, B., Wolfgang, B., Stefan, M.: Augmented reality under water. In SIGGRAPH 09: Posters. ACM, 97. (2009)
10. Shogo, Yamashita., Xinlei, Z., Jun R.: AquaCAVE: Augmented Swimming Environment with Immersive Surround-Screen Virtual Reality. In Proceedings of the 29th Annual Symposium on User Interface Software and Technology. ACM, 183184. (2016)
11. Hiroyuki, O., Takatoshi, Y., Yoichi, O.: Optimized HMD system for underwater VR experience. ACM SIGGRAPH 2017 Posters. ACM, (2017)
12. Slawson, S. Conway, P. Justham, L., West, A.: The development of an inexpensive passive marker system for the analysis of starts and turns in swimming. Procedia Engineering. 2. 2. 2727–2733. (2010)
13. Rolland, J., Hua, H.: Head-mounted display systems. Encyclopedia of optical engineering. 1–13. (2005)