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Evaluation of Virtual Reality Tracking Systems Underwater

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Abstract

The objective of this research is to compare the effectiveness of various virtual reality tracking systems underwater. There have been few works in aquatic virtual reality (VR) - i.e., VR systems that can be used in a real underwater environment. Moreover, the works that have been done have noted limitations on tracking accuracy. Our initial test results suggest that inertial measurement units work well underwater for orientation tracking but a different approach is needed for position tracking. Towards this goal, we have waterproofed and evaluated several consumer tracking systems intended for gaming to determine the most effective approaches. First, we informally tested infrared systems and fiducial marker based systems, which demonstrated significant limitations of optical approaches. Next, we quantitatively compared inertial measurement units (IMU) and a magnetic tracking system both above water (as a baseline) and underwater. By comparing the devices' rotation data, we have discovered that the magnetic tracking system implemented by the Razer Hydra is approximately as accurate underwater as compared to a phone-based IMU. This suggests that magnetic tracking systems should be further explored as a possibility for underwater VR applications.

CCS Concepts

• ***Human-centered computing*** → ***Interaction devices;*** • ***Hardware*** → *Hardware reliability screening;* • ***Computing methodologies*** → *Virtual reality;*

1. Introduction

If VR systems could be used effectively in real underwater environments, there are many potential beneficial applications, such as entertainment, SCUBA diver training, and aquatic rehabilitation. Aquatic rehabilitation [TR09] is a recommended rehabilitation approach for many injuries and disabilities because it keeps patients cool, results in low stress on patients' joints, and offers additional resistance to improve exercise effectiveness. The increasing use of aquatic rehabilitation and the benefits of land-based virtual rehabilitation heighten the need for usable and accessible VR systems that work underwater. However, there are very few VR systems that have been developed for use in real underwater environments. The first instances of adapting a VR or augmented reality (AR) system for underwater use was Blum et al. [BBM09] and Morales et al. [MKMK09] underwater AR system, in which the users had a waterproof video-see-through head mounted display (HMD) that enabled them to swim in a real pool with virtual fish or visualize commercial diving assembly tasks, respectively. Since then, research has been conducted to develop systems for AR enhanced underwater vehicle tele-operation [CDD*12]. Other underwater VR/AR systems - DOLPHYN [BDO*13] and AREEF [OBLS13] - demonstrate that underwater VR/AR games are possible. However, the technical challenges, such as tracking, are complex.

The primary objective in this paper is to provide a better understanding of tracking performance for underwater VR. Based on the limitations of previous works, we evaluated and compared several off the shelf orientation tracking approaches including optical, magnetic, and inertial. This paper presents these results and offers suggestions on how to design aquatic VR systems in the future.

2. Background and Related Work

2.1. Underwater VR and AR

There are few AR/VR systems actually being used in a real underwater environment. From our review of literature, we found only a few related papers. AR-enriched tele-operation of an underwater robot [CDD*12], an underwater augmented reality system for commercial diving operations [MKMK09], the DOLPHYN system [BDO*13], and AREEF - Augmented Reality for Water-based Entertainment, Education and Fun [OBLS13]. Here we discuss the details of these systems, the resulting lessons learned from the three works, and highlight needed research for the future.

Morales et al. developed an underwater augmented reality system for commercial diving operations [MKMK09]. This system used an eMagin HMD and a Logitec Quickcam Pro 9000 inside of a watertight enclosure to enable underwater AR. Users visualized parts and procedures for augmented assembly tasks underwater. The authors used fiducial markers to enable registration and

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tracking, which had to be manually calibrated, but was reported to still be highly error prone. The authors suggest that future work includes improving the HMD to be optical see-through, smaller, and more watertight. Moreover, they proposed that an acoustic tracker may yield better tracking results than fiducial markers, but more work is needed to investigate this.

The DOLPHYN [BDO*13] is a tracked display for augmented reality that was designed specifically for underwater use. It consists of a large waterproof case with positive buoyancy (i.e., it floats) that houses a tablet computer, a web camera, a joystick, and a mouse. They developed a series of games for both education and training. To facilitate these games, they used fiducial marker-based optical tracking with minimal changes to the setup of a standard AR system (e.g. similar to Morales et al. [MKMK09]). Moreover, the DOLPHYN did have WiFi capability, but its use was not discussed. The paper has some pictures of the games but leaves evaluation of tracking and usability for future work.

Oppermann et al. [OBLS13] developed AREEF - a multi-player augmented reality game for use underwater. Each user holds an AR-enhanced smart tablet while swimming underwater to search for specific types of virtual fish. To 'catch' a virtual fish, players had to be close enough to the fish and keep it rendering on the tablet display for a short period of time, thus eliminating the need for buttons. When a player 'catches' a fish, they must return to the surface and go to a scoreboard on a large LCD display to log their findings in competition with others playing the game. The authors report on technical issues that they faced. First, WiFi did not work well underwater, which is why the game required the users to return to the surface to report their findings. That is, the authors stated that the intent was to hide when WiFi disconnected underwater and automatically reconnect when above water. Secondly, they reported on problems with marker tracking. They suggested that it was important to calibrate the cameras underwater. They first tried using the pattern on the bottom of the pool itself for the marker, which proved problematic for absolute poses. The authors suggest that this problem might be reduced through optical flow tracking. Moreover, they mention that caustic effects underwater would often cause problems with the optical tracking, especially in outdoor pools. Also, in outdoor pools the bright sunlight caused visibility problems with the tablet displays. They did not report analysis of tracking or usability and thus left these evaluations as future work.

Osone, Yoshida, and Ochiai [OYO17] designed an HMD that has a sufficient field of view even when it is filled with water. The device was tested with five volunteers, each of which swam with a water-tight HMD and the custom HMD that allowed water inside it. The participants reported higher satisfaction in field of view and ease of head movement when using the custom HMD.

A wired HMD for use in underwater VR was created by Hatsushika, Nagata, and Hashimoto [HNH18]. The HMD uses the Oculus Rift DK2 in a custom waterproof housing to keep the water from destroying the HMD's electronics. No blurring of the image or water ingress was found during testing. However, the usability of the system was not tested.

2.2. Tracking Robots Underwater

The majority of underwater tracking research has been conducted in automating robots for underwater applications. However, there has been minimal research that has investigated the use of underwater tracking techniques for user interaction in VR. This is the focus of our work.

Couiten et al. [CDD*12] explored the use of tele-operated underwater vehicles as combined with AR. In this application, the user remotely controls an underwater robot through a web-based graphical user interface. The robot has a camera on board and is tethered to a control box above water, which facilitates remote communication and streaming the live video over the internet. While this work does not focus on putting users in a real underwater environment, it does mention testing several optical tracking techniques for AR in a real underwater environment. The first was contextual scene augmenting, which did not track specific objects but rather used the internal sensors of the robot to augment the scene with fish for decorative reasons. Second they tried affixing markers to buoys. The third was natural feature tracking. The authors showed pictures of the marker tracking and contextual augmentation. Future work includes an evaluation of these tracking techniques and usability.

Lee et al. [LKK*12] created a system that used cameras to detect objects in an underwater environment. Due to the several limits in visual tracking, this work created ways to improve the usability of the data obtained through cameras. Through color restoration, the ability of the system to detect objects in the water was increased by ten percent. Their future goals include improving the performance of their color restoration and develop an autonomous navigation method in natural underwater environments.

Sakagami and Choi [SC16] developed a method of stationary object tracking by combining different sensors: visual, inertial, and magnetic. By combining the data from the different sensors, objects were tracked even when outside the view of the camera. While tracking accuracy was far greater inside the camera view, it was still reasonably accurate.

DeMarco et al. [DWH13] used a high-frequency sonar system to track a human diver. The system converted the sonar data into a gray scale 2D image for processing. Using Hidden Markov Models, they successfully classifying image clusters as a diver with a high success rate. Future work includes further refinements to allow for the sensors to be moving along with the tracked diver.

3. Optical Tracking for Underwater VR - Preliminary Experiments

To investigate the best approaches for optical tracking underwater, we performed several informal experiments with a Microsoft Kinect 360, a Naturalpoint OptiTrack motion capture system, and fiducial marker tracking (i.e. Vuforia) in a swimming pool.

To test these approaches underwater, we used a small aquarium to keep the devices dry and sank half of the aquarium into the swimming pool. We attempted to minimize the distance between the glass of the aquarium and cameras of the devices to have minimum reflections from the glass. We firstly tested the Microsoft Kinect 360. We pointed the Kinect to the front and bottom of the tank, with the bottom giving marginally better results. Although we could identify the shape of the objects seen from the Kinect camera within about one and a half meters, we still could not get the skeleton identified or calibrated.

Then we tried an infrared approach with an OptiTrack Naturalpoint Camera. We expected that the OptiTrack would yield better results underwater than the kinect as the intensity of the infrared of the OptiTrack camera could be adjusted. However, using a trackable object with three passive retro-reflective balls, the observation range was about half a meter from both the front and bottom directions. Lowering the infrared intensity of the camera and using another trackable object with 3 active infrared LED lights, the observation range extended to approximately 1.5 meters from both the front and bottom sides.

Lastly, we experimented with a fiducial marker tracking system on board a waterproof phone - Vuforia. Similar to previous reports by Oppermann et al. [OBLS13], we found that the visible light optical tracking did indeed work. However, it was slightly less effective than fiducial marker tracking above water and was subject to the same line of sight and environmental lighting limitations. Thus, we expect that using a visible light optical tracking approach would work effectively if implemented with clusters of track points similar - e.g., Optitrack's approach but with visible light. However, to our knowledge, there are no commercially available, off the shelf systems that meet this need.

4. Quantitative Comparison of Magnetic and IMU Underwater Tracking Approaches

Due to the limitations of optical tracking, we aimed to evaluate Inertial Measurement Unit (IMU) tracked interfaces and magnetically tracked interfaces in an underwater environment. Based on preliminary studies, IMUs seemed to work effectively for orientation tracking underwater. Thus, we compared magnetic orientation tracking (i.e., a waterproofed Razer Hydra) to waterproof phone IMUs as a reference both above and below water.

4.1. Apparatus

The apparatus to test the tracking accuracy of the two approaches consists of a rod, Razer Hydra, Samsung Galaxy S4, and Sony Xperia ZR (Figure 1). A laptop is used to log data from the Razer Hydra while the phones log their own data. The Razer Hydra is a consumer game controller that uses magnetic tracking for position and rotation [Raz]. The controllers are covered in silicone putty for waterproofing purposes. The Galaxy S4 is in a waterproof case and the Xperia ZR is manufactured to be waterproof.

4.2. Procedure

In order to compare the accuracy of the different devices both in and out of the water, the devices were securely attached to the rod using several rubber bands. The logging system was first turned on and then the apparatus was manually randomly rotated around its center as one Hydra controller and one phone are underwater and the other Hydra controller and phone are above water (Figure 2).

Figure 1: *The apparatus has a Razer Hydra controller on each end with the Sony Xperia ZR on the right and and the Samsung Galaxy S4 on the left.*

In our experiment, we performed 6 trials of movement for approximately one minute each trial. Between trials the system was reset so as to minimize the effect of IMU drift.

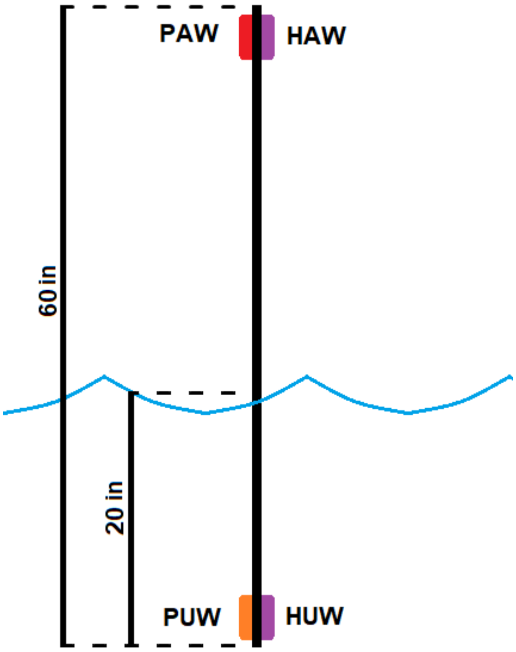

Figure 2: *A diagram of the study setup with the different components labeled. Components include the Hydra Above Water (HAW), Hydra Under Water (HUW), Phone Above Water (PAW), and Phone Under Water (PUW).*

4.3. Analysis

To analyze the data, we followed the methodology described in Sessa et al. [SZL*13]. First, the axes data were manually aligned due to the differing default alignments of the devices. Then, a base offset was computed and applied to align the orientations. Once the alignments were done, the Phone Under Water (PUW) was dynamically time warped in relation to the Phone Above Water (PAW) using the statistics package R. The time warp aligns the data points so that any differences based on network or capture time latency minimally affect the error comparison calculations (Figure 3). The Hydra Under Water (HUW) and Hydra Above Water (HAW) were connected to the laptop and recorded at the same time, which means no time warp was required (Figure 4). Finally, we computed the quaternion distance to analyze the differences in rotation between the devices. We present the root mean square (RMS) of the quaternion distances.

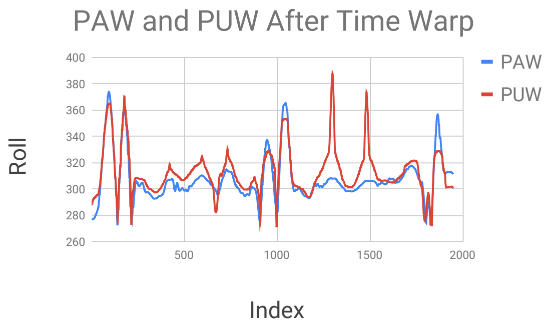

Figure 3: *Time warping aligns the data due to the differing recording times. Index is the*

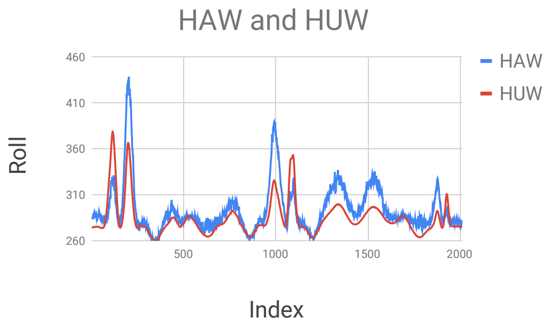

Figure 4: *The Hydra controllers are wired to the computer and thus record at the same time, requiring no time warping.*

4.4. Results

The differences in the rotation of the devices are calculated with a RMS and are shown in Table 1. The two hydras were mostly consistent with each other, with less than 10 degrees of rotation difference. The two phones were slightly more consistent, at just under 9 degrees.

Table 1: *RMS of the quaternion distances.*

	RMS (degrees)
HAW-HUW	9.839
PAW-PUW	8.991

5. Discussion and Conclusion

Based on the relatively low RMS error of the HAW - HUW and PAW - PUW, orientation from both the IMU and the magnetic sensor seem to be minimally affected by water. The RMS data we collected in this experiment is similar to pilot experiments we performed to determine baseline RMS.

In this paper, we presented our studies on finding the most effective tracking system underwater. Infra-red optical trackers do not track effectively underwater. Visible light fiducial marker systems seem to work slightly worse than they do on land. IMUs and magnetic tracking system work well in water. However, the magnetic system is not affected by orientation drift and is thus our recommended underwater VR tracking approach.

For our current studies, we were limited to a short range of motion due to the Razer Hydra requiring a wired connection. Our future goals are to evaluate other tracking systems, such as acoustic tracking, and study the effects on user interaction underwater.

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