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AquaCAVE: An Underwater Immersive Projection System for Enhancing the Swimming Experience

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Abstract

AquaCAVE is an underwater immersive projection environment which faithfully reproduces the swimming experience in the virtual space. AquaCAVE is inspired by the surrounding projection system known as the CAVE Automatic Virtual Environment, where the stereoscopic images are projected to the surfaces surrounding the user, but addresses several water-specific problems that were not studied in previous systems. In this paper, we describe techniques to overcome the water-specific issues for configuring the immersive projection system. Three characteristics of water that mainly cause problems are pincushion distortion, reflection, and infrared (IR) radiation absorption. Existing motion capture systems based on IR or blue lights are not feasible for an underwater immersive projection environment since IR are absorbed, and blue lights disturb a user to see the stereoscopic images. Therefore, we propose a setup for visible-light head tracking, which is functional for AquaCAVE. As a result, the proposed circular polarization-based method was shown to be valid to enable a constantly clear view, stable head tracking, and reflection reduction. With this methodology, we can build the proposed AquaCAVE that can be applicable to future underwater entertainment and enhanced swimming training.

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Virtual reality

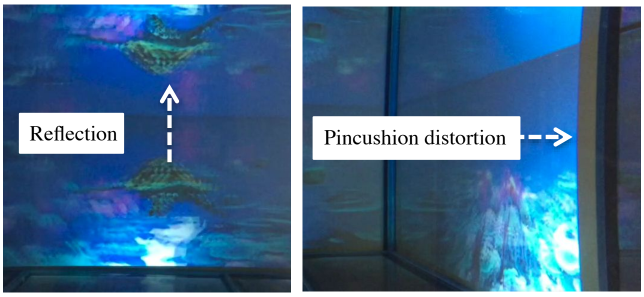
1. Introduction

Swimming is one of the best workouts for cardiovascular health. It is effective for burning calories and puts adequate stress on the body. On the other hand, to develop good workout habits can be difficult for beginners. Thus, there have been several attempts to support the swimming activity with digital technologies such as Virtual Reality (VR) systems. However, swimming is also a full-body experience that induces unique perceptual recognitions and feelings (e.g. water flows, pressure, etc.), which contain complicated integration of various haptic senses over the whole body not only with visual and auditory sensation. For this reason, reproducing swimming experiences with VR systems is quite challenging within existing research.

In this study, we introduce an underwater immersive projection environment. This configuration is inspired by the CAVE Automatic Virtual Environment [CNSD93], where the stereoscopic images are projected to the surfaces surrounding the user. As the images are controlled based on the user's head position, the environment can provide 3D synthetic experience to the user. In our case, the environment is filled with real water, which faithfully reproduces the swimming experience in a virtual environment. Swimmers can literally dive into the surrounding scenery as if they were for instance swimming in a real sea with coral reefs (Figure 1). At the same time, this underwater configuration poses new technical challenges which are not addressed by the previous studies.

Figure 1: *AquaCAVE: An underwater immersive projection environment.*

To configure immersive projection environments, accurate head tracking for detecting eye positions, and projection with appropriate view frustums are required. However, the characteristics of water such as optical distortion and reflection make the necessary con-



(a) Reflection on the surface of water (b) Pincushion distortion in the water

Figure 2: *Examples of issues caused by water.*

ditions difficult to satisfy. In addition to these issues, water absorbs a wide range of infrared radiation (IR). For this reason, IR motion captures and/or head tracking devices that are widely used in existing VR systems are unusable for our purpose. In this paper, we describe techniques to overcome the water specific issues for configuring the immersive projection VR system.

2. Related work

Previous research using multimodal feedback enables users to dive into realistic scenes. Jain et al. [JSG*16] proposed a system that produces the sensation of diving into the water by using a motion platform with user's outstretched arms and legs placed in a suspended harness. Haptic turk [CLL*14] is a motion platform to provide an interactive experience as a flight simulation in VR. To create the sensation in the virtual world, the system uses tactile feedback produced by humans. Thus, the representation is limited by the tools that humans can handle, such as a spray and a fan. Systems using textiles can not represent sensations that the whole body senses such as water pressure and flow since the user is not intended to be in a space filled with the water, but air instead. However, AquaCAVE is filled with real water, which faithfully provides the actual swimming sensation in VR.

Underwater AR displays [MKMK09] and Swimoid [UR13] can show information in front of the user in the water. Nevertheless, these systems were not able to create the immersive environments like VR because of the limited size of the displays while the entire view is covered in AquaCAVE [YZR16].

3. AquaCAVE: Underwater immersive projection system

In this study, we introduce an augmented swimming pool with stereoscopic screens, based on the virtual reality environment with surrounded rear-projection screens known as CAVE in the water. In AquaCAVE, a user is able to enjoy the surrounding scenery as if they were swimming in a real sea with coral reefs. AquaCAVE can also enhance the swimming experience by showing information such as ideal swimming forms and sensing data in the 3D space.

To implement AquaCAVE, there are several difficulties caused by water specific issues. Bellow are three characteristics of water that mainly cause problems for impressive projection setup.

Infrared radiation (IR) absorption: IR motion capture and head tracking are widely used for VR. However, tracking-devices using IR cannot be used for AquaCAVE, since IR decays greatly in the water.

Pincushion distortion: Pincushion distortion is an effect from the water, which causes images to become pinched in the center. This optical distortion is seen in images taken in the water because of the difference in the refractive index between air and water.

Reflection: AquaCAVE consists of acrylic panels with rear-projection sheets. The Acrylic panels reflect the images displayed on the other screens. This reflection also occurs on the surface of water in the pool.

Figure 2 (a) is an example of reflection on the surface of the water, (b) is the pincushion distortion in the water.

4. System implementation

Figure 3 is the system configuration of AquaCAVE. The pool is $3m \times 2m \times 1m$, and made of $3cm$ thick acrylic panels. The inside of the pool is coated with circular polarizing sheets. Six ultra-short throw projectors (RICOH PJ WX4141) are used for the projection. Each projector is capable of displaying stereoscopic images with a frame sequential method, and all images for projectors are provided from a single Mac Pro with six Thunderbolt display ports. Stereoscopic images are projected on each wall of the swimming pool, and goggles with liquid-crystal display (LCD) active shutter glasses separate images for left and right eyes. In AquaCAVE, the swimmer's eye position is tracked by the system to correctly project a 3D scene that can be extended across the boundaries of the pool walls.

To cope with optical distortion caused by water, image processing like camera calibration [LRL03] is valid. We used a dome-type lens, which can correct pincushion distortion optically [BBM*11].

4.1. Stable head tracking in the water

Existing motion capture systems based on IR or blue lights do not fit our purpose. Qualisys Underwater Motion Capture is a motion capture setup using visible light, which consists of several cameras emitting blue lights, and passive markers. This system can track the 3D positions of the markers in the water. However, since the cameras need to emit strong visible lights to the environment, the structure is not preferable for the projection environment.

We implemented a visible-light head tracking method, which is functional in the water. To achieve both of stable head-tracking and clear view in AquaCAVE, we used circular polarization as described bellow.

To provide a clear view of the projected images to the user, we put quarter wave sheets on the active shutter glasses to make these equivalent to right polarizing sheets. To provide a stable background to the camera, we put a left polarizing sheet on the lens. Figure 4 shows a light shielding and a transmission by a right circular polarizing sheet on the front screen in the water. Each image is taken through a left circular sheet (a), and a right circular polarizing sheet (b).

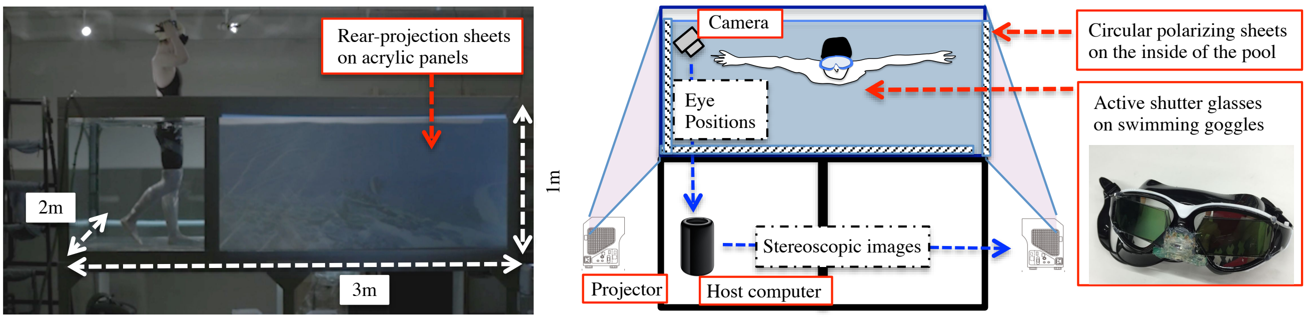
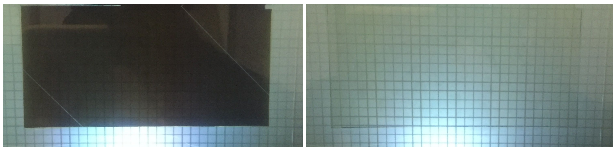


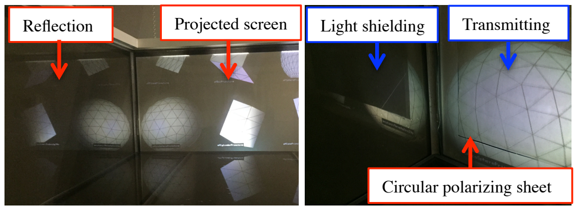
Figure 3: *The system configuration of AquaCAVE: Stereoscopic images are projected on each wall of the swimming pool. The user wears 3D glasses on swimming goggles in the pool, and the head position is tracked for configuring an immersive environment. The inside of the pool is coated with circular polarizing sheets for a constantly clear view, stable head tracking, and reflection reduction.*



(a) An image of front screen taken through a left circular polarizing sheet

(b) An image of front screen taken through a right circular polarizing sheet

Figure 4: *Light shielding and transmitting by circular polarization.*



(a) An example of reflections on other screens from a projected screen

(b) Light shielding caused by a change in polarization property

Figure 5: *Reflection reduction by circular polarization.*

The mechanism of the light shielding and transmitting in the pool is described bellow. Right circular polarizing sheets on the screens polarize the lights from projectors, and the lights are shielded by a left polarizing sheet on the lens of the camera for head tracking. On the other hand, the user wearing LCD active shutter glasses can see the images on the screen clearly, since the glasses are equivalent to right circular polarization sheets. The reason why LCD active shutter glasses become right circular equivalent is that the LCD are made of two linear polarizing sheets with the same axis. If the slow axis of the quarter wave sheet is at 45°to the axis of the polarizer, the LCD works the same as a right circular polarizing sheet.

4.2. Reflection reduction

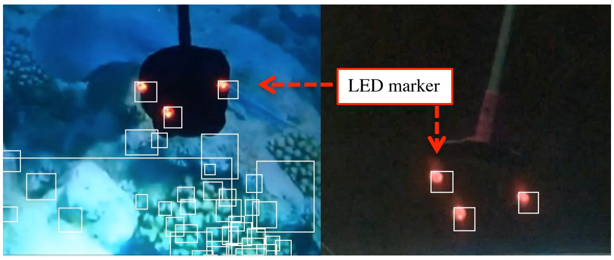
Right circular polarization sheets in the pool reduce reflection to other screens significantly. Figure 5 (a) shows an example of the reflection from the front screen. (b) is an image taken through a right circular polarizing sheet. The part of the front screen coated with the right polarizing sheet is visible while the reflection is dark. The reason why this light shielding happens is that the reflected lights become left-handed circularly-polarized lights. This means that the right circular polarization sheet prevents the images from being displayed on the other screens. The surface of the water also reflects images from scenes. This reflection may enhance the swimming experience if the scene is 2D, but causes the same issues for immersive projection environment. We apply a water current on the surface to blur the reflection. By this installation, the reflection becomes controllable.

5. Evaluation on light shielding for head tracking

For position detection using visible lights in the water, two main types of markers are available. One type of the markers is a fiducial marker widely used for AR applications. The other is a LED marker emitting visible lights. We tested the stability and limitation of each type of markers.

Natural Feature Tracking (NFT) [NY99] is functional even if some parts of the marker are covered. This situation is occasional in AquaCAVE since the user is intended to float in the water using his/her legs and arms. However, the detection of feature points used in NFT is strongly dependent on the illumination of the scene [MTS*05], [PCZ13]. We put each marker on a human head model and placed in the projection environment. NyARToolkit for Processing 3.0.2 is used to track an NFT marker. For testing the capacity of the marker, a video taken in the sea filled with coral leafs is projected on a screen. As a result, the system can track the NFT marker only in a bright light condition, which unable a clear projection.

LED markers are stable in a dark light condition, but only with a simple background. For testing the capability of LED markers, we put waterproofed LED markers on a swimming cap, and moved it in a pool displaying an underwater video. We used a library for processing called BlobDetection for LED marker tracking. The tracking system detects blobs in images with a simple brightness threshold. As a result, the system was not able to detect the LED markers accurately with any thresholds for luminosity since the background



(a) Front screen with an underwater scene, affecting blob detection

(b) Circular polarizing sheet on the front screen, making LED markers recognizable

Figure 6: *Background image stabilization for LED tracking.*

image contains a number of blobs, which have a variety of sizes and brightness as shown in Figure 6 (a). However, the markers became traceable with the light shielding by circular polarization as shown in Figure 6 (b). In other words, the light shielding improved the stability compared to the situation without polarizing sheets.

6. Discussion and future work

6.1. The effects of water to human perspectives

Objects appear larger in the water than in the air. This expansion and optical distortion may affect the immersive environment. Therefore, we conducted a test watching a stereoscopic video through a water tank. As a result, even though the video is slightly distorted and expanded, observers were able to watch the stereoscopic video as 3D. However, the effects to the stereoscope images may cause issues to immersive environments, which requires accurate depth information.

In addition, according to a research on human perspectives in the water [RN03], objects in the water usually appear beyond their optical distance and slightly enlarged in linear size, but in accordance with size-distance invariance for humans. This discrepancy might affect the underwater CAVE depending on eye positions and/or gaze direction. Thus, further investigation on the effects of water for humans in an immersive projection environment are required.

6.2. Water flow tracking as a user interface

We also conducted a feasibility test of a novel water-flow tracking method using a photoelastic effect as a user interface for AquaCAVE.

In the test, we used polyethylene (PE) sheets floating on the water in a water tank. We put a polarizing sheet on bottom of the tank, and took a video by using a camera with a polarizing sheet. Through the camera, we were able to see the colored PE sheets by the photoelastic effect. As a result, optical flow was valid to track the movement of PE sheets moving along a water flow in a water tank. This method may enable interactions using water flow in AquaCAVE. PE sheets are transparent from the view of user and/or a camera without any polarizing sheets. This means the objects floating on the surface of water does not affect the view, and 2D motion capture of the user is still possible in the pool.

7. Conclusion

We introduced AquaCAVE, an immersive projection environment in the water. In this study, we investigated water-related issues to make a CAVE setup, such as IR absorption, pincushion distortion, and reflection. As a result, circular polarization enabled the system to provide both a constantly clear view and stable head tracking with a complex background. Moreover, the installation reduces the reflection of the projected images to other screens. However, further investigation on the effects of water for humans is required. AquaCAVE is applicable to future underwater entertainment and enhanced swimming training.

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