Immersive Terrestrial Scuba Diving Using Virtual Reality

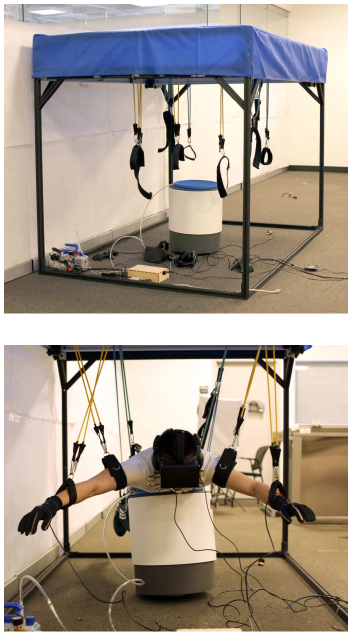

Figure 1. Amphibian is an immersive virtual reality system that enables people to experience ocean SCUBA diving in a convenient terrestrial setting. Images above show (a) the Prototype II suspension frame and (b) a user suspended in the harness, as needed for experiencing Amphibian.

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Abstract
SCUBA diving as a sport has enabled people to explore the magnificent ocean diversity of beautiful corals, striking fish, and mysterious wrecks. However, only a small number of people are able to experience these wonders as diving is expensive, mentally and physically challenging, needs a large time investment, and requires access to large bodies of water. Most existing SCUBA diving simulations in VR are limited to visual and aural displays. We propose a virtual reality system, Amphibian that provides an immersive SCUBA diving experience through a convenient terrestrial simulator. Users lie on their torso on a motion platform with their outstretched arms and legs placed in a suspended harness. Users receive visual and aural feedback through the Oculus Rift head-mounted display and a pair of headphones. Additionally, we simulate buoyancy, drag, and temperature changes through various sensors. Preliminary deployment shows that the system has potential to offer a high degree of presence in VR.

ACM Classification Keywords
H.5.1. Information interfaces and presentation (e.g., HCI): Multimedia Information Systems—Artificial, *augmented, and virtual realities.*

Introduction

Oceans are home to more biodiversity than anywhere else on the planet [1]. Fortunately, recreational diving or sport diving has enabled people to explore oceans for purposes of leisure and enjoyment. Although modern equipment and training have made diving relatively safe, divers are exposed to numerous psychosocial and physiological risks [6,11]. Additionally, diving is an expensive and time-consuming hobby. To overcome these limitations, we have designed our diving simulator to be as immersive as possible, recreating the feeling of being underwater by including elements such as buoyancy, temperature and more. We have attempted to go beyond visual and aural feedback, which are the most common aspects of currently available VR diving simulations.

A few examples in research have attempted to build realistic diving simulators by asking users to swim in a pool or be immersed in a tank full of water. Though this makes the diving simulation feel more realistic, we believe it is not as accessible as our system which is a fully terrestrial, water-free simulator. Unlike common diving simulators, Amphibian users do not control their swimming motion with a joystick or mouse. Instead they intuitively move their arms and legs as they would while swimming in the real world to propel themselves through virtual waters. This is made possible with the user lying face down, resting their torso on a motion platform with their arms and legs placed in a suspended harness. An Oculus Rift head-mounted display is used to provide visual and audio feedback. Peltier modules attached to the user's wrists simulate temperature changes. An inflatable airbag placed under the user's torso allows them to move up and down with their breathing. Users also wear gloves with embedded flex sensors and IMUs that track their hand movements to allow swimming in the virtual underwater environment.

Background and Related Work

We provide some background on the terms *immersion* and *presence* as distinguished by Slater and Wilbur. Immersion describes the extent to which the computer displays are capable of delivering an inclusive, extensive, surrounding and vivid illusion of reality to the senses of a human participant. *Inclusive* indicates the degree to which physical reality is shut out. *Extensive* indicates the range of sensory modalities accommodated. *Surrounding* signifies the extent to which this virtual reality is panoramic rather than limited to a narrow field. *Vivid* indicates the resolution, fidelity, and variety of energy simulated within a particular modality (for example, the visual and color resolution) [9].

Presence is a user's response to an immersive system. It includes three aspects: a sense of "being there", the extent to which the virtual environment takes precedence over the real one, and the way users refer to their experience as having been to a "place" vs having seen a place [*ibid*]. Presence is an increasing function of immersion. For example, a system that accommodates multiple sensory modalities (extensive) will increase the user's sense of "being there".

Scuba Diving Simulations

There are many PC games that simulate maritime environments [12–14] usually including navigation through interactive marine wildlife, shipwrecks, rocks, caves etc. Though the visuals and graphics of these games are compelling—inspiring the visuals in our

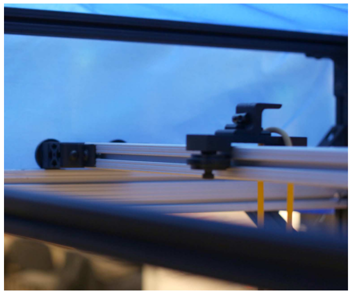

Figure 2. Horizontal sliders move in the XY plane as the user moves their arms to mimic a swimming gesture. The sliders are attached to resistance bands (in yellow), which are attached to user's arms and legs to simulate drag forces. Neoprene sleeve attachments are used to distribute forces uniformly on the user's limbs.

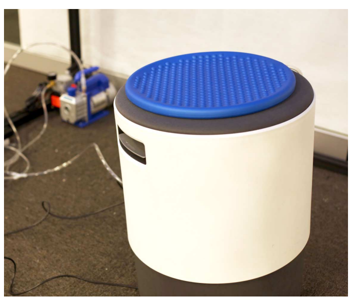

Figure 3. Inflatable cushion that rises and falls in sync with the user's breathing, while their torso rests on it.

system—the games are designed to primarily stimulate the visual and auditory human senses. A more immersive simulation would need to include other senses like kinesthetic or temperature to better recreate the feeling of being under water.

Frohlich [5] and Takala et al. [10] enclose the user in a room and project 3D images of the marine world onto the walls to create an *inclusive* cave-like simulation system. In Slater's terms, such environments are more inclusive than PC games, as they completely enclose the users in a virtual world. However, more human senses can be targeted to make simulations more *extensive*, like in Amphibian. For instance, in Takala et al's simulation, the user stands on the ground and wears gesture detection gloves whereas in Amphibian, the user rests their torso on a platform with their arms and legs suspended in a harness system, mimicking the swimming posture more closely.

There are also systems that immerse users in a pool or a tank of water to simulate the experience of being in the ocean. For instance, Blum et al. used augmented reality and a waterproof head-mounted display to visually enhance a regular swimming pool with virtual maritime objects displayed on a mobile PC device mounted in front of a diving mask [2]. Similarly, AquaCAVE is a computer-augmented water tank with rear-projection acrylic walls that surround a swimmer, providing a cave-like immersive stereoscopic projection environment [15]. These systems feel realistic because the user is actually immersed in water, something that is difficult to simulate on land. In Amphibian, we create a feeling of being immersed in water, in a terrestrial setting, by using various methods and targeting multiple senses as described below.

Virtual Reality Suspension Systems

Structurally, our system has elements similar to those in Birdly [8], Swimming Across the Pacific (SAP) [4], and Haptic Turk [3]. Birdly is an art installation that simulates flying using an Oculus Rift headset paired with an inverted massage chair like surface and a fan for creating a wind effect, providing a full-body VR experience. The user mimics a bird by resting their torso on the chair with their arms stretched out and resting on a plastic hand-rest with buttons for starting or stopping flight. Users navigate by using their arms and hands, while the Oculus Rift displays a bird's-eye view of their virtual surroundings.

SAP is another artistic installation that simulates swimming. It suspends the user in an 8ft cubic volume via a hang gliding harness. The pulleys and cords provide counter forces to the user's movement simulating drag forces. The graphic system renders the virtual swimmer and the scenery. Preliminary user experiences suggested that the system was capable of providing realistic swimming sensations.

Haptic Turk uses humans known as 'turkers' to create physical motion for the person wearing an HMD. These 'turkers' manually lift a person and tilt or push the player's limbs or torso to provide haptic feedback.

System Design

The objective of this work is to recreate the sensations and physical conditions of SCUBA diving in a convenient terrestrial setting. We built two prototypes of our system, and describe the preliminary evaluation of Prototype I in the section below. Due to space constraints, we only describe the design and implementation of Prototype II which derives from

Figure 4. Mouth piece with Sensirion gas flow sensor [20] that measures the amount of air inhaled and exhaled by the user.

lessons learned during the preliminary deployment of Prototype I.

One of the authors is a SCUBA diver. This allowed us to better understand sensory distortions experienced while in the ocean. Due to differences in reflectivity, light transmission and varied magnification, we experience poor contrast, severely reduced visual range and impaired object magnification. Additionally, our hearing underwater is quite distorted. Sound travels five times faster in water than in air. As a result, we cannot localize sound effectively underwater. Our other senses are also severely muted. We cannot smell at all underwater and we avoid tasting things. Our sense of touch is considerably reduced since water causes fingertips to prune, thereby reducing sensitivity [16].

Other sensory modalities like thermoception (sense of temperature), equilibrioception (sense of balance), and proprioception (sense of kinesthesia) are relatively unaltered, but are nevertheless stimulated. For instance, in the underwater environment, divers move freely in the 3D space, while using their breath to rise and fall slightly and balance themselves. Divers also feel a noticeable decrease in temperature as they go deeper in the water [17].

Since there is so much more to the experience of being underwater than just visual feedback, we designed our system to incorporate five different sensations, namely – opthalmoception (sight), audioception (hearing), proprioception (kinesthetic sense), thermoception (temperature), and equilibrioception (balance). Out of these senses, prior VR research SCUBA simulations have not focused much on proprioception and thermoception and therefore we discuss those in a little more detail than the others.

Proprioception (Kinesthesia)
The final design of the suspension system was a culmination of input from the first author's personal experience with SCUBA diving, feedback from the preliminary evaluation of Prototype I and inspiration from the suspension systems of Birdly and SAP as discussed in the Related Work section.

Prototype II has a robust and smoothly moving structure, assembled with 80/20 beams and roller wheels [18] (Figure 1a). For the design of the harness, we considered two forces exerted by water on the submerged human body – buoyant forces, which provide counter effect to gravity, and drag forces, which restrict voluntary motion. We attach resistance bands to the user's limbs to counter motion and simulate drag forces (Figure 1b, 2). To simulate buoyant forces, we use a Turnstone buoy stool as torso support [19]. The buoy has a vertical damping effect that feels buoyant when the user lies on it. It also provides unrestricted swivel in 3D space.

Besides limb motion, SCUBA diving relies heavily on breathing for buoyancy control. To simulate that, we implemented breath motion in our system. By attaching an accurate gas flow sensor (Sensirion) [20] to the user's mouth piece, we measure the amount of air inhaled and exhaled (Figure 4). The torso rest contains an inflatable cushion that is connected to an air and vacuum pump (Figure 3). This cushion inflates and deflates proportionally to the air inhaled/ exhaled by the user. This causes the user's body to rise up and fall down in sync with their breathing, similar to how it

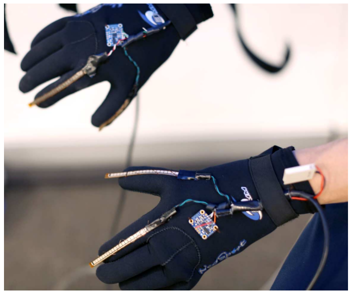

Figure 5. Gloves worn by the user. Each glove contains (a) an accelerometer, to track the user's hand position, (b) flex sensors, to track finger movements, and (c) a Peltier module, to simulate temperature change.

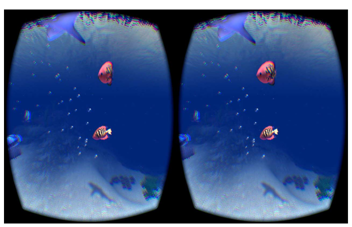

Figure 6. A scene from the Oculus Rift application showing fish and a sandy ocean bed with aquatic plants.

happens in water. The breath sensor also causes the appearance of air bubbles in the Oculus Rift display.

Thermoception (Temperature)
Real oceans have thermoclines which cause the temperature to decrease at certain depths from the sea surface [17]. Since the Oculus Rift app allows the user to dive deep, we simulated temperature changes using Peltier thermoelectric cooler module [21]. Additionally, we added cool gel packs to the neoprene bands described earlier to enhance the overall coldness sensation. Studies show that local cold on the wrist can give a body-wide sensation of coolness due to the radial artery being close to the skin's surface [7]. Since the user already needed to wear gloves, we decided to attach one Peltier module to each glove's wrist to simulate fall in temperature with depth (Figure 5).

Audio-visual
We use a custom version of an application downloaded from the Oculus app store [22] with full permission to modify it by the developer. In the app, the user swims in a confined area underwater with rocky topography that changes with depth. The ocean simulation also contains a variety of aquatic plants, schools of small fish, and two big fish that appear randomly during the user's exploration (Figure 6). The addition of these elements was inspired by various SCUBA diving games mentioned earlier in Related Work. Similar to real-life diving, our app is dimly lit to simulate reduced visual range, a characteristic of the real diving environment. The sound is also tuned to the underwater environment. Particularly significant is the loud sound of user's air bubbles. The noise-cancelling headphones ensure the user's presence in the simulation by shutting out sounds from the real world.

The user's hands are tracked using gloves that contain an accelerometer and flex sensors (Figure 5). The accelerometers detect the swim gestures and move the player in the Oculus Rift app. The flex sensors track the bend in a user's fingers and simulate that in the app.

Preliminary deployment

To garner feedback, we designed an initial prototype of our system (Prototype I) and deployed it in our lab space. This prototype had a small wooden rig for suspending the bands where the user's arms and legs rested (Figure 7). The custom-built torso consisted of three large springs on a wooden base and was topped with a water bed (see Figure). There were no gloves used. Instead, we attached an accelerometer to the user's wrist to get preliminary hand position data. Breathing based buoyancy control and temperature simulation were not implemented in Prototype I.

We deployed the system in our open lab space for people to experience it during the lab's semi-annual open house. A total of 36 participants tried our system, for a duration of approximately 10 minutes each (Figure 8). In general, reactions were positive. Most people appreciated being able to feel buoyant and navigate underwater. Some people remarked that the combination of the waterbed with the 6DOF torso base made them feel weightless as they swam through the VR application. A primary concern that emerged from the feedback was the restricted arm movement. This was due to the small size of the wooden harness system and we changed that for Prototype II. Additionally, the swimming gesture was not smooth as the wooden sliders attached to the suspension bands had a lot of friction. This was indeed a limitation since being underwater is effortlessly elegant with gliding

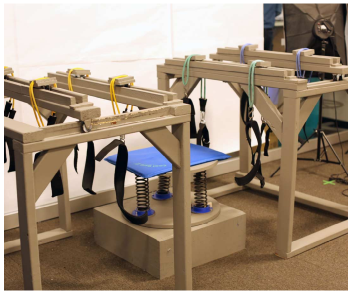

Figure 7. Amphibian Prototype I consisting of a smaller wooden rig and a spring torso rest.

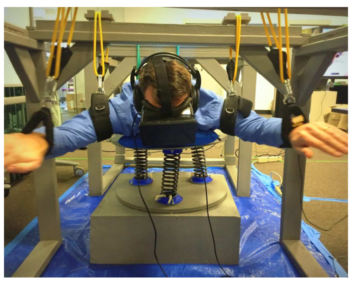

Figure 8. A user wearing an Oculus Rift, with their torso resting on a wooden base and their arms and legs suspended from the wooden frame, experiencing Prototype I during preliminary deployment.

movements. Another concern we resolved in Prototype II was related to increased horizontal swivel of the torso that was missing in the first prototype. The suggestion to connect breathing and buoyancy came from two divers who tried our prototype.

Discussion and Contribution

As described in the Background section, we use the terms *immersion* and *presence* as distinguished by Slater & Wilbur with immersion being a description of a technology and the extent to which it can deliver a vivid illusion of reality to the senses, and presence being a user's response to an immersive system [21].

To increase the immersion of our system, we design for a range of senses, namely the sense of sight, hearing, kinesthetic sense, temperature and balance (*Extensive*). The user rests horizontally on a swiveling torso support with their arms and legs suspended in a harness system. They wear an Oculus Rift and noise cancelling headphones that provide panoramic visuals and vivid sounds from the underwater environment (*Surrounding*). This helps to keep the user engaged and away from the visual and auditory cues from reality (*Inclusive*). The fidelity and resolution of the visual simulation, high quality audio, the wide range of movements supported by the suspension system, and temperature simulation provide a vivid representation of the underwater world (*Vivid*).

A potential application of our system is training people to scuba dive before they go diving in the ocean, in addition to training in swimming pools. For a training system, a high degree of presence is crucial as argued by Slater and Wilbur. A higher sense of presence means a higher chance that participants will behave in a virtual environment in a manner similar to their behavior in a similar real world environment [9]. We see other applications in education, exploration, and meditation. Our system stimulates various senses and has the potential of offering a high degree of presence to the user. This is, to some extent, also corroborated with our preliminary deployment. For example, some divers said they were able to feel buoyant and weightless like real scuba diving even with Prototype I. We have high-hopes for our much-improved Prototype II and are targeting rigorous user studies for evaluation. Apart from asking the user about their experience of "being" in the virtual world, we will also objectively compare the user's behavior in the virtual world with real-life scuba diving. Due to the addition of the breathing and temperature stimulations and a much improved suspension system, we hypothesize that the system can provide an increased sense of presence.

Conclusion

We described the design and implementation of a virtual reality scuba diving simulator. Compared to the common VR diving simulators that mostly include visual and auditory simulations, our system is highly immersive since it incorporates a range of other senses, namely, kinesthetic sense (propriocetion), temperature (thermoception) and balance (equilibrioception). In the future, we plan to rigorously evaluate Prototype II and implement applications like a scuba diving training system, an exploratory adventure in uncharted territories, and an educational experience, that can, for example, teach how to identify fish, or create awareness about ocean environmental damage by incorporating visuals from real life.

Acknowledgements

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References

[1] Sinauer Associates. Where Is the World's Biological Diversity Found? http://www.sinauer.com/media/wysiwyg/samples/PrimackEssentials5e_Ch03.pdf

[2] Lisa Blum, Wolfgang Broll, and Stefan Müller. 2009. Augmented reality under water. *SIGGRAPH '09: Posters on - SIGGRAPH '09*, ACM Press, 1–1.

[3] Lung-Pan Cheng, Patrick Lühne, Pedro Lopes, Christoph Sterz, and Patrick Baudisch. 2014. Haptic turk. *Proceedings of the 32nd annual ACM conference on Human factors in computing systems - CHI '14*, ACM Press, 3463–3472.

[4] S. Fels, Y. Kinoshita, Y. Takama, et al. 2005. Swimming across the Pacific: a VR swimming interface. *IEEE Computer Graphics and Applications* 25, 1: 24–31.

[5] Torsten Fröhlich. 2000. The virtual oceanarium. *Communications of the ACM* 43, 7: 94–101.

[6] D Z H Levett and I L Millar. 2008. Bubble trouble: a review of diving physiology and disease. *Postgraduate Medical Journal* 84, 997: 571–578.

[7] S D Livingstone, R W Nolan, and S W Cattroll. 1989. Heat loss caused by immersing the hands in water. *Aviation, space, and environmental medicine* 60, 12: 1166–71.

[8] Max Rheiner. 2014. Birdly an attempt to fly. *ACM SIGGRAPH 2014 Emerging Technologies on - SIGGRAPH '14*, ACM Press, 1–1.

[9] Mel Slater and Sylvia Wilbur. 1997. A Framework for Immersive Virtual Environments (FIVE): Speculations on the Role of Presence in Virtual Environments. *Presence: Teleoperators and Virtual Environments* 6, 6: 603–616.

[10] and Tapio Lokki. Takala, Tapio, Lauri Savioja. 2005. Swimming in a Virtual Aquarium. https://mediatech.aalto.fi/~ktlokki/Publs/va_2005.pdf

[11] Report on decompression illness, diving fatalities and project diver exploration. https://www.diversalertnetwork.org/medical/report/2005DCIReport.pdf

[12] World of Diving. http://divegame.net/

[13] Infinite Scuba. https://www.infinitescuba.com/

[14] Depth Hunter 2. http://store.steampowered.com/app/248530/

[15] AquaCAVE: Augmented Swimming Environment with Immersive Surround-Screen Virtual Reality. http://lab.rekimoto.org/projects/aquacave/

[16] Challenges of Sensing in Water. http://www.elasmo-research.org/education/white_shark/challenges.htm

[17] Temperature of Ocean Water - Windows to the Universe. http://www.windows2universe.org/earth/Water/temp.html

[18] 80/20 Inc. - Home Page. https://www.8020.net/

[19] Buoy Modern Office Chairs & Seating | Steelcase Store. http://store.steelcase.com/seating/lounge/buoy

[20] Low-Pressure-Drop Mass Flow Meter SFM3000. http://www.sensirion.com/en/products/mass-flow-meters-for-gases/mass-flow-meter-sfm3000/

[21] Peltier Thermo-Electric Cooler Module: Adafruit Industries. https://www.adafruit.com/products/1330

[22] Ocean Rift. http://ocean-rift.com/