Dissertation

A Virtual Reality Head Mounted Display for Underwater Training and Recreational Purpose

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Master of Science (Research) in Computing Sciences

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CERTIFICATE OF ORIGINAL AUTHORSHIP

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as part of the collaborative doctoral degree and/or fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Name

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Zhang, W., Tan, C.T. & Chen, T. 2016, 'A safe low-cost HMD for underwater VR experiences', *SIGGRAPH ASIA 2016 Mobile Graphics and Interactive Applications*, ACM, p. 12.

Abstract

This thesis introduces an interactive underwater virtual reality headset as an engaging and convenient tool for educational and recreational purpose.

Recreational sea diving and other related underwater activities are common exhilarating experiences for many people. However, it is dangerous, costly and time-consuming for novices to learn. Virtual Reality presents a possible approach to this problem. Most of the consumer level virtual reality headsets can only be employed under dry conditions. Through a detailed literature review of virtual reality (VR) research field, a small gap that has not been filled which refers to the use of VR in wet or underwater scenarios.

In order to fill the identified gap, a head mounted display prototype called *UnderwaterVR* was designed and implemented. The prototype is a safe and low-cost alternative for novices to learn diving in a controlled swimming pool environment, which at the same time serves as a novel entertainment platform to experience interactive underwater games. The proposed prototype is a cable-free, mask-like, waterproof VR goggles. In the virtual world, participants behave autonomously and being able to interact with the environment continuously.

To evaluate the prototype, an autoethnographic study was conducted. The prototype was reported to be engaging and that, interestingly, there was less cybersickness in the prototype than in a normal VR setup out of water. A hypothesis is presented to interpret the reason why there was less cybersickness.

This thesis presented a low cost but efficient way for making a waterproof head mounted display via 3D printing. The failures and redesigns that we had during the development contribute to the further research. Another contribution we have made in this thesis is to explore the underwater interactivity for VR/AR.

Chapter 1 Introduction

Scuba diving is an amazing sport for the modern generation. It allows us to have a glance at sea life in a way that nothing else can. However, scuba diving can also be dangerous. If there is a problem with the air supply or if the driver is trapped, he or she will experience difficulties, which may even be life threatening. Changes of the air pressure may cause injury in scuba diving. The deeper the diver go under water, the more pressure around increase. If the pressure becomes too much, the eardrums or sinuses can be damaged. And if the diver come up from deep underwater too quickly, decompression sickness may occur. Before diving into the water, it is essential that the participant has received a proper certification. Basically, most of the rental agencies will not rent the equipment to a diver without proof of certification. If we can simulate the underwater environment in order to let people feel the similar or same experience of scuba diving but under a relatively safe condition. The ability of virtual reality technology is therefore argued to be suitable for enabling this experience.

Virtual reality (VR) refers to the term that describes a three dimensional, artificial environment which can be explored ineractively by a person (Hannema 2001). Head Mounted Displays (HMD) are usually used in virtual reality applications. It is a device that has a display in front of user's eyes (one eye or both eyes). There is also an optical HMD which can reflect projected images and allows a user to see through it. Numbers of innovative VR applications based on HMD have been developed. Some researchers have used the commercially available Oculus Rift to implement a cycling exergame in order to motivate exercise (Bolton et al. 2014). In another work, HTC Vive was used as part of a system to simulate flying (Rheiner 2014). However, what about real underwater VR experience? How and what kind of experience will be encountered by users? Quite few related research works have been done in this realm. My thesis is to design and develop a waterproof HMD and explore the underwater VR experience.

1.1 Background

Several efforts have also been made to explore computer vision technology under the water. Blum et al. (Blum, Broll & Müller 2009) implemented an underwater augmented reality (AR) game using a complex setup. They claimed that they put an optical see-through display in front of the mask and a snorkel was integrated with the mask. A total of 8 participants wore their prototype and gave positive feedback regarding the handling. The main drawback of the system was the small field of view of the display. Bellarbabi et al. (Bellarbi et al. 2013) implemented Dolphyn, a complex and bulky but more operational setup. Compared with Blum's work, Dolphyn has two joysticks for controlling, a Wi-Fi device for data connection and a thermometer. It requires the whole device to be kept close to the water surface when using the Wi-Fi device. The user has to hold with his/her hands underwater to interact with the game content. Both of these works, other than seemingly requiring costly setups, primarily implemented AR solutions and not VR.

Most of the virtual reality solutions are designed for on land activity. For instance, Bolton et al. presented a gaming system *Paperdude* for exercise at CHI 2014 (Bolton et al. 2014). They used an Oculus Rift VR HMD, a power trainer, a Microsoft Kinect sensor and a bicycle to create the system. The participant acted as a postman in the game by throwing newspapers into neighborhood mailboxes. The Microsoft Kinect sensor helped HMD capture participant's gesture. The aim of their work is to allow user to do exercise via an immersive game.

Birdly (Rheiner 2014) is flight simulation application which allows user to fly like a bird in the virtual environment. The participants are able to control the sensory-motor coupled simulators with their hands and arms on a platform. The simulators can reflect user's gesture which directly correlates to the 3D model in the application. In addition to the simulators, *Birdly* also provided detailed sensory input such as wind feedback for providing a better experience. According to the speed in the virtual environment, the simulator regulates the headwind with a fan to provide an appropriate experience.

These researches have made great contributions to the exploration of the capability of VR/AR techniques. However, by analyzing and reviewing their efforts, there is still a small gap that hasn't been filled. The following table reveals the gap.

	Paper Dude	Birdly	Dolphyn	Blum's work	Gap
VR feature	✓	✓			✓
AR feature			✓	✓	
Underwater feature			✓	✓	✓

Table 1 The gap of the existing research

The current existing research hasn't been raised enough attention to investigate the underwater VR experience. How and what kind of experience will be encountered by people? A special Head-Mounted Display which contains all those three features need to be designed and evaluated.

1.2 Research questions

Motivated by these types of efforts, we looked at how full-body experiences can be enabled for underwater activities like scuba diving. Most of the consumer level head mounted display are not able to be used underwater hence a new type of HMD needed to be developed. The research questions can be concluded as follows:

- How can we design and develop a HMD for underwater VR activities?
- How can we add an interactive feature to the HMD?
    - Positional tracking may enhance user's experience. However, most of the vision-based tracking technique is for on-land activity. Will they still be effective within under water condition?
- What are the novel experiences in the Underwater HMD?
    - Will special dimensions like presence and immersion for measuring virtual reality experience will be needed?

1.3 Stakeholders & Significance

Scuba diving is a specialized activity that normally requires a structured training program to certify individuals who wish to take up the sport. Even with proper training and experience, scuba diving is still known to be a dangerous and costly activity. The cases of a little mistake leading to diving-related injury are not rare. There are also medical requirements which prevent some populations of people from ever trying it out due to innate physical abilities. If there is a device which is able to reduce the risk of recreational diving, more people will have a chance to experience the full enjoyment of this adventurous aquatic sport. Additionally, the existing related underwater VR/AR devices are bulky and costly laboratory equipment. It is not convenient in terms of maintenance and handling for casual activities. My research aims to provide a safe and low-cost solution that is accessible to a large audience.

1.4 Research Methodology

In order to explore the underwater experience, two solutions were explored: enhancing an existing consumer level HMD or implement a new one from scratch. By analyzing the advantages and disadvantages of these two approaches, we decided to create a novel prototype by using 3D printing. We will introduce more details about the hardware implementation in Chapter 3.

A survey was conducted by interviewing three volunteers who have diving experience. Based on their feedback, we filtered four keywords which are mentioned by the volunteers. We created the related 3D models for in-game content that referred to the keywords. By using the Unity 5 game engine, a tropical shallow undersea virtual environment that contains essential visual elements was established.

Due to the ethical complications of underwater testing and potential dangers, the pilot study was designed to be undertaken using autoethnography (Wingrave & LaViola 2010) by the author. This is also motivated by similar extreme sports studies in Human-Computer Interaction that have applied autoethnography due to ethical reasons, e.g., skateboarding technology testing (Pijnappel & Mueller 2013).

In our case, the experience of wearing the developed prototype is the autobiographical personal narrative. One observer was invited to watch while the author was experiencing the prototype. An interview was conducted after the observations. We chose for this approach for three reasons:

- Autoethnography allows researchers to touch the full account of an experience, because no information is lost in communication or interpretation between participant and researcher (Boehner et al. 2007). It is a valuable tool for exploring the underwater virtual reality experience.
- Autoethnography allows for agile design iterations (Mueller et al. 2011), enabling the researchers to test a range of different prototypes and quickly improve prototypes.
- Finally, doing experiment underwater has potential dangerous factors for participants. Autoethnography allowed the researchers to conduct uncommon ideas without compromising participants' safety (except the author himself).

Chapter 2 Literature Review

Many research efforts have been made recently to explore the augmented/virtual reality experience. Augmented/virtual reality attracts increasing attention and gets significant progress in recent years. Not only emerging technologies, the evaluation method of game experience have also been well studied by numerous researchers. A lot of work of this field can be found in high quality journals and conferences. Therefore, we will review the related work in virtual/augmented reality research realm.

2. 1 On-land Virtual/Augmented Reality Applications

Bolton et al. presented a gaming system *Paperdude* for exercise at CHI 2014 (Bolton et al. 2014). They used an Oculus Rift VR HMD, a power trainer, a Microsoft Kinect sensor and a bicycle to create the system. The participant acted as a postman in the game by throwing newspapers into neighborhood mailboxes. The Microsoft Kinect sensor helped HMD capture participant's gesture. The aim of their work is to allow user to do exercise via an immersive game. Unlike other VR games, they combined external devices to enhance the game experience. They reported that the *Paperdude* system can minimize the symptoms of cybersickness. However, they didn't present any evidence or data to support their viewpoint.

Birdly (Rheiner 2014) is flight simulation application which allows user to fly like a bird in the virtual environment. The participants are able to control the sensory-motor coupled simulators with their hands and arms on a platform. The simulators can reflect user's gesture which directly correlates to the 3D model in the application. In addition to the simulators, *Birdly* also provided detailed sensory input such as wind feedback for providing a better experience. According to the speed in the virtual environment, the simulator regulates the headwind with a fan to provide an appropriate experience. The feedback from the participant who experienced Birdly are quite positive. "*The simulation completely immersed me in the experience of flying, or what my mind believed flying like a bird would be like,*" wrote Norman Chang, "*It was almost dream-*

like. Immersion is achieved through the combination of low-latency head tracking, full-motion feedback (the bed actually tilts on several axes)" (CHAN 2017).

Amphibian (Jain et al. 2016) is a virtual reality system designed by MIT. It simulates scuba diving experience via a suspension type simulator. Participants are asked to lie on a round motion platform and outstretch their limbs. Suspended harness will help them support their body. The Oculus Rift HMD and headset will provide visual and aural feedback. Amphibian doesn't require a joystick to let participants control their swimming motion in the virtual world. One of the advantages of Amphibian is allowing users to move their arms and legs as natural form of swimming in the real world.

In order to simulate the scuba diving better, the author also implemented breath motion in their system. An air flow sensor was attached to the participant's mouth piece. The motion platform contains an inflatable cushion which connected to a pump. The cushion inflates and deflates in order to match the user's breath which is similar to how it happens in the water. The air bubbles in the Oculus Rift display also matches the breath sensor. Additionally, they simulated temperature changes using Peltier thermoelectric cooler module as well. The author of Amphibian reported a total of 36 participants tried their system. The feedback is positive.

The disadvantages of Amphibian are also obvious. First of all, the arm movement of participant is restricted due to the size of the arness system (they changed this problem in iteration II). Second, the whole system is bulky and costly. Third, the system might not allow for long time using. The user's limbs will be hung in the air which is easily to cause fatigue. Their evaluation only allowed volunteer to experience 10 minutes. The author mentioned their system can be used for training people how to scuba dive before they really go diving in the sea. That train should be longer than 10 minutes. I suspect if the participants experienced Amphibian longer than 30 minutes, they will feel uncomfortable.

2.2 Underwater Virtual/Augmented Reality Applications

Ukai et al. (Ukai & Rekimoto 2013) developed *Swimoid* which is a robot system for helping novice how to swim. The robot recognizes user's swimming form and presents information to user via mounted display.

Swimoid has three different functions for swimmers: self-awareness, coaching and game. Self-awareness function enables swimmers to recognize their swimming form in real-time by displaying the captured images it on the display. The coaching function captured and transferred the swimmer's form to the monitoring computer which enables swimmer's coach to instruct the swimmer by drawing shapes. The author also integrated a camera with the system to develop a simple game for children. When a child touches the camera mounted on the robot, the system can make some responses.

Although the *Swimoid* can help non-professional swimmers a lot for the training, its disadvantages are more than advantages it can bring. First of all, it is bulky and cost which means it can only be a laboratory thing. Second, the *Swimoid* is not allowed for a long-time due to the user's limitation of breathing capacity. Additionally, the author didn't detail the user study they have done. The author mentioned a wearable -based method is a better approach for the *Swimoid*. I agreed with this point of view and how to develop a wearable VR HMD is my research question as well.

Blum (Blum, Broll & Müller 2009) et al. presented a system allowing users to sense virtual corals and fishes even physically under water by developing a mobile prototype using Augmented Reality techniques to enhance a public swimming pool with virtual objects. An optical see-through display was set up in front of a scuba diving mask, a mobile PC connected to the display via a flexible tube and complicated position tracking sensors were used within the development of the prototype. Based on author's report, 8 participants tried this prototype and feedback are quite positive. Like other underwater devices, bulky and the small field of view are the biggest drawback.

AREEF (Oppermann et al. 2013) presented by Leif is multi-player underwater augmented reality recreative system. The system contains a score board, consumer level tablets and waterproof markers. When playing the game, each player need to hold a tablet which is sealed in a waterproof case. A score board is set up near the swimming pool. A cartoon octopus was developed for participants through the game scenario, providing the guidance. Several visual markers are distributed all over the pool. The synchronization between players is based on Wi-Fi network. Notably, there is no Wi-Fi signal underwater hence the synchronization is only occurred when user bring the tablet out of water.

Compared with Blum's previous work, AREEF is low cost and has the capability of interaction within different users. An underwater multiplayer entertainment system is very innovated which leads a new approach for the system design. The author didn't detail a lot about the experience of the end-user in the user study. They mentioned the aim of their work was to bring traditional entertainment applications from into the water. However, the author didn't compare the difference of user experience. If the technique changes from augmented reality to virtual reality, I assume the user may feel more immersion and presence during the play. This conjecture need to be proved in the future.

AquaCAVE is a system (Yamashita et al. 2016) for enhancing the swimming experience. It is a visual augmented swimming pool with rear-projection acrylic walls around for providing an immersive environment. The participant needs to wear goggles with 3D shutter glasses. Cameras installed above the pool will track swimmer's position. Virtual environments such as coral reefs, outer space, or any other computer generated elements can be viewed during the swimming.

AquaCAVE still needs to address some problems regarding the limited size of the pool and water characteristics. The author reported that they asked a highly-trained swimmer with ten years' experience to swim in the environment. As a result, the limited space could support a realistic swimming experience, because the trained swimmer could stay in the same position. However, for untrained swimmers, staying at the same position was not easy.

2.3 Summary of findings

From the researches listed above, we can see an external enhancement may improve user's experience in VR application. However, very few of the researches detailed the underwater experience for VR. Most of the presented devices for underwater applications are bulky and expensive. The potential of underwater VR applications, namely the design improvement and underwater experience, still need to be explored.

Chapter 3 Approach and Implementation

When people see the word "virtual reality", the first understanding to come into mind may be "A technology helps people to simulate the real world by an artificial tool". This artificial tool includes several types and the most well-known by consumers of them is HMD. Melzer and Moffitt (Melzer & Moffitt 2011) describe an HMD as "*an image source and collimating optics in a head mount.* " Manning and Rash (Manning & Rash 2007) provide a more generalized description of visual HMDs which is applicable to both military and commercial applications. There are four basic components for a HMD:

- A mounting platform.
- An image source.
- Relay optics, that transfer the image information to the eye(s).
- A head tracker, which is optional if the HMD is used only to present status.

All of these engineering and human factor considerations are interrelated. Therefore, tradeoffs are required in order to achieve a design that will be functionally acceptable for a specific operational application. As the tradeoffs are implemented, it is essential that the developer and the user be aware of the performance implications of these tradeoffs. In this chapter, the prototype that we are going to design and build is an interactive HMD for underwater use.

3.1 Hardware development

3.1.1 Background of Head Mounted Display

After Ivan Sutherland built the first HMD with micro monochrome cathode ray tubes (CRT) in 1968, several HMD systems have been created. Kocian et al. developed a system was called Visually Coupled Airborne System Simulator (VCASS) for military aircraft (Kocian 1977).

Welch et al. have developed a fiber optic helmet-mounted display system (FOHMD) for flight simulators (Welch & Shenker 1984). They used a mechanical approach to allow the user to see through to the control panel with four light valves and pancake optic. The field of view (FOV) of this system is 135 degree horizontally by 64 degree vertically. There is also a high resolution inset field in the display.

In 1987, Fisher (Fisher et al. 1987) built a non-see-through HMD based on monochrome liquid crystal display (LCD) portable television displays and the Large Expanse Extra Perspective (LEEP) wide angle stereoscopic system (Howlett 1983). The LEEP optics acted as a simple magnifier. This system didn't have mechanical interpapillary distance (IPD) adjustment because the LEEP optics system has very large exit pupils.

Now, almost five decades later, the technology has improved significantly; It was not only designed for military, but numbers of consumer level HMDs were also implemented and put into market. With the promotion of 3D printing service, people can create a custom virtual reality HMD at home with an entry level 3D printer and a smart phone. What kinds of design are suitable for an underwater HMD?

3.1.2 Common visual parameters for Head Mounted Display

The HMDs are both engineering and human-centered systems. Creating an optimal design fits all the requirements is impossible. The idea of a one-fits-all HMD is a false one, primarily due to the wide variation in user tasks and users themselves; a HMD designed for the pilot of a warfighter will not meet the needs of entertainment.

Although there are some common design approaches – primarily driven by visual limitations and human perceptual (Melzer et al. 2009). Table 2 listed several common optical/visual parameters for HMD design.

Ocularity (monocular, biocular or binocular)
Pupil-forming versus non-pupil-forming architectures
Field-of-view (FOV)

Resolution
See-through versus non-see-through considerations
Integrated versus separated type

Table 2 optical/visual parameters for HMD design

a. Ocularity

The HMD has three classical patterns:

•Monocular – an optical instrument with one source for one eye

•Biocular – an optical instrument with one source for both eyes

•Binocular – an optical instrument with independent source for both eyes

The Google Glass is a classic monocular HMD. It contains a liquid crystal on silicon (LCoS), field-sequential color system and a LED illuminated display as image source. The beam from image source shines directly into the wearer's right eye. The biocular/binocular design is more complex than the monocular approach because it has to independent image source for both eyes.

Biocular display refers to the optical system that provide two-eye vision from one view point. De Vos et al. (De Vos & Brandt 1990) provided a compact design that using holographic optical elements with single beam. A holographic combiner is used to merge the standard combiner function with the collimation function usually performed by an additional refractive optical element.

Different to biocular system, in a binocular display each eye views an independent image source. Most of the consumer level HMD is binocular optical display system.

If the HMD will be used to provide a moving map or text information, a monocular design is best. However, if we are trying to create a consumer level low-cost HMD, the width of field of view will be a problem for a recreational HMD. To achieve the widest field-of-view (FOV) possible, the HMD must be either biocular or binocular.

b. Pupil-forming versus non-pupil-forming architectures

HMDs have been explored for a few years for both military and consumer devices. The applications for military are typically focused on the quality of the optical performance, while consumer devices are more often focused on the design and cost. Because of this difference, there are mainly two different optical architectures of HMDs: the pupil forming and the non-pupil forming architectures.

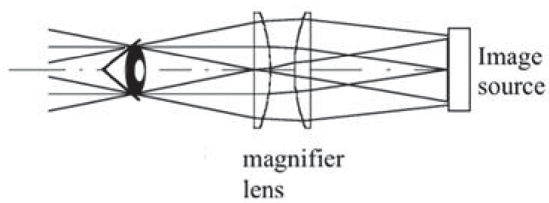


Figure 1 non-pupil-forming architecture

In the non-pupil forming architecture (see Figure 1), there is no intermediate image formed. It suffers from a short distance between the image source and the viewer, putting the whole assembly close to the eyes. This architecture is typically used by consumer electronic HMDs such as Oculus Rift for simple viewing applications.

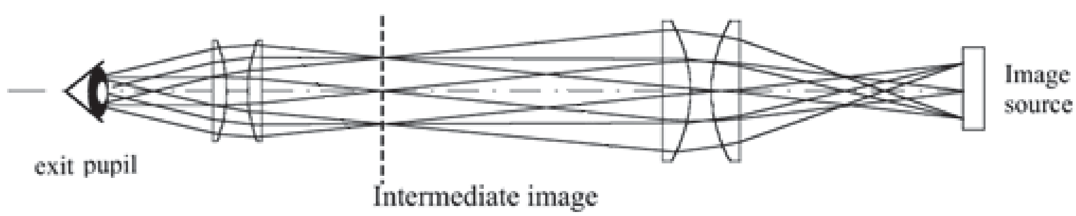


Figure 2 pupil-forming design

The pupil-forming architecture is like the compound microscope, the first set of lenses creates an intermediate image of the source, and then, this intermediate image is relayed by another set of. Therefore, the pupil-forming HMD don't have to be mounted in front of user's face. On the contrary, it is a more complicated and heavier design. Adjustment and calibration need to be done as well when the user is changed.

In this research, the proposed prototype should be a low-cost waterproof HMD for a larger audience. Obviously, a complicated and bulky pupil-forming HMD doesn't meet the requirements. I'll put more focus on non-pupil forming architecture within the prototype development.

c. Field of View

A 3D image is orthostereoscopic when it perfectly replicates human vision (Mendiburu 2012). As user move through the world, images of the surrounded objects fall onto retinas. The entire procedure can be considered as signal input which is able to be simulated. When user walk past a stationary object, watching it from various angles, the shape of the images on user's retinas may change as well.

The current state of the art in VR provides us virtual objects that change their position, rotation, size and shape while head moves. These properties of the objects appear to change while the head moves around. If the field of view (FOV) is very limited, the image will be 2D-like.

FOV refers to how extensive the image exposed to the user, measured in degrees as viewed by one eye (for a monocular HMD) or both eyes (for either biocular or binocular HMDs). The human visual system has a total binocular FOV of 200° horizontal (H) by 130° vertical (V) (George & Atchison 1997).

Since our goal is to create a fully immersive HMD for gaming or training, a large FOV is desirable in order to stimulate the ambient visual mode and provide a more compelling sense of immersion. This is similar to the feeling encountered when watching a large screen IMAX® film, that of "being in" rather than "looking at" it. Patterson et al. (Patterson, Winterbottom & Pierce 2006) showed that limiting the FOV to 50° reduced the perception of self-motion. Their study also showed increased levels of "presence" up to 140° FOV (Patterson, Winterbottom & Pierce 2006). Based upon their findings, Patterson and his colleagues recommend a minimum 60°-FOV to achieve a full sense of immersion for simulator applications. As for the consumer level

HMD hardware, in order to let user feels more immersive, especially in electronic entertainment realm, most of the manufacturer provide a wide FOV for their product.

HTC Vive	110°(H) 110°(V)
Oculus Rift	110°(H) 110°(V)
PlayStation VR	100°(H) 100°(V)
GearVR	96°(H) 96°(V)

Table 3 Field of View for consumer level HMD

d. Resolution

Resolution refers to the number of distinct pixels in that can be displayed of an image source. Resolution contributes to overall image quality, but it also influences the performance. Increased resolution means there are more pixels or available to let the user to observe the virtual objects. Rather than simply rendering a single image, one creates two related images which may then be viewed on a stereo monitor, which needs more hardware resource. A tradeoff between resolution and performance need to be made.

e. Integrated vs separated

The Graphics Processing Unit (GPU) of consumer level smart phone has been able to provide high quality graphic rendering. The higher performance a GPU has, the corresponding size of the chip is bigger and it also consumes more energy. There are two dominant types of head mounted display types after decades of evolution: integrated type and separated type. The integrated type refers to a head mounted display contains essential chips and other hardware for image processing and rendering. HoloLens (Microsoft 2017a) is mixed reality HMD which is developed and manufactured by Microsoft. In addition to an Intel Cherry Trail SoC containing the CPU and GPU, HoloLens also contains a custom-made Microsoft Holographic Processing Unit (HPU) (Microsoft 2017b), a co-processor manufactured specifically for the HoloLens by Microsoft. Thus, the HoloLens can be considered as the combination of laptop and multi-sensors into a HMD.

On the contrary, without a graphic card, an independent head mounted display will not work for the separated type. HTC Vive is a virtual reality headset developed by HTC and Valve Corporation. It uses ding a MEMS (Microelectromechanical systems) gyroscope, accelerometer and laser position sensors. By setting up a 15-by-15-foot tracking area, two "Lighthouse" base stations can track the user's movement with sub-millimeter precision. The Lighthouse system (Valve 2017) uses simple photosensors on any object that needs to be captured. Since HTC Vive doesn't provide any image processing ability integrated into the HMD, it requires to be cabled to a desktop PC with high performance graphics card. Compared with integrated type HMD, it can be difficult to wearing a wired device underwater, even though it may provide higher resolution and rendering performance.

3.1.3 Implementation Approach

The most important features which make this prototype unique are low-cost and waterproof. Therefore, a smart phone is an ideal component for an integrated non-pupil forming head mounted display. Based on the non-pupil forming, a smart phone can be considered as a micro display field.

Although the low-cost 3D printing offers the possibility to rapidly construct a wide range of objects, printing an integrated HMD with different materials is still a difficult task. Re-purposing 3D objects presents an alternative approach. A number of projects have attempted to integrate the construction of physical objects with electronic or interactive components. Savage et al. (Savage et al. 2015) presented Makers' Marks that enables users to generate physical objects using sculpting material and annotation stickers. Enclosed (Weichel, Lau & Gellersen 2013) is a software tool that allows users to simply create lasercuttable enclosures for electronic components. Reprise (Chen et al. 2016) is a design tool for specifying, generating, customizing and fitting adaptations onto existing household objects. The imagination of this prototype HMD is a scuba diving mask-like headset which contains a pair of virtual or augmented reality eyepieces, and the screen of a mobile for display. By integrating a scuba diving mask with 3D printed components can enormously decrease the efforts of the implementation.

The design process starts with 3D model establishment. Two completed different plans were proposed: 1) surface enhanced HMD 2) 3D printing from scratch.

a. Surface enhancement

The purpose of this plan is to enhance the surface of a consumer level HMD that allows user to use it underwater. In consumer HMD, take HTC Vive and Oculus Rift as example, there is always a cushion ring (see Figure 3) between the main frame and wearer's face, namely the eye-region and nose-region of the wearer's face. This cushion ring is made of sponge or sponge-like material which is not water proof. By changing the material and filling the voids of the ring-face-junction, the functionality of water proof will be implemented for the HMD. The advantage of this plan includes performance, content and endurance. An onshore PC will do the rendering and processing task for the HMD which allows it to play its full strength. The disadvantage of this design is the distance and safety. There must be a cable connected between HMD and supporting PC. We also considered using Wi-Fi connection to transfer binocular graphic data instead of wired connection, however, the range and stability are limited in water. Water's resonant frequency is in the 2.4GHz band which means water will absorb 2.4GHz waves extremely well (Lin, Wu & Wassell 2008). Notably, the connection also brings a potential risk that the cable may cause an entanglement. Some of the application may not tell user the real virtual environment's detail, the free movement of a participant may lead his/her neck entangled by the cable.

Figure 3 Cushion ring of consumer level head mounted display

b. 3D printing from scratch

The 3D printed portable HMD plan will not remake any existing HMD. On the contrary, it aims to create a customized integrated waterproof HMD from scratch. Like Google Cardboard, a smart mobile can provide most of the necessary hardware (e.g., display, CPU, GPU and IMU) for a HMD. Based on non-pupil-forming architecture, it is possible to create a HMD skeleton by 3D printing. The advantage of this plan is that it is low cost, low risk and convenient. However, the disadvantage is also obvious, performance and endurance will be its limitation. The rendering performance mainly depends on the GPU. Although the consumer level smart phone has a powerful graphic card, there is a disparity between a mobile graphic card and a standard graphic card.

	Surface enhancement approach	3D printing approach
Performance	High	Low
Power Supply	Unlimited	Limited
Mobility	Low	High
Potential risk	Entanglement	Few

Table 3 Comparison between two approaches

Table 4 detailed the advantages and disadvantages of the two approaches. Although surface enhancement approach has high performance and almost unlimited power supply, potential risk for the participant cannot be ignored. The safety of the people who got involved is essential. Therefore, we choose 3D printing approach to create the underwater HMD prototype.

3.1.4 Implementation Process

Figure 4 shows the design of our first iteration. It is a binocular non-pupil-forming HMD. There are three main parts for the prototype body: case, lens holder and cap.

The case is the cover of the whole prototype for waterproofing. Within the non-pupil-forming architecture, the micro display field is directly collimated to form an image at infinity via lens. The focal length of the lens is 42.0mm hence a support was designed for holding a pair of lens in front of user's eyes. The lens holder (see figure 5) holds a pair of eyepieces which help the user to focus on the mobile display. It is notable that the designed lens support is only suitable for the author himself because of the Interpupillary distance (IPD). Interpupillary distance (IPD) is the distance between the pivot of the pupils of the two eyes. IPD is essential for the design of HMD because both eye pupils can't be offset the exit pupils of the viewing system (Moffitt 1997). An incorrect IPD value can cause blurry vision, double vision images, headaches, nausea, and fatigue (Reisner et al. 1969). However, the evaluation will be conducted under autoethnography, more details will be discussed in Chapter 4. By measuring the author's interpupillary distance, the inter-lens distance is fixed to 62mm.

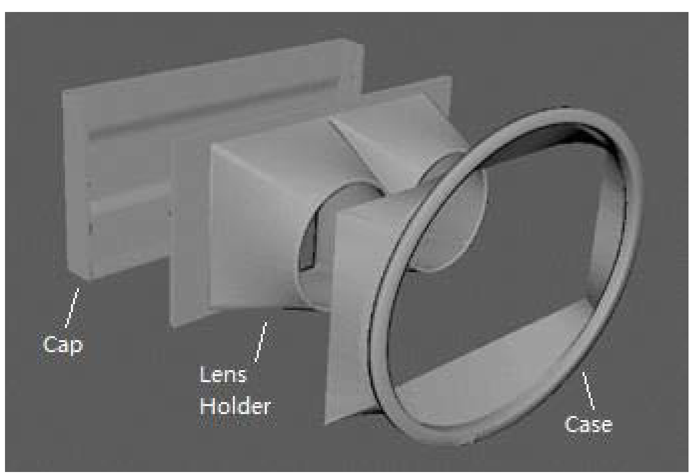


Figure 4 structure of first iteration

The bottom barrier structure divides the mobile display equally to a pair of square interiors. Each square interior raises and transits to a round interior in order to hold the eyepieces.

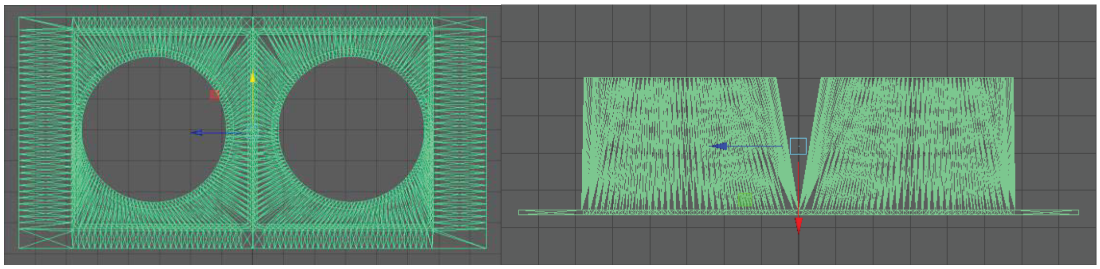


Figure 5 Lens holder

A Nexus 5X smart phone was used as display for the prototype. By creating stereoscopic visual application, each eye views an independent image source for providing a relative larger field of view. Table 4 details the specification of Nexus 5X.

Dimension	147.0 x 72.6 x 7.9 mm
Screen size	5.2inches 11.5*6.5cm

Table 4 Nexus 5X dimensions

A rubbery skirt which fits the user's face, namely the eye-region and nose-region of the wearer's face, is needed for watertight purposes. The skirt and case will be connected to each other by a means of chemical bond. The 3D models are implemented using Maya 2016, Simplify3D slicer 9 and build on two different entry level 3D printers, Ultimaker 2 and Mankati Fullscale XT. The normal PLA filament was used to print the case and lens holder and the skirt was printed by flexible filament. However, when we tried to create the skirt via 3D printing, we found the waterproof performance is not good enough, especially for the skirt. The creation of a 3D printed object is achieved using stacking-processes. In an stacking-process, an object is created by laying down successive layers of plastic till the object is formed. Each of these layers can be considered as a thinly sliced horizontal cross-section of the final object. Although we minimize the slice as thin as possible, due to the resolution limit of the printer, the printed skirt is not able to seal user's face region properly. Additionally, specific support structure needs to be printed because of the 3D printing mechanism. After printing, there were several salient points left on the surface of the skirt. Based on feedback, the HMD is not comfortable when wearing the skirt and the waterproof performance is not good enough due to the 3D printer's printing resolution. Therefore, we change the implementation strategy. We purchased a scuba diving mask and repurpose the skirt of the mask.

Figure 6 shows the skirt used from the purchased scuba diving mask. In order to connect with it, we changed the size of 3D models. We did an initial test after assembling them and found another problem of our design. We used watertight adhesive to connect each part of the prototype. The tensile strength of watertight adhesive is lower than none watertight adhesive. The resistance underwater is much higher than in the air and the attachment surface of each part is quite small which leads to water leaking. Besides, the mobile was sealed in this design which is inconvenient for debug and test. Therefore, we applied the bottle-cap structure to the prototype design.

Figure 6 Skirt of scuba diving mask

The frame can be considered as a bottle. A screw thread is molded onto both the body exterior and cap interior (see figure 7). There are four brackets that are able to fix mobile and lens support molded in close proximity to the inner edge of the bottleneck of body part. Each bracket is coupled to one corner of the lens support.

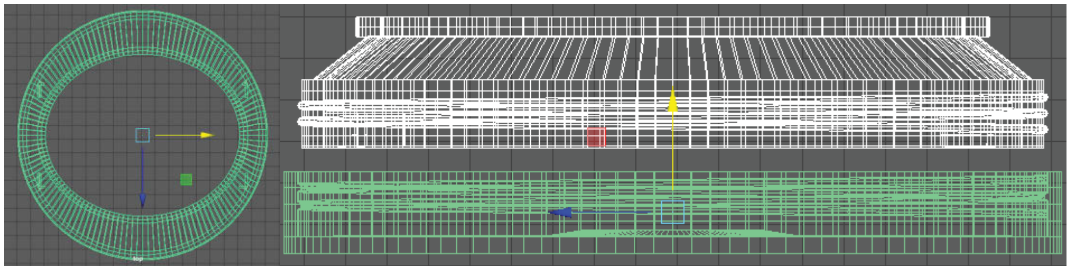


Figure 7 case (bottleneck) and cap

By rotating the cap, we can easily pick out the mobile or put it into the prototype. The center of the cap is replaced by transparent material. This transparent material can be glass or polystyrene. Figure 8 identifies the detailed structure of the frame.

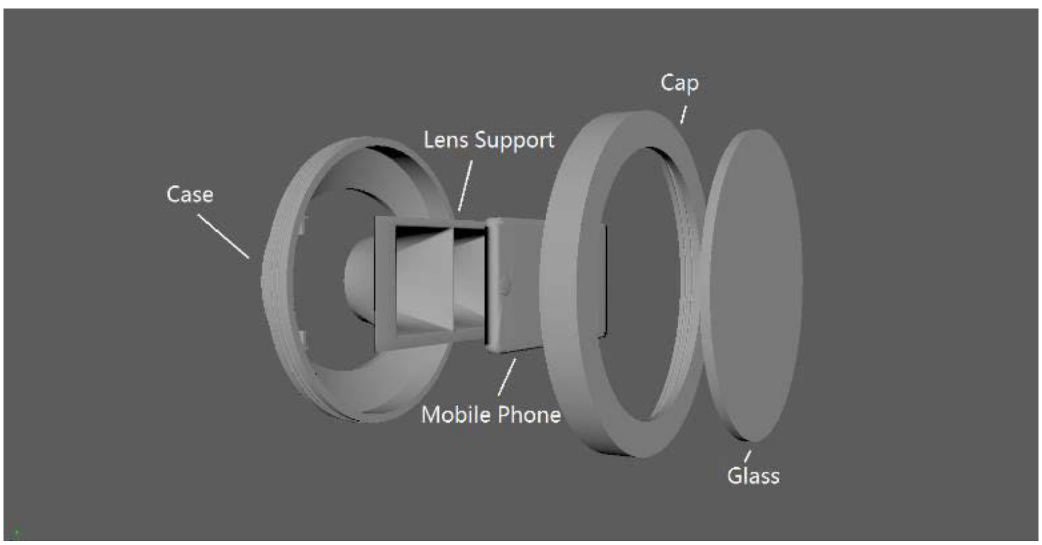


Figure 8 Structure of last iteration

An initial test was conducted for the improvement design, it exposes another problem. It becomes very difficult to screw off the prototype after tightening it. In addition, it seems that it still leaks water within long time using. The contact surface is about 6mm wide circular ring. Due the precision of the 3D printer, there are several tiny artifacts between the contact surface. Therefore, we slightly changed the bottle-cap structure.

The bottom surface of bottle neck was applied a 15 degrees inward-angle (see Figure 9).

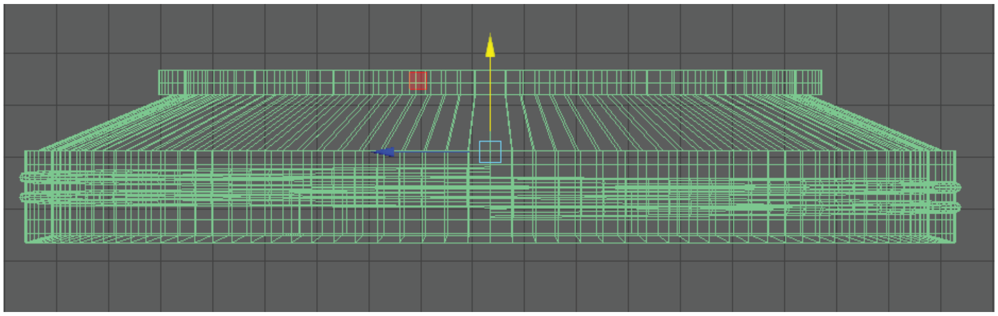


Figure 9 Improved bottle neck structure

Compared with previous cap, a circular groove was formed on the inner surface (see Figure 10). A seal ring is attached to the inner top of the cap that fits the outer edge of the body bottleneck. By spinning the body part and cap based on the screw thread, the bottleneck is able to connect the seal ring tightly. The contact surface between the cap and the seal ring is quite small, the seal ring is relatively soft and can fits the surface of 3D printed object appropriately.

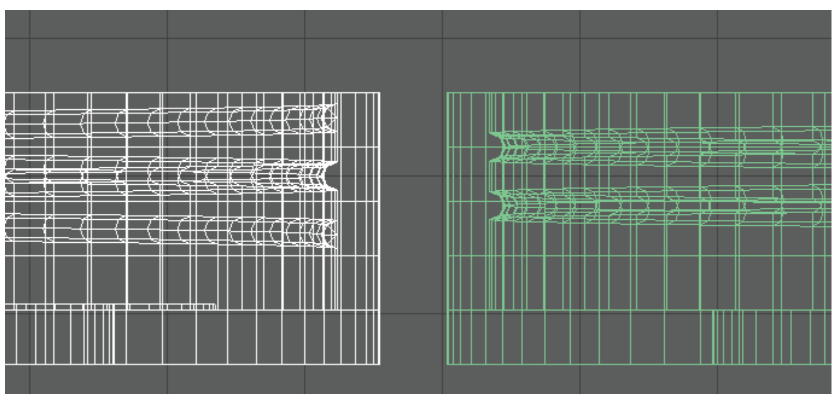


Figure 10 Difference between new and old cap structure

Figure 11 identifies the appearance of the prototype. There are two buckles attached to the lateral sides of the frame by means of two brackets, made of a flexible material, that extend on a plane substantially perpendicular to the frame. The buckles of flexible material are molded directly onto the material of the frame. A flexible strap that has its two ends connected to two buckles, which allows its length to be adjusted.

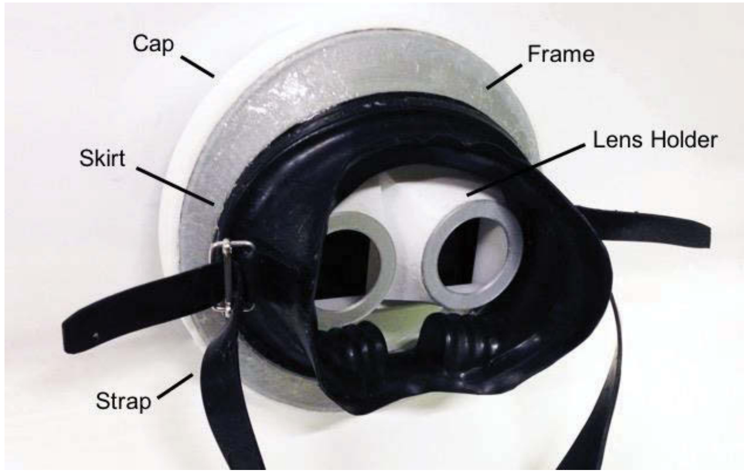


Figure 11 Appearance of the prototype

3.2 Software development

In order to evaluate the proposed prototype, a related underwater scenario is essential. Using a game engine to create a stereoptic virtual scene is a suitable solution for this. In the past many researchers have chosen from the available commercial or open source game engines such as Unreal (Carpin et al. 2007; Wang, Lewis & Gennari 2003) and Unity (Bourke 2009; Craighead, Burke & Murphy 2008). In this paper, we chose Unity 5 and Google VR SDK as the basis to establish the development environment.

Game engine refers to the software designed for the development of video games on various platforms (e.g., consoles, mobile devices and PCs). The core of a game engine typically includes a rendering engine for graphics, a physics engine, artificial intelligence (AI) support, network management, thread management, optimization, and may include animation support for cinematics.

The Unity game engine is developed by Unity Technologies in Denmark. Unity integrates with the nVidia PhysX physics engine and Mono which is implementation of Microsoft's .NET libraries (Craighead, Burke & Murphy 2008). Listed here are the reasons why we chose Unity game engine.

- Documentation. The Unity engine has full documentation with examples for its API.

- Support. There is an online developer community which offer assistance for developers.
- Drag& Drop System. Unity allows the developers to simply assign objects and scripts by “drag and drop”.

The author proposed a set of design aspects to address the most common issues found regarding the usability and suitability of such systems for underwater purpose. Hence, the following design criteria were utilized for the development of the UnderwaterVR system:

- The system should be able to provide the experience which is the same as or be similar to real underwater experience.
- The platform should provide a natural interaction as this enhances the engagement with the system.
- The system must be accessible and cost-effective by utilizing affordable game technology and a simple setup.

The software content is about the diving adventure. We assume that the participant will engage with the content displayed on HMD if it is good enough. However, the measurement “good” is not quite clear for content design. A survey was conducted for understanding what kinds of details of the scene may influence the user’s experience. The participants were asked what kinds of elements should be seen during diving. Figure 12 shows the summary of 10 participant’s feedback.

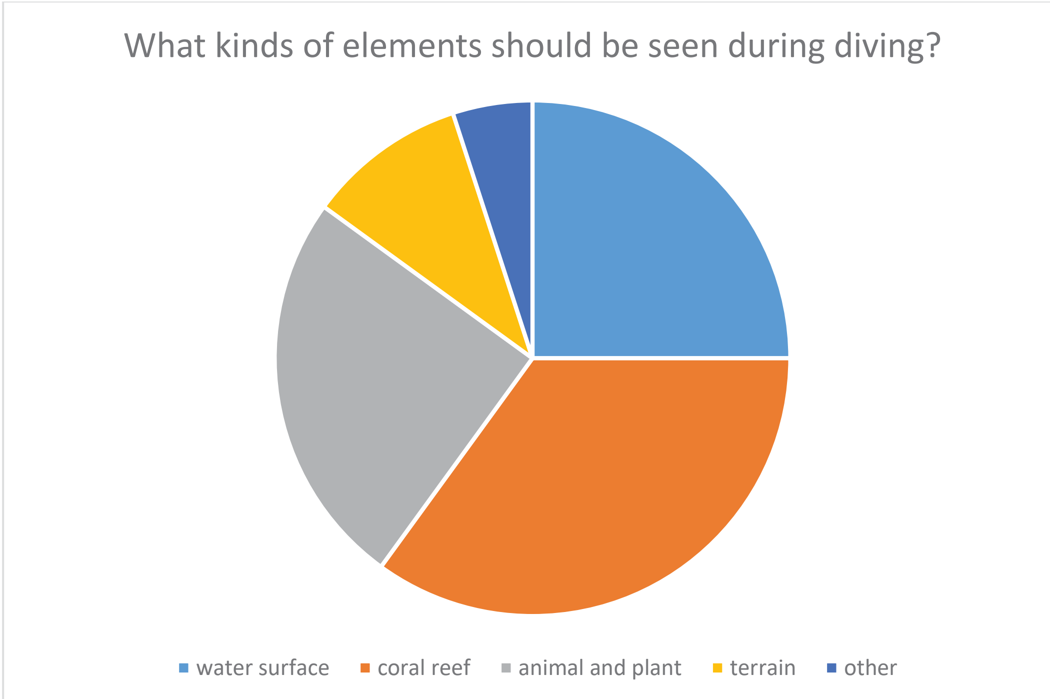


Figure 12 summary of questionnaire result

We have also interviewed 3 of 10 participants who has scuba diving experience. They were asked to describe the memory of their diving adventure.

"The Ulong Channel in Palau impressed me. It had spectacular coral, lots of big fish and sharks as we drifted for quite a long distance. I remember it had incredible diversity and pristine coral."

"Cairns. I went there with my girlfriend. The underwater world has incredible visibility, beautiful soft coral on a very lively wall. I love it."

"I saw a huge red star fish, a stingray and hundreds of sea urchins on the sand. Clown fish, large amount of coral. I've seen a few things I've never seen before. They were very nice. The coral reef was good, very impressive."

From the participants' feedback, an initial scene can be imagined: shallow undersea environment with multiple coral reefs and fish. Reality refer to the likeness to the real world that a designed virtual environment has hence the designed game content is based on this imagined scene.

Unity engine will help us compile the contents to an executable application for the target platform. However, it doesn't provide the functionality to create a stereoptic camera. Google VR SDK is provided for Google Cardboard support. Cardboard is a form of VR that relies on a smart phone's motion sensors to perform head tracking.

3.2.1 Build an initial scene

The first virtual scene we built is a non-interactive scene that simulates the scuba diving experience. It is based on a sub-tropical shallow sea and we added elements (godray effect, clownfish, shadows, etc.) to make the environment more realistic. The goal of this scene is to prepare novice users with a realistic diving experience.

a. Terrain

Unity's Terrain system allows uses to add landscapes into the scene. A *terrain* is a mesh representing an area of ground where each point on the ground has a particular height from a baseline. The *heightmap* for a terrain stores the greyscale values in an image where each pixel corresponds to a coordinate on the ground. The greyscale values are used to generate the terrain mesh.

Even though a heightmap is not viewed directly as an image, there are still common image processing techniques that are useful when applied to the height data. For example, adding noise to a heightmap will create the impression of rocky terrain while blurring will smooth it out to produce a softer, rolling landscape. In this virtual scene, we decide to design a crater-like terrain. Figure 13 left shows the heightmap that was created in Photoshop. Figure 13 right shows the textured terrain created by importing the height map.

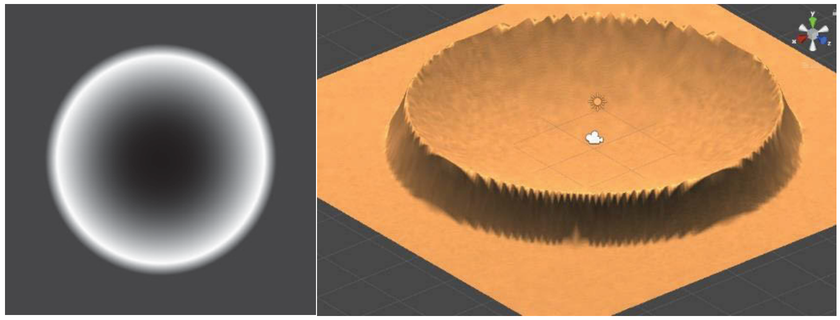


Figure 13 Terrain

The main reason for building a crater-like terrain is the Cybersickness issue. Previous research shows that motion-sickness-like symptoms during VR experience is very common (Davis, Nesbitt & Nalivaiko 2014). Cybersickness has been reported in virtual reality research since its inception. It can result in a wide scope of symptoms including nausea, disorientation and headaches which are very similar to motion sickness. The actual cause is still uncertain, however, the most acceptable theory for cybersickness, sensor conflict theory, indicates are that the conflicts of visual system and vestibular systems which are engaged in virtual environments cause the symptoms (Oman 1990). It states that our body has an expected sensory input which may be based on past experiences and biology and if the actual sensory input is different, this causes the cybersickness (e.g., imagine that you are running away from your enemies in a VR first person shooting game but in real life, you are sitting in your room). Therefore, we assume that keep the camera staying at a fixed world coordinate in the virtual scene and require the participant to stay at the same location will be able to minimize the symptoms. From the camera's perspective, the terrain is like a basin. The camera located at the central of the basin. During the evaluation, the participant will not be allowed to move back or forward in the water since the camera is fixed, moving may cause the Cybersickness symptoms.

b. Water surface

Using shaders to simulate water surface is the best and most efficient way. A shader is a program running on a GPU which draws the triangles of 3D models. Figure 14 simply represents the shows the role of 3D model, material and shader in the rendering flow of Unity3D.

Basically, 3D models are a set of vertices (3D coordinates). Each vertex can contain a lot of information, such as color, normal and UV data. Materials can be seen as wrappers that contain a shader. Different materials can share the same shader with different data.

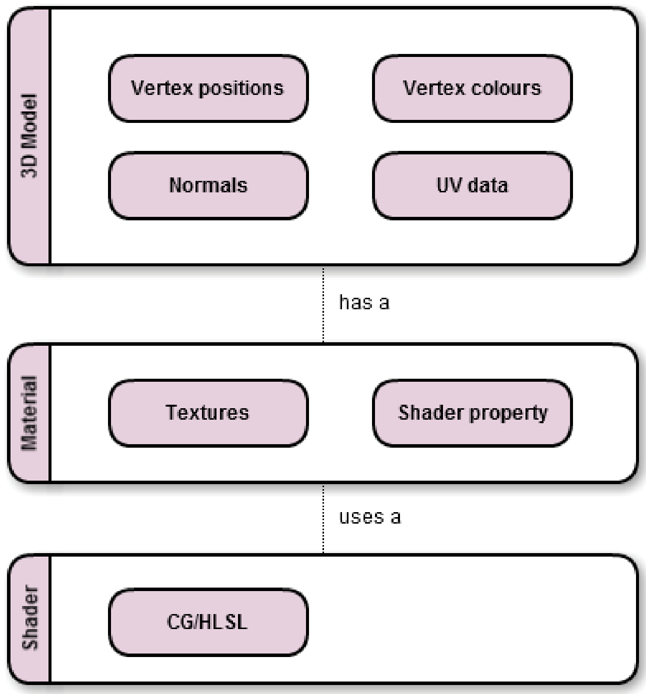


Figure 14 Rendering workflow of Unity3D

Unity engine supports two different types of shaders: suface shaders and vertex& fragment shaders. Surface shaders (see Figure 15) hide the light reflection calculation and allows to specify “stacking” properties (including albedo, normal, reflectivity, etc) in function *surf*. These values will be applied into the selected lighting model for deciding the final RGB values of each pixel.

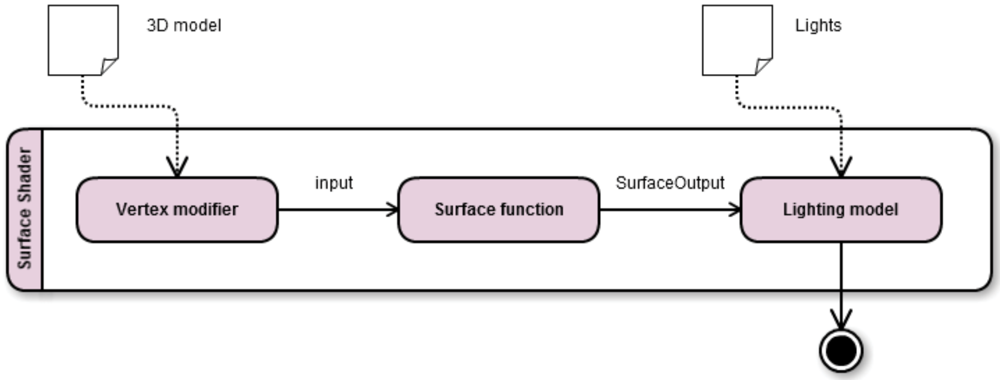


Figure 15 Surface shader

Vertex and fragment shaders, as the name suggests, the computation is done in two steps (see Figure 17). The geometry of 3D model will be passed through the function *vert* which can alter its vertices. After that, individual triangles (a collection of vertices) are passed through the function *frag* which decides the final RGB color for each pixel.

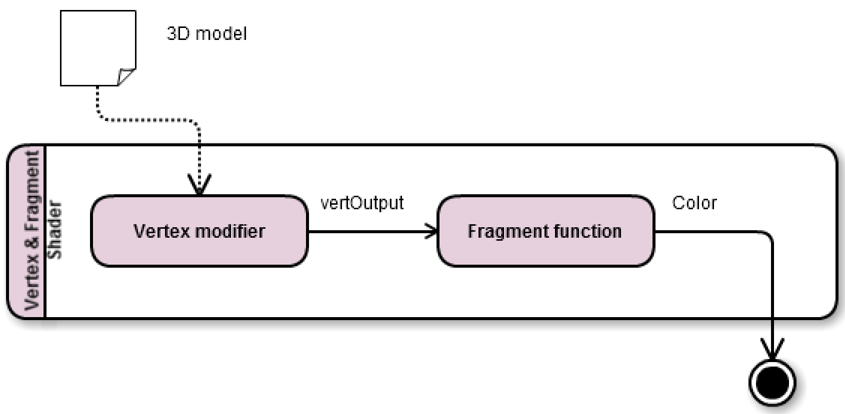


Figure 16 Vertex and fragment shader

Unlike normal water surface shading, simulating water surface from below is a bit more complicated. When you're underwater, you are in a medium with an index of refraction (IOR) of 1.33. To see anything above the water, which is in air with an IOR close to 1.

Notably, we notice Fresnel reflection also occurs under water. Take water surface reflection as an example, if you observe the see at near-grazing incidence, the ocean surface can be mirror-like. But you will find much less reflection from the water close to the location where you are standing.

The phenomenon occurs beneath water is similar. If you observe towards the water surface, you will find the distorted mirror image. When you look up the water surface vertically, there is little reflection and you will see through the interface (see Figure 17).

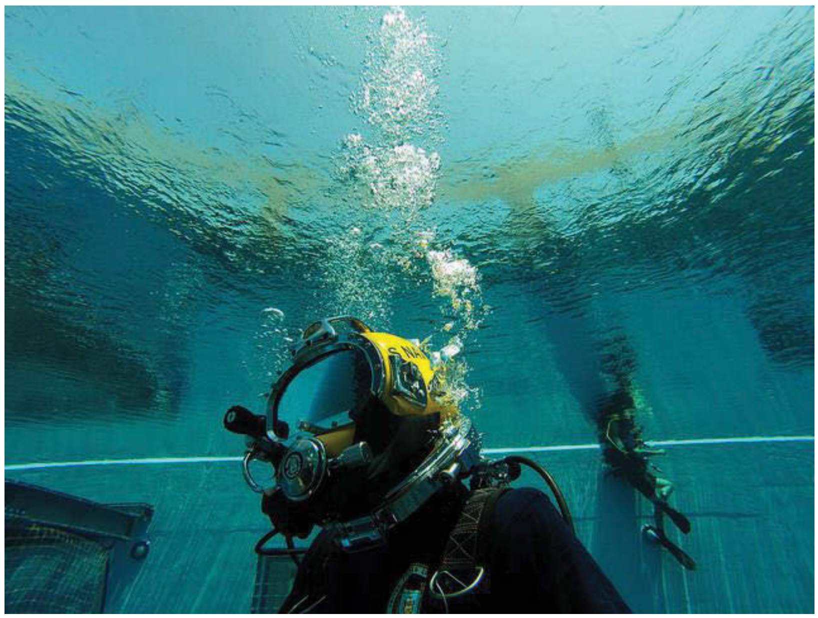


Figure 17 (Coast Guard diver training 2017)

Total internal reflection(TIR) is a phenomenon created when light travels above a certain angle of incidence with respect to a surface where the IOR decreases. When the light wave reaches the surface between different medias with different refractive indices, part of the wave will be refracted at the surface, and part of the wave is reflected. However, if the incident angle is greater (i.e. the direction is closer to being parallel to the surface) than the critical angle, the wave will not cross the boundary. Instead, it will be totally reflected back.

Allowing a mobile device to render the full detail of water surface is too difficult. Therefore, from the designer's perspective, we don't want the user to be able to look up through the surface. The entire visible surface will be past the angle where total internal reflection occurs.

From Figure 18 we can see that the distortion and reflection works fine. The scene was deployed to the Nexus 5X and the frames per second (FPS) range floats between 45-50.

Figure 18 Game screen capture

However, after adding coral reef models, particle system and godray effect, the FPS decreased significantly (floating between 20-25 FPS). By removing the water plane, the FPS recovered. The profiler shows that calculating the distorted reflection consume too many hardware resources. There are two solutions for this problem, either remove some of the underwater contents or change the water surface shading approach.

Since the purpose of designing is to simulate the scuba diving environment, removing coral reef or other contents may reduce the realness. It seems that changing the shading approach is a better choice. We notice that the when the camera location is far away from water surface, there is almost no reflection (Figure 19) because of the diffuse reflection. Diffuse reflection refers to an incident ray is reflected at many angles rather than at one angle like specular reflection.

Figure 19 (Scuba 2017)

When we dive into the sea and observe the water surface, the bumped surface reflects the water incident light to all sides. Based on this feature, we decide to remove the functionality of mirror refection.

This time, the FPS range is recovered to 35-42 which is acceptable. Figure 20 shows the comparison of unity statistics between two shaders in the same scene on Desktop. Obviously, the number of triangles and vertices draw on screen reduced significantly after removing reflection.

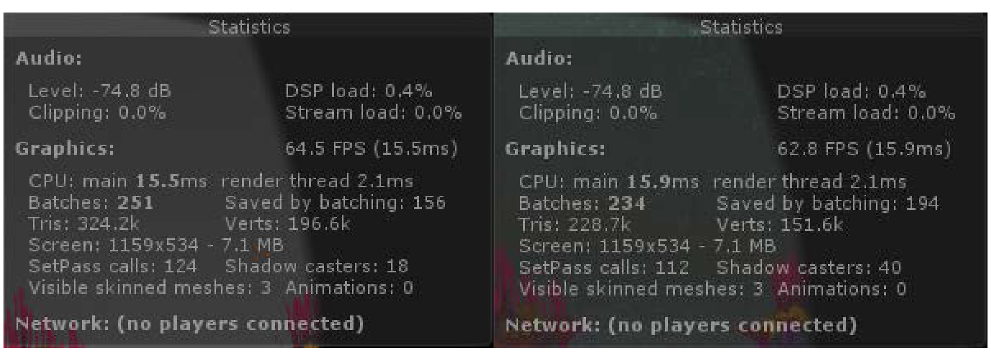


Figure 20 Unity statistics comparison

Here are key properties of Unity statistics.

- Time per frame and FPS
  - The amount of time taken to render one frame.

- Tris and Verts
  - ➢ The number of triangles and vertices drawn on screen.
- Visible Skinned Meshes
  - ➢ The number of skinned meshes rendered.
- Animations
  - ➢ The number of animations playing.

Figure 21 shows the completed virtual scene. Being lack of interactivity is the largest disadvantage of this implementation. In virtual environments, one of the major problems is the lack of physical constraints (Hannema 2001; Mine, Brooks Jr & Sequin 1997). Interaction in the real world is aided by physical properties of objects around us. Two of the most important include adherence to gravity and not being able to move through solids. Virtual environments do not have any of such restrictions. Picking up an object is therefore difficult in a virtual environment. Therefore, if we change the scene to a see-through content, the physical boundary of real world will be applied. It will also bring the interactive capability to the prototype. Therefore, we started to build the second scenario - an interactive scenario.

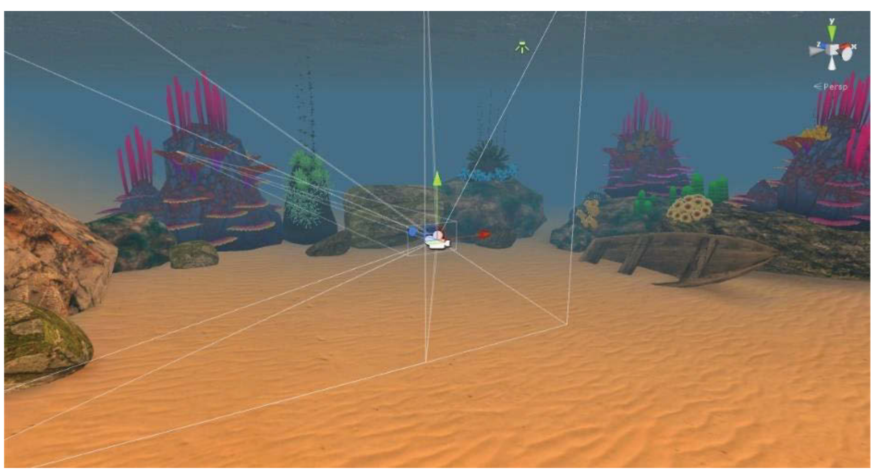


Figure 21 Game screen capture

3.2.2 Tracking techniques

Interactivity is very important towards achieving immersion and presence in virtual reality hence most consumer electronics use tracking technique to enhance the experience. For example, Valve's 'Lighthouse' tracking system affords the HTC Vive a 'room-scale' tracking space for the VR headset and its controllers through the area-sweeping lasers. There are three dominant types of tracking techniques: sensor-based tracking, vision-based tracking and hybrid tracking techniques.

a. Sensor-Based Tracking Techniques

Sensor-based tracking techniques are based on various sensors which have their respective advantages and disadvantages (Zhou, Duh & Billinghurst 2008). For example, Ivan built a head tracking system in order to explore the use of an ultrasonic phase-difference head tracking system (Sutherland 1968). The main advantage of phase-difference trackers is their ability to generate high data rates (Rolland, Davis & Baillot 2001). Therefore, it is possible to use filtering to overcome environmental perturbations. The main disadvantage is their vulnerability to cumulative errors in the measurement process.

b. Vision-Based Tracking Techniques

Vision-based tracking techniques can use image processing methods to calculate the camera pose relative to real world objects (Bajura & Neumann 1995). In some applications on highly integrated devices, vision-based tracking technique is more convenient. However, the external conditions such as light can impact vision based tracking easily.

c. Hybrid Tracking Techniques

When vision based tracking alone cannot provide a reliable tracking solution, the hybrid method that capture both sensory and vision input becomes dominant. In the past view years, a few researches of the underwater computer vision has been explored.

Most of the study is about AR and within them, sensor-based tracking combined with marker tracking is dominant.

Blum et al. implemented a water-based Augmented Reality setup for entertainment. Her seminal work allowed sensing virtual corals and fish even when physically underwater and in locomotion by using a mobile prototype using Augmented Reality techniques to enhance a public swimming pool with virtual objects for playful interaction. Although the prototype by Blum worked fine, it still needs improvements for everyday scenarios, because it was quite bulky and fragile (user needs to host the computer in backpack).

Leif et al. (Oppermann, Blum & Shekow 2016) presented a multi-player Underwater Augmented Reality setup which is called AREEF for swimming pools. They using off-the-shelf components combined with a custom made waterproof case and an innovative game concept, AREEF puts computer game technology to use for recreational and educational purposes in and under water. For playing AREEF, each child is required to equip a tablet that is sealed in a waterproof case. In addition to these tablets, a base station is placed at the border of the swimming pool basin, consisting of a marker and a (also waterproof) tablet computer attached to a larger display. Several visual markers are sunk in the water and distributed in the pool in a triangular setup, keeping a few meters distance between them. Those markers are augmented based on Vuforia (Vuforia 2017) feature tracking. The base station marker is augmented by a virtual character that provides guidance for the children, telling them what to do.

Either Blum's work or Leif's work made great contributions for the underwater AR/VR technique. Both of their work put the markers in the fixed locations. It seems that marker tracking is dominant when choosing a tracking technique for physical underwater applications. Therefore, we proposed a similar interactive scene (figure 22) for prototype. The second scene is a simple box picking underwater game with video-based AR, i.e., the display shows the video stream from the camera. The actual virtual objects are augmented by means of ARtoolkit tracking, are sunk in the water and distributed in the pool.

Figure 22 Interactive picking up game

Since the ARtoolkit is not explicitly designed for underwater purpose, after developing we did an initial test. The AR tracking worked fine, even though sometimes the camera's image is affected by different effects such as a distortion. Loss of tracking was primarily caused by extreme viewing angles, too large distance or occlusion caused by other people. Using even larger markers could improve performance, given that the actually augmented area, the virtual objects in this case, will not become bigger.

The initial scene is a completed virtual environment with non-interactivity. The second scene has the capability that allow user to interact with the environment but is lack of undersea elements. Hence the third scene was created as an integration, i.e. a non-see-through scene with the capability of interaction via markers.

3.2.3 Interactivity in UnderwaterVR

Allowing the virtual environment to reflect the locomotion in the real world is the basic mechanism of interactivity for *UnderwaterVR*. We have tried two different types of tracking techniques via phone camera: OpenCV standard blob detection and ARToolkit.

a. Light tracking

Not only a marker is unique in a swimming pool, a spot light source can be unique as well. Therefore, we created a bar that contains one light emitting diode (LED) and an AAA size battery. A test tube (150 mm tall with 14 mm inside diameter) was used as the body as well as handle of this bar. The LED was wrapped by shading cloth and a hole was left on the cloth to make sure the LED can be considered as a point light source. The user will be required to hold the bar as a controller in the water. When moving hands underwater, the light emitted from led will mark the position of user's hand. The emitted light can be captured by OpenCV as a Blob. The Blob is a collection of connected pixels within an image that has common property (e.g., grayscale value).

The Canvas is an area that all UI elements should be inside. Its normal can be changed with the camera's direction. We use a crosshair to represent the hand position. When camera captured the blog, its coordinates of current image frame will be transferred to the coordinates on Canvas (See Figure 23).

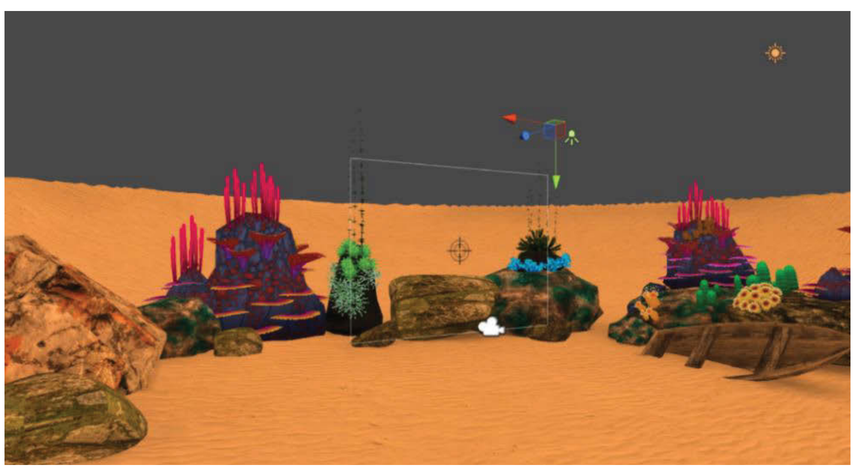


Figure 23 UI Canvas

There are two disadvantages of this implementation: noise and orientation. The light condition influences the accuracy and stable of the blob detection significantly. Unlike normal image detection, the light reflection and refraction make the light source more complicated than on-land. For example, the light rays that reflected and refracted by the curved surface, i.e. the water surface, will generate caustics (Figure 24). The intensity of connection of the overlapped caustic is similar to the LED's intensity which may cause lots of errors within detection.

Figure 24 Caustics

Orientation is another problem. With one or two light source, it is difficult to tell the correct orientation of the user's hand since there is no depth sensor on most of the consumer level mobile. When user rotate the holding hand and keep it at a fixed location, the crosshair flickers. Additionally, if the user twists the wrist but keep the light source at the same position, the crosshair will not move which may make the user confused.

b. Marker tracking

In the light tracking solution, the tracked object's coordinate of the camera image frame is transferred to the UI coordinate system. Unlike the previous implementation, the marker tracking solution is to reflect the tracked objects in world coordinate system. It allows for 6 DOF tracking comparing to the position tracking in light tracking. Therefore, a printed marker was attached to the top instead of LED light source and handle was also changed from test tube to a ruler.

In the original ARToolKit library, it provides the position of the marker in the camera coordinate system, and uses OpenGL matrix system for the position of the virtual object (see Figure 25).

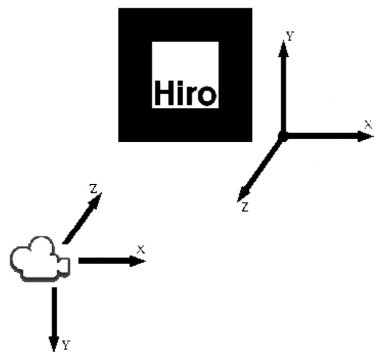


Figure 25 ARToolKit coordinate system

The output values correspond to these coordinate systems. The marker coordinate system has the same orientation of the OpenGL coordinate system, so any transformation applied to the object associated with the marker needs to respect OpenGL transformation principles. However, we need the virtual object to reflect the user hand's position and rotation, the matrix of marker transformation need to be inversed. Here is the matrix inversion action in ARTrackedObject script.

```
Matrix4x4 pose;
if (marker == baseMarker) {
// If this marker is the base, no need to take base inverse etc.
  pose = origin.transform.localToWorldMatrix;
} else {
  pose = origin.transform.localToWorldMatrix * baseMarker.TransformationMatrix.inverse *
marker.TransformationMatrix;
}
transform.position = ARUtilityFunctions.PositionFromMatrix(pose);
transform.rotation = ARUtilityFunctions.QuaternionFromMatrix(pose);
```

A game object was used to hold the AR configuration objects, i.e. the ARController and ARMarker in the unity scene. The ARController is used to handle the initialization and management of the framework. Different layers were used to separate out parts of the scene. In this scene, the video background will be marked as “AR Background” that will not be shown on the screen. The other elements, i.e. coral reef, plant, terrain and so on, are marked as “AR Foreground” layer where every marker's content will be shown.

A pistol was attached as an AR content for the marker (see Figure 26). When the position and rotation of the marker changed at runtime, it will be changed as well. Google Cardboard SDK will help render the stereo scene.

Figure 26 Pistol in the game

After development, we did an initial test underwater for this scene. Compared with light tracking technique, although the tracking may be lost for the marker’s distortion (the marker is not printed on the bar, we used a paper maker with plastic cover. The resistance underwater may distort the marker when moving it. Changing the shape from cylinder to rectangular columnar is useful for mitigating the distortion) which makes marker tracking become more stable.

Chapter 4 Evaluation

The evaluation of the prototype requires the participant to wear it and go into water. Some traditional methods of user study are not suitable for underwater experiments. For instance, Think-aloud (THA) is one of the most valuable usability engineering method (Holzinger 2005). The think-aloud protocols are used to let participants “thinking aloud” within experiments. The participants are required to speak whatever comes into their mind (e.g., what they are thinking and feeling). It may help the researchers to understand the participant's cognitive processes as explicit as possible. However, as an experiment underwater, the participants are not able to speak.

Autoethnography is *“an autobiographical genre of writing and research that displays multiple layers of consciousness, connecting the personal to the cultural”* (Ellis & Bochner 2000). Within it, the researcher will change the gaze and put focus on self (Babcock 1980). It is used to describe and analyze personal experience (Ellis 2004). The author’s self can be considered as an ethnographic exemplar in autoethnographic research.

It is very essential that the researcher observes their own behaviors and write down their thoughts within autoethnography. Chang called the autoethnographic research which is done by researcher individually “introspective self-observation” (Chang 2008). The essence of self-observation is that it brings hidden and elusive personal experiences like cognitive processes to the surface.

Although the researcher is required to avoid personal bias within technical writing in most of qualitative research, autoethnography is written by means of first person perspective. Denzin and Lincoln (Denzin & Lincoln 2011) described autoethnography as a research that combines personal consciousness. In this dissertation, the author describes his story of constructing an identity as an unexperienced scuba diving enthusiast. The author used his own observations to understand and speculate on his personal.

In this dissertation, autoethnography is the selected methodology because the author tells a story by means of his personal experience and exploration. In choosing autoethnography, the author is asking the readers to feel the truth of his story (Ellis 1996).

4.1 Archived Data

The purpose of this autoethnography is to detail and explore the underwater VR experience. The construction of the author's identity is the underwater HMD pilot entails an introspective look as what kinds of experience the underwater HMD can provide. However, only narrative data is not enough to compare multiple evaluation results. Here we describe quantitative data for exploring the user's experience.

Tan et al. (2015) reported they used think aloud protocol to explore the experience of playing Half-Life 2 on Oculus Rift. Half-Life 2 is a popular commercial a first-person shooter game that can be considered as representing the classic single-player first person shooter games (Valve 2009). 10 participants were asked to play the same game scene of Half-Life 2 twice. The first time is to play the game by using the Rift, and the second time is to play the game by using a desktop PC. They also asked participants to complete flow (FSS-2) and immersion (IEQ) questionnaires immediately after playing games.

After analyzing the collected data, they came to the following conclusion:

- Participants have more intense experiences on the HMD.
- Cybersickness hardly affects immersion.
- In-game interaction type directly affects experience.
- There is more flow/immersion on the Rift.
- Participants were more engaged with passive elements in the game.

Within the research of Tan et al. (2015), several dimensions of gameplay user experiences were mentioned, including flow (Csikszentmihalyi & Csikszentmihalyi 1992), presence (IJsselsteijn et al. 2000) and immersion (Jennett et al. 2008). These words are most commonly presented by games researchers as key measurements to evaluate gaming experiences (Tan et al. 2015).

a. Flow

Flow was introduced by Csikszentmihalyi in his book *“Optimal experience: Psychological studies of flow in consciousness”*. It refers to *“the state in which individuals are so involved in an activity that nothing else seems to matter”*. The most widely used instruments for measuring flow are the Flow State Scale (FSS) and Dispositional Flow Scale (DFS) (Jackson & Marsh 1996).

Jackson (2002) presented the FSS-2 and DFS-2 which is an improvement of the original. Although FFS and DFS are not specialized instruments for game user studies, they can help the researcher understand if the participant’s experience meets the game developer's expectation.

b. Immersion & Presence

Immersion as well as *Presence* can be explained as the degree that users feel “being in the game”. In most of the first-person perspective games, especially in VR games, people are often asked if they can feel *“being there”* which refers to *immersion* and *presence* during interviews. In order to measure immersive experience, Immersive Experience Questionnaire (IEQ) was created (Jennett et al. 2008) by Jennett et al. in 2008. Within their paper, they noticed that the subjective experience of a participant may affect the *presence*, however, they didn’t give a conclusion of this finding. Their viewpoint is:

“We argue that presence is only a small part of the gaming experience: whereas presence is often viewed as a state of mind, we argue that immersion is an experience in time.”

Presence has several determinations. Wijnand A. IJsselsteijn et al. (IJsselsteijn et al. 2000) think presence is *e*ssential for virtual reality and they presented valid means of measuring *presence.* One of the features of virtual reality is to let people feel their *presence* in the virtual world. Most types of existed virtual reality game applications are first person perspective games which aim to provide strong immersive experience (i.e. *presence*) for players.

For this study, the self-observation and questionnaire data are archived data. The observational data consists of 1.5GB videos. The content is the author wearing the designed HMD in a public swimming pool with 3 different scenarios. During the exploration, another researcher took notes and used a camera to record the participant's experience. The videos were done in the same week but different places. Half of them were recorded in an indoor public swimming pool and the others were recorded in an outdoor swimming pool. The participant, who is also the author, was required to finish the questionnaire immediately after the experience. The questionnaire data is used to support the narrative data.

In this autoethnographic study, the author himself is the primary data source. The experiences for this study of underwater VR explorer identity construction and change of practices are recounted by memory, self-observational (videotape) and external data (questionnaires, see Appendix A& B) are used for support.

This study doesn't involve the conversation with other people. Rather author is required to ask himself the following questions in order to bring credibility and trust to the research.

"Is my writing convincing to the reader as to its validity and truthfulness?"

"Am I really being what I am like a scuba diving enthusiast?"

4.2 Scenarios

My work resulted in 3 scenarios: a scene without interactivity, a scene that tracked user's action by light and a scene that tracked user's action by marker. These three scenarios were conducted in a room, an indoor swimming pool (classic 25-meter pool) and outdoor swimming pool (classic 50-meter pool). Below are the autoethnographic observations recorded after experiencing each scenario in each of the physical environments.

4.2.1 A tropical shallow sea virtual scene without interactivity

a. In the room

I can see a tropical undersea scene. I was standing on the bottom where surrounded by rock and coral reefs. The bottom is full of sand and the corals are very beautiful. I raise my head to observe the water surface, it looks real. Sun rays cast down from top and change randomly. I move around and then I found I can't move the camera. It feels strange. When I stopped moving, the strange feeling disappeared. I have experienced a lot of virtual reality scenes. As an application runs on mobile, the performance is not bad and I can feel I was being in the environment. However, I think it is just a normal VR scene. It doesn't give me the sense like "Oh, it is better than others". Although all the elements look good, but I can still realize they are fake. After 30 minutes of exploration, I can feel a bit fatigue and nausea.

b. Indoor swimming pool

I noticed the depth of the swimming pool is lower than my height. I have to keep floating or leaning back in the water. I can see some corals around me and there is a wreck beside the rocks. The bottom is full of golden sand, however, when I touched the bottom with my feet, I felt I am standing on a smooth and cold tile. At that time, I can also feel a bit uncomfortable, a bit nausea. But it disappears soon. Then I started to look around the environment carefully. The coral reefs with clown fishes are very attractive, although I can realize they are not real. However, it doesn't make me feel less immersion, i.e., being in the environment. I tried to rise my head and see the water surface, the buoyance of the HMD pull it away from my face. I get out of water and check if there is some water get into the HMD. It was just "I am feeling the HMD is leaking water". The truth is "nothing happened".

I adjust the buckles and dive into water again. Suddenly, I realized I was just "getting into the virtual world". When I was thinking "Oh, no. The mask is leaking", I didn't think I was using an HMD to simulate diving. It's really like I was diving until I stand up and get out of water. I rotate my body and turn head to look around in the water, everything is so natural. When I try to move forward in the scene, the camera doesn't move. This made me a bit confused, then

I remembered the camera is fixed in the scene. I keep moving in the water and try to see if there is something will happen, I felt a bit uncomfortable. Actually, the sense is very difficult to describe, it's a bit like nausea but less than previous experiment. I even felt a bit horror at that time. Then I stopped moving, just floating in the water and watch the environment. I can hear the voice of the water which made me felt the scene is so true, even though I knew it is not real.

c. Outdoor swimming pool

The weather of the day I went to conduct the underwater research is fine. Unlike the indoor swimming pool, the sunlight shines into the water directly which is nature. Before I test the scene, I dive into water and observe the real environment. The depth of the pool is almost the same with my height. I can see those caustics changing their shape on the bottom. I can see the sun rays like spot light clearly. Then I put on the HMD and experience the same scene again. It is almost the same when I experience it at an indoor swimming pool. Since I just watched the real underwater environment, I compared it with the virtual scene I am looking at, especially for the water surface and sunlight. In the virtual scene, I can feel that my location is further away from surface. I can't see the mirror reflection that I have seen a moment ago. I still can see the curved water surface up and down from below. Some sun rays pull down from top and keep changing behind the coral reefs. It's beautiful. I have tried this scene in the lab, at that time I thought it was a just normal VR scene. However, after I get into water, everything seems to have changed. I don't have any experience about scuba diving, but currently what I am experiencing is very close to what I imagined. The experience was unlike any other that I had experienced before.

4.2.2 A tropical shallow sea virtual scene with light tracking

a. In the room

The elements haven't been changed. I can see a tropical undersea scene. I was standing on the bottom surrounded by rock and coral reefs. The bottom is full of sand and the corals are very beautiful. I have a stick that reflects my hand's locomotion in the scene. I've never seen such an application before. By putting the stick in front of the goggle, a crosshair can be seen in the screen. The crosshair is not part of the environment. If the aim of scene is to let participant feel the virtual environment more realistic, the crosshair is more like a virtual *object inside the virtual scene, like an AR in the VR. The content is interesting. However, the light tracking seems to be unstable. The tracked object is easy to be lost when the light condition is changed.*

b. Indoor swimming pool

This is not my first time to experience this virtual scene. I can see a tropical undersea environment. I was standing on the bottom where surrounding by rock and coral reefs. The bottom is full of sand and the corals are very beautiful. The difference is, this time, I have a handle to interact with environment. I can see a crosshair when I raise the real handle in front of my face. When I move the handle close to the mask, the virtual object trembled violently. I tried several times, in some cases, it suddenly disappeared. When I moved the handle around, the virtual object reflects the approximate location of the real handle but not very accurate. It cannot tell some slight motion. For example, If I keep the location but tilt the handle a little bit, the virtual object doesn't change at all. Except for the crosshair, the environment looks good like before. Even though sometimes the crosshair annoys me, the other elements such as fish, water and low gravity made me calm down. It feels like I am on a vacation.

c. Outdoor swimming pool

I took on the HMD and watch the scene again. I can see a tropical undersea environment. I was standing on the bottom surrounded by rock and coral reefs. The bottom is full of sand and the corals are very beautiful. However, the tracking functionality didn't work well this time. Even I kept the handle stationary, the virtual handle still move violently. I assume the sun light impact the tracking. Since the crosshair fluctuate before me and my eyes felt fatigue significantly. Although the interaction didn't work well, it didn't impact my immersion sense. The feeling it gave me is like "a tool was broken". I can still feel I was swimming in a tropical sea.

4.2.3 A tropical shallow sea virtual scene with marker tracking

a. In the room

I can see the same elements in the previous environment. I can see a tropical undersea scene. I was standing on the bottom where surrounding by rock and coral reefs. The bottom is full of sand and the corals are very beautiful. The difference is this time the tracked object is a part *of the scene. It's a real thing in the simulated world. I can see a gun in front of me. When I moved the stick, the gun will reflect the stick's status which including the location and direction. The stick is like the handle of a gun which made me feel the scene more realistic. I felt it enhance the immersion a lot when I compared it with the non-interactive scene. The virtual object may disappear sometime but not very often. The environment looks very real.*

b. Indoor swimming pool

I can see a tropical undersea scene. I was standing on the bottom surrounded by rock and coral reefs. The bottom is full of sand and the corals are very beautiful. Compared with the indoor experience, the displayed virtual object is more stable. From my own perspective, whether the virtual object can show some slight movement which match the user's action is an essential point for me to judge the simulation is good or not. I hence observe the wand in the scene very carefully. I rotated my wrist in the water and the virtual gun moves. When I tried to tilt up and down the handle, the virtual gun also tilt up and down. It simulated the handle's movement well.

After I played with this scenario for 15 minutes, I didn't feel any fatigue as I sensed in the light tracking scenario. I also got accustom to the virtual gun. It was like a tool in a science fiction movie which increased my engagement.

c. Outdoor swimming pool

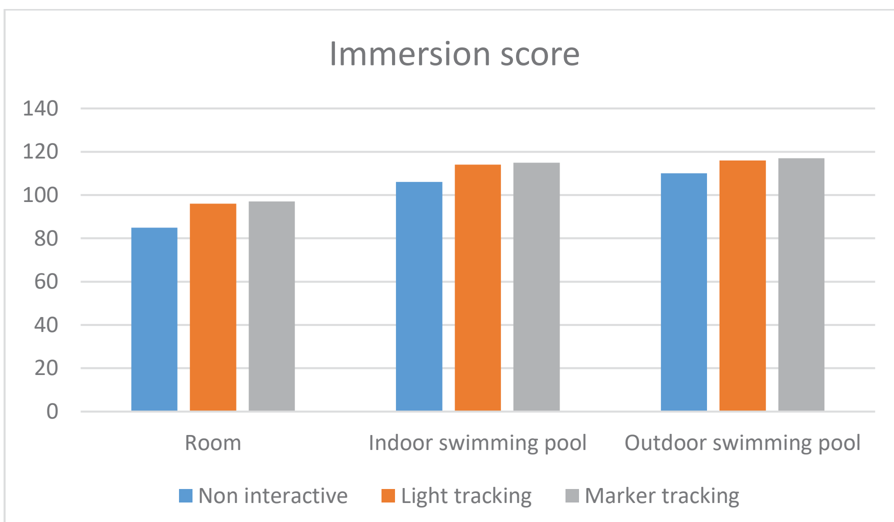
The experience is very close to the indoor swimming pool. I can see a tropical undersea scene. I was standing on the bottom where surrounding by rock and coral reefs. The bottom is full of sand and the corals are very beautiful. It seems that the nature light noise won't impact underwater marker tracking. I rotated my wrist in the water and what and how does the virtual gun moves. When I tried to tilt up and down the handle, the virtual gun also tilt up and down. It simulated the handle's movement well. I played with this scenario for a long time and I didn't feel any fatigue.

4.3 Summary of findings

The *UnderwaterVR* goggle was tested in an indoor swimming pool and an outdoor public swimming pool with the participant wearing it whilst being allowed to freely move underwater. The participant trialed the *UnderwaterVR* goggle in two conditions on separate days of 40 minutes use each. The two conditions basically involve the three different scenes implemented as described in Section 3, i.e., the first condition involves the non-interactive underwater adventure scene, whilst the second and third condition involves the interactive underwater game. During the experience, the author is required to stay underwater the whole time. Due to the safety consideration and UnderwaterVR doesn't support position tracking, the user was also asked not to walk around underwater. After experiencing the scene, the author is required to finish the immersion questionnaires (Jennett et al. 2008) and FSS questionnaire (Jackson & Marsh 1996) immediately. The key observations are as follows.

4.3.1 Enjoyable underwater experiences

Based on user's report and the result of questionnaire, all the experiences are immersive and enjoyable.



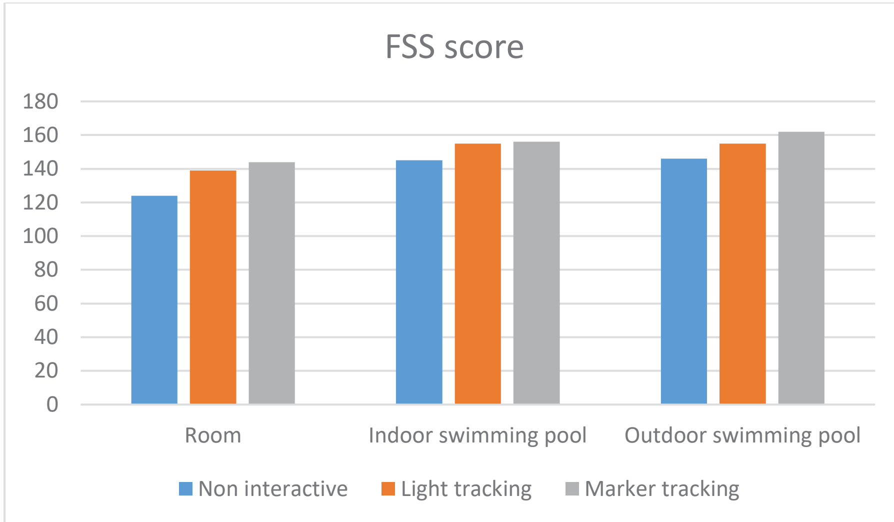


Figure 27 Immersion & FSS score

The participant gave a rather high score in the immersion questionnaire. Especially in the questions like: "Did you lose track of time?" "Did you feel as though you were separated from your real-world environment?" "Was your sense of being in the game environment stronger than your sense of being in the real world?" The user gave the full score (the score range is 1 to 5).

Figure 27 shows the interactive features increased the immersion scores and flow scores as well. The score of outdoor swimming pool experiment is slightly higher than indoor swimming poor. Within the author's feedback, he mentioned that he conducted the experiments on a sunny day which is close to the preset weather in the scene. We assume the psychological suggestion influenced the user's sense perception. Except for these small differences, indoor and outdoor swimming pool conditions should be the same for underwater VR goggle. The goggle was also reported to be simple to operate and the interactive part in the second scene simple to follow, however, the participant is also the developer hence the significance of his usability account is low.

We also found that the real water environment may help enhance user's experience. Without interactive capability, the immersion score of the in-water environment is about 13% higher than on-land. The interactive component increases the scores around 7%. In 4.2.1 c, the user wrote: *"I have tried this scene in the lab, at that time I thought* *it was a just normal VR scene. However, after I get into water, everything seems to be changed."* Although the stability issues of the light tracking method made the participant feel fatigue during the experiment, the participant didn't give a low score for those scenes. Interestingly, when the author tried the first scene in the room, he wrote: *"I think it is just a normal VR scene. Although all the elements look good, but I can still realize they are fake"*. However, when tried the same scene underwater, "*I rotate my body and turn head to look around in the water, everything is so natural*". It seems that the *UnderwaterVR* enhances the underwater scene significantly.

4.3.2 Less cybersickness than usual

The participant reported feelings of mild "strangeness" at several instances when he was moving around in the pool. For example, when his feet touched the bottom bed of the pool: *"I didn't feel uncomfortable until my foot touched the bottom of the pool. In the virtual scene, the ground is full of sand, however, I am standing on a tile floor. Suddenly, a bit of uncomfort came out but it is still acceptable."* Interestingly, the participant felt less fatigue and nausea experiencing *UnderwaterVR* than when experiencing the same virtual scene in a Google Cardboard setup in a normal desktop environment. Additionally, the participant was also familiar with other HMDs and indicated that he had much more cybersickness symptoms playing Half-Life 2 on the Oculus Rift than with the *UnderwaterVR* experience. Although this account is not well controlled for in an actual experiment, it mildly reinforces the notion that less cybersickness might be exhibited in the *UnderwaterVR* setup. Briefly, cybersickness is a commonly experienced discomfort in HMDs but the exact causes are still uncertain (Davis, Nesbitt & Nalivaiko 2014), although it is shown that cybersickness relates well to the vestibular system (Regan & Ramsey 1996). A recent study into gameplay experiences on the Oculus Rift also revealed that cybersickness seemed to be unavoidable (Tan et al. 2015).

Chapter 5 Conclusion and Future work

5.1 Conclusion

Scuba diving is an popular sport for the modern generation. However, it can be considered as an attractive but costly sport. By using virtual reality technology, it is possible to find a low-cost and relatively safer way for underwater adventure. We reviewed the existing virtual reality and augmented reality applications. A number of innovated devices and applications of virtual or augmented reality have been previously created. Within the applications with underwater enhancement, very few of the researchers detailed the underwater experience. Additionally, most of the presented devices for underwater applications are bulky and expensive. Therefore, we designed and implemented *UnderwaterVR*. *UnderwaterVR* is a safe and low-cost solution to enable realistic underwater simulations, applicable to both professional (e.g., scuba diving) and recreational (e.g., water theme parks) activities.

By analysing the advantages/disadvantages of head mounted displays, we chose to build a new prototype from scratch. The first iteration is a binocular non-pupil-forming head mounted display. It contains multiple components: a square cap, lens holder and frame. The lens holder holds a pair of eyepieces which helps users to focus on the mobile display. We used 3D printer to print all the essential parts. A Nexus 5X smart phone was used as the display. A rubbery skirt which fits user's face, namely the eye-region and nose-region, is needed for watertight purpose. After we printed the skirt, we found there several salient points left on the surface of the skirt. Based on the participant's feedback, it was not comfortable when wearing the skirt and the waterproof performance was not good enough due to the 3D printer's printing resolution. In iteration 2, we got removed the 3D printed skirt and used a purchased scuba diving mask. We slightly changed the dimensions of the previous design and created a new prototype by repurposing the mask. We used watertight adhesive to connect each part of the prototype. The tensile strength of watertight adhesive was lower than none watertight adhesive. The resistance underwater is much higher than in the air and the faying surface of each part was quite small which lead to water leaking. We applied the bottle-cap design to the prototype. Although the waterproof performance was improved by doing this, the prototype was still leaking water during long use times. Additionally, after tightening the prototype, it was rather difficult to screw off the cap. Therefore, we put a soft seal ring on the inner surface of the cap and reduced the contact surface between cap and frame which increased the waterproof performance significantly. Our experience from above presented a low cost but efficient way for making a waterproof head mounted display via 3D printing. The failures and redesigns that we had during the development contribute to the further research.

In order to simulate the scuba diving experience, a survey was conducted for collecting essential elements underwater. The volunteers were asked on questions like "what kinds of elements should be seen while diving" and were also asked to narrate an exciting scuba diving memory. Based on their feedback, we created a tropical shallow sea virtual scene. However, it was lacking interactivity features. Due to the constraints and limits of the underwater situation, we added a simple interactive feature into the virtual scene by light tracking and marker tracking.

The *UnderwaterVR* goggle was tested in an indoor swimming pool by using autoethnography. The participant trialled the *UnderwaterVR* goggle in two conditions on separate days for 40 minutes each. After experiencing the scene, the author was required to finish the immersion questionnaire (Jennett et al. 2008) and flow state scale questionnaire (Jackson & Marsh 1996) immediately. From the result, the immersion score of underwater experiment is higher than on-land experiment, hence revealing a huge potential for the real underwater VR applications. We also found that the real water environment may help enhance user's experience. Without interactive capability, the immersion score of in-water environment is about 13% higher than that of on-land. The interactive component increases the scores at around 7%. In section 4.2.1 c, the author wrote: *"I have tried this scene in the lab, at that time I thought it was a just normal VR scene. However, after I get into water, everything seemed to have changed."* Although the unstableness of the light tracking made participant feel fatigue during the experiment, the participant didn't give a quite low score for those scenes. Interestingly, when the author tried the first scene in the room, he wrote: *"I think it is just a normal VR scene. Although all the elements look good, but I can still realize they are fake"*. However, when tried the same scene underwater, *"I rotate my body and turn head to look around in the water, everything is so natural"*. It seems that the *UnderwaterVR* enhance the underwater scene significantly. Briefly, the participant's feedback is quite positive. Through autoethnography, we detailed the underwater experience of virtual reality applications. Although the participant is also the developer which means the significance of his usability account is low, the user study does provide some insights about the virtual reality applications. Another contribution we have made in this thesis is to explore the underwater interactivity for VR/AR. Two different tracking techniques have been test within the evaluation of prototype. The light tracking allows the UI system to reflect user's hand position. The marker tracking is to simulate a virtual object which allows user to interact with. Based on the evaluation, both of these two tracking techniques slightly increase the immersion that felt by user.

5.2 Unexpected finding

By analyzing the findings of evaluation, the author mentioned he felt less cybersickness than on-land applications. Cybersickness is a common issue for virtual reality applications. In Tans experiment, 8 of 10 participants experienced cybersickness during the gameplay (Tan et al. 2015). Cybersickness refers to physiological symptoms induced by watching 3-dimension scene. The symptoms may include nausea, headaches and eye strain (Davis, Nesbitt & Nalivaiko 2014). A number of research of cybersickness have been done, but unfortunately the actual cause of cybersickness is still uncertain (Davis, Nesbitt & Nalivaiko 2014; LaViola Jr 2000). There are 3 different theories that tried to explain the actual cause of cybersickness.

The *sensory conflict theory* is mostly accepted theory by researchers for the cause of cybersickness (Davis, Nesbitt & Nalivaiko 2014; LaViola Jr 2000). *Sensory conflict theory* mainly presents that the conflicts of visual system and vestibular system that engaged in virtual scenes induce the cybersickness (Oman 1990). It states that human body has an expected sensory input which may base on personal experiences and if the actual sensory input is different (e.g., imagine that you are running away from your enemies in a VR first person shooting game but in real life, you are sitting in your room), hence causing the cybersickness.

5.2.4 Cybersickness Reduction

Since the symptoms of cybersickness are very similar to the symptoms of motion sickness and there are some drugs has been proved to be useful for motion sickness, what about using those drugs for cybersickness? Some researchers tried to use medicine that is used for motion sickness to treat cybersickness. In 1996, Regan, E. and A. Ramsey's experiment showed that hyoscine hydrobromide is effective in mitigating symptoms that induced during immersion in virtual reality (Regan & Ramsey 1996). Hyoscine hydrobromide is a well-known drug to prevent motion sickness by suppressing the effect of vestibular system in man (Brand & Perry 1966). This experiment shows that the cause of cybersickness is highly correlated with vestibular system.

5.3 Hypothesis

The fact that participants felt less cybersickness attracted more of our attention than we expected. Before developing the non-interactive virtual scene, we assumed the possible cause of the cybersickness is similar to motion sickness based on sensory conflict theory. However, previous research proved vestibular stimulation is sufficient to cause motion sickness and vision is a contributing factor (Kennedy, Hettinger & Lilienthal 1990). Cybersickness can be induced without vestibular stimulation, e.g., it can be caused by the visually-caused perception of self-motion while the participant didn't actually move (LaViola Jr 2000). How can we explain this? To understand the external environment, our brain uses multiple sensory input (including vision, touch and audition). Related research shows that under multisensory conditions, one sensory stimulus may completely dominates the percept (IJsselsteijn et al. 2000) and the percept will change when user's experience changes.

When experiencing the virtual world displayed via VR glasses at least four sensory estimates about the presence can be derived: visual, auditory, stability and proprioceptive. In order for these four signals to be integrated, they firstly have to be transformed into the same coordinates and units. For this, the visual and auditory signals have to be combined with the other signals to help brain interpret the presence. However, in some virtual reality situations, the vision and auditory signals against the other signals. Different with the event happened in the real world, our brain could realize that the vision and auditory signals are artificial and we force our brain to self-identity these signals. These visual and auditory signals which can be considered as consistent external effects that influence the perception.

5.2.1 Sensory Integration Model

In 2004, the research of Marc O. Ernst et al. shows that in order to understand the information we receive from the environment, human brain always follows two general strategies: *sensory combination* and *sensory integration* (Ernst & Bülthoff 2004).

Sensory combination refers to the way that the human brain keeps reconstructing the input information (e.g., vision, audition and feeling) from external environment and generates understanding of the world. After *sensory combination*, human brain will present a unique but maybe not accurate understanding to the external environment. If the generated understanding mismatches the past experience or expectation, human brain will try collect more and more information about the percept and finally derives an answer to resolve the mismatch. Different with *sensory combination*, when more than one sensory input available for understanding the external environment, information from the different sensory input have to be integrated which is called *sensory integration*. Marc O. Ernst et al. assumed that the multi-sensory signals can be integrated by using Maximum Likelihood Estimation (MLE) Model (Ernst & Bülthoff 2004) via a linear way. The integrated estimate $\hat{s}$ w_i The index σ_i^2 is.refers to the different sensory signals.

$$\hat{s} = \sum_i w_i \, \hat{s}_i with \sum_i w_i = 1$$

$$w_i = \frac{1/\sigma_j^2}{\sum_{i=1\dots,j,\dots N} 1/\sigma_i^2}$$

Depending on the situation, the sensory signal's quality can vary and the sensory estimate thus has different measurement reliability.

Based on Ernst's theory, the sum of reliabilities of all sensory input should be one in nature. However, in the real world there should be a lot of other sensory input which is able to support the vision input. Unfortunately, the existing VR applications hardly can provide all the sensory input for participants hence the mismatch within the brain cognition process probably cause the cybersickness. We assume that within the virtual reality experience, if the proportion of the weight of vision decreased within all the input, the symptoms of cybersickness will be mitigated. Obviously, this hypothesis need to be tested in the future.

The fact that cybersickness symptoms were experienced less underwater leads to some rather interesting observations in relation to prior work. Particularly, this phenomenon might be acquainted with Ernst et al.'s work (Ernst & Bülthoff 2004), which states that different humanoid senses can be summed up in the following manner:

$$\hat{s} = \sum_i w_i \, \hat{s}_i with \sum_i w_i = 1$$

where $\hat{s}$ is the sum of each ith sensory signal $\hat{s}_i$ (sight, touch, etc.) scaled by its relative weight w_i. In a typical VR experience, the w_{vision} is the highest in contrast with w_{haptic} and w_{audition}, etc. This means that perhaps the *UnderwaterVR* experience actually increased w_{haptic} and reduced w_{audition} to compensate for it. This is because submerging a person underwater provides a whole-body sensation of the water and is much more visceral than watching a VR underwater scene itself. One possible hypothesis to be tested in the future is hence whether such alterations of sensory weights can actually lead to reduced cybersickness.

5.4 Future work

In this thesis, the author created an underwater VR setup and used different approaches to endow the interactivity with the headset. A detection issue was found in the light tracking approach because of the sunlight pattern. By adding a temporal pattern (e.g., fast blinking) in the LED light may help distinguish the LED light source from the sunlight in the future. The hypothesis presented in this report may interpret the cause mechanism of cybersickness hence presents an approach to mitigate the symptoms of the cybersickness. An autoethnography study cannot prove the hypothesis hence more experiments need to be conducted to test the hypothesis. Testing Cybersickness of underwater and on-land conditions regarding different level of activities (e.g., walking/swimming forward, navigating in place, and following a path underwater) in the same VR scene seems to be a good design.

The headset design is unique and general. Although using a waterproof does not provide any technical improvement, it may make the size of the prototype smaller. As future work, we may improve the design of prototype and make it more delicate. We will also perform longitudinal ethnography over several months to perform a more substantial analysis of the experiences *UnderwaterVR* affords. We also aim to include the testing of our hypothesis that increasing non-visual forms of sensory input mitigates cybersickness symptoms. In addition, an autoethnography has its inherent limitations being a single-user study with findings limited to the profile of the single user (e.g., our participant is a non-scuba diver). In order to better generalize our results, we aim to obtain a compromised ethical approval for our multi-user study, and thereby perform a larger evaluation of experiences across a wider population. Nevertheless, a long-term study needs to take place before we can make more substantial claims as the novelty factor subsides.

Appendix A. Immersion Questionnaire

Please answer the following questions by circling the relevant number.

To what extent did the game hold your attention?

Not at all 1 2 3 4 5 A lot

To what extent did you feel you were focused on the game?

Not at all 1 2 3 4 5 A lot

How much effort did you put into playing the game?

Not at all 1 2 3 4 5 A lot

Did you feel that you were trying you best?

Not at all 1 2 3 4 5 A lot

To what extent did you lose track of time?

Not at all 1 2 3 4 5 A lot

To what extent did you feel consciously aware of being in the real world whilst playing?

Not at all 1 2 3 4 5 A lot

To what extent did you forget about your everyday concerns?

Not at all 1 2 3 4 5 A lot

To what extent were you aware of yourself in your surroundings?

Not at all 1 2 3 4 5 A lot

To what extent did you notice events taking place around you?

Not at all 1 2 3 4 5 A lot

Did you feel the urge at any point to stop playing and see what was happening around you?

Not at all 1 2 3 4 5 A lot

To what extent did you feel that you were interacting with the game environment?

Not at all 1 2 3 4 5 A lot

To what extent did you feel as though you were separated from your real-world environment?

Not at all 1 2 3 4 5 A lot

To what extent did you feel that the game was something you were experiencing, rather than something you were just doing?

Not at all 1 2 3 4 5 A lot

To what extent was your sense of being in the game environment stronger than your sense of being in the real world?

Not at all 1 2 3 4 5 A lot

At any point did you find yourself become so involved that you were unaware you were even using controls?

Not at all 1 2 3 4 5 A lot

To what extent did you feel as though you were moving through the game according to you own will?

Not at all 1 2 3 4 5 A lot

To what extent did you find the game challenging?

Not at all 1 2 3 4 5 A lot

Were there any times during the game in which you just wanted to give up?

Not at all 1 2 3 4 5 A lot

To what extent did you feel motivated while playing?

Not at all 1 2 3 4 5 A lot

To what extent did you find the game easy?

Not at all 1 2 3 4 5 A lot

To what extent did you feel like you were making progress towards the end of the game?

Not at all 1 2 3 4 5 A lot

How well do you think you performed in the game?

Not at all 1 2 3 4 5 A lot

To what extent did you feel emotionally attached to the game?

Not at all 1 2 3 4 5 A lot

To what extent were you interested in seeing how the game's events would progress?

Not at all 1 2 3 4 5 A lot

At any point did you find yourself become so involved that you wanted to speak to the game directly?

Not at all 1 2 3 4 5 A lot

To what extent did you enjoy the graphics and the imagery?

Not at all 1 2 3 4 5 A lot

How much would you say you enjoyed playing the game?

Not at all 1 2 3 4 5 A lot

When interrupted, were you disappointed that the game was over?

Not at all 1 2 3 4 5 A lot

Would you like to play the game again?

Not at all 1 2 3 4 5 A lot

Appendix B. Flow State Scale Questionnaire

Please answer the following questions in relation to your experience in the event you have just completed. These questions relate to the thoughts and feelings you may have experienced during the event. There are no right or wrong answers. Think about how you felt during the event and answer the questions using the rating scale below. Circle the number that best matches your experience from the options to the right of each question.

Rating Scale:

Strongly disagree 1 Disagree 2 Neither agree nor disagree 3 Agree 4 Strongly agree 5

1. I was challenged, but I believed my skills would allow me to meet the challenge.

Strongly disagree 1 2 3 4 5 Strongly agree

2. I made the correct movements without thinking about trying to do so.

Strongly disagree 1 2 3 4 5 Strongly agree

3. I knew clearly what I wanted to do.

Strongly disagree 1 2 3 4 5 Strongly agree

4. It was really clear to me that I was doing well.

Strongly disagree 1 2 3 4 5 Strongly agree

5. My attention was focused entirely on what I was doing.

Strongly disagree 1 2 3 4 5 Strongly agree

6. I felt in total control of what I was doing.

Strongly disagree 1 2 3 4 5 Strongly agree

7. I was not concerned with what others may have been thinking of me.

Strongly disagree 1 2 3 4 5 Strongly agree

8. Time seemed to alter (either slowed down or speeded up).

Strongly disagree 1 2 3 4 5 Strongly agree

9. I really enjoyed the experience.

Strongly disagree 1 2 3 4 5 Strongly agree

10. My abilities matched the high challenge of the situation.

Strongly disagree 1 2 3 4 5 Strongly agree

11. Things just seemed to be happening automatically.

Strongly disagree 1 2 3 4 5 Strongly agree

12. I had a strong sense of what I wanted to do.

Strongly disagree 1 2 3 4 5 Strongly agree

13. I was aware of how well I was performing.

Strongly disagree 1 2 3 4 5 Strongly agree

14. It was no effort to keep my mind on what was happening.

Strongly disagree 1 2 3 4 5 Strongly agree

15. I felt like I could control what I was doing.

Strongly disagree 1 2 3 4 5 Strongly agree

16. I was not worried about my performance during the event.

Strongly disagree 1 2 3 4 5 Strongly agree

17. The way time passed seemed to be different from normal.

Strongly disagree 1 2 3 4 5 Strongly agree

18. I loved the feeling of that performance and want to capture it again.

Strongly disagree 1 2 3 4 5 Strongly agree

19. I felt I was competent enough to meet the high demands of the situation.

Strongly disagree 1 2 3 4 5 Strongly agree

20. I performed automatically.

Strongly disagree 1 2 3 4 5 Strongly agree

21. I knew what I wanted to achieve.

Strongly disagree 1 2 3 4 5 Strongly agree

22. I had a good idea while I was performing about how well I was doing.

Strongly disagree 1 2 3 4 5 Strongly agree

23. I had total concentration.

Strongly disagree 1 2 3 4 5 Strongly agree

24. I had a feeling of total control.

Strongly disagree 1 2 3 4 5 Strongly agree

25. I was not concerned with how I was presenting myself.

Strongly disagree 1 2 3 4 5 Strongly agree

26. It felt like time stopped while I was per- forming.

Strongly disagree 1 2 3 4 5 Strongly agree

27. The experience left me feeling great.

Strongly disagree 1 2 3 4 5 Strongly agree

28. The challenge and my skills were at an equally high level.

Strongly disagree 1 2 3 4 5 Strongly agree

29. I did things spontaneously and automatically without having to think.

Strongly disagree 1 2 3 4 5 Strongly agree

30. My goals were clearly defined.

Strongly disagree 1 2 3 4 5 Strongly agree

31. I could tell by the way I was performing how well I was doing.

Strongly disagree 1 2 3 4 5 Strongly agree

32. 1 was completely focused on the task at hand.

Strongly disagree 1 2 3 4 5 Strongly agree

33. I felt in total control of my body.

Strongly disagree 1 2 3 4 5 Strongly agree

34. I was not worried about what others may have been thinking of me.

Strongly disagree 1 2 3 4 5 Strongly agree

35. At times, it almost seemed like things were happening in slow motion.

Strongly disagree 1 2 3 4 5 Strongly agree

36. I found the experience extremely rewarding.

Strongly disagree 1 2 3 4 5 Strongly agree

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