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Master's Thesis
Academic Year 2023

Blind Diver: Prototyping an Underwater Haptic Navigation Device for Public Safety Divers

Keio University
Graduate School of Media Design

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A Master's Thesis
submitted to Keio University Graduate School of Media Design
in partial fulfillment of the requirements for the degree of
Master of Media Design

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Abstract of Master's Thesis of Academic Year 2023

Blind Diver: Prototyping an Underwater Haptic Navigation Device for Public Safety Divers

Category: Science / Engineering

Summary

Professional divers such as public safety, rescue, cave, and police tech divers find themselves often working in murky, high-turbidity aqueous environments. Those challenging frontiers oftentimes are the scenes of rescue missions, key evidence recovery, and new scientific discoveries. Working under those harsh conditions requires specialized training and despite rigorous safety protocols it remains to be a risky profession. Some of the main risks are disorientation, entanglement, injury as a result of a collision with an unseen object, and running out of gas as a result of a prolonged stay underwater in an attempt to orientate oneself. Therefore, the main focus of this research thesis is to prototype an assistive device for underwater navigation for specialized divers. The main contributions of the following thesis are (1) a Systematic review of navigation technology for recreational and commercial diving (2)a Proposal of a haptic-sonar navigation module that can be integrated with a diving suit. (3) Conducting experiments aiming at assessing the potential strengths and drawbacks of the proposed haptic technology in marine environments.

Keywords:

underwater navigation, haptics, diver technology design, workshop

Keio University Graduate School of Media Design

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Chapter 1

Introduction

Technical scuba diving and public safety diving are two branches of underwater activities that are indispensable for recovering evidence for criminal investigations, repair of key underwater infrastructure, and removal of biohazards from aqueous environments. However, underwater navigation in turbid environments, such as murky lakes or rivers, can be a challenging task for professional divers. Low visibility conditions can make it difficult to orient oneself, locate landmarks, and follow established routes [1]. Current surface state of art navigation systems, such as GPS and compass, can be unreliable in these conditions [2]. Furthermore, the underwater navigation technology advances in recent years have been limited and most research funding was granted for autonomous vehicle navigation projects rather than for public safety diver navigation systems [3]. Therefore, there is a need to explore new navigation technologies that can help divers navigate safely in turbid environments.

1.1. Background and motivation

The motivation for the proposed research in diver navigation systems is twofold: personal and scientific. Given the author's academic background in software and electronics engineering, as well as licensure as a PADI scuba diver, the primary personal motivation is to explore new frontiers in electronic technology design in extreme environments. The scientific motivation is to establish an understanding of diver navigation system preference as well as investigate the usability of competing assistive technologies (artificial muscle and haptic technology) in aquatic environments.

Therefore the research goals of this project will be the following:

- Understand navigation challenges, practices, and preferences
- Identify a gap in diver navigation technology
- Develop and test competing navigation systems addressing the gap

The proposed study aims to answer the following research question:

“What is the utility of assistive technology for divers in terms of improving navigation and enhancing safety in high turbidity marine environments?”.

Underwater navigation plays a critical role in various diving activities, including scientific research and public safety operations. Therefore by answering the research question the proposed research aims to establish a better understanding of diver preferences and outline guidelines for marine personal navigation technology inventors. To ensure familiarity with the subject studies the author of this research has herself conducted 30 dives with various dive teams in Japan and Korea and obtained the following PADI license training: Open Water, Advanced Open Water, Deep diving, Dry suit diving, Nitrox diving, Peak Buoyancy, and Rescue diving.

1.2. Problem Statement

This paper presents a comprehensive review of navigation technology for recreational and public safety diving. By analyzing current navigation systems and their limitations, the study provides new insights into the needs and challenges of navigating in marine environments. Building on this review, the author surveys professional divers regarding their navigation practices and a gap in navigation technology. The proposed research aims at developing a prototype of an assistive electronic technology aiming at increasing diver safety that does not exist on the market and is constructed based on direct diver feedback and needs.

1.3. Thesis Structure

This thesis has a structured layout that is divided into several sections. The first two Chapters outline the Related Works, as well as the state of the art of the relevant technologies. Chapter 3 focuses on describing iterations of the prototype based on direct professional diver feedback. Chapter 4 and 5 outline the observations from dry and marine environment tests and draw conclusions based on the interactions with the study participants. It is important to understand the chronology of individual steps of the proposed research, as the prototyping and validation steps took place iteratively throughout the project. Furthermore, an additional literature review was conducted based on diver preferences. Therefore, although it cannot be seen in the structure of the Chapters of this written work, each step was repeated multiple times when new insights were learned about the preferences of the target audience.

- **Chapter 1: Introduction** outlines the research goals and presents the research question
- **Chapter 2: Literature Review**, provides an overview of navigation technology and capabilities of electronic technology at high atmospheric pressures
- **Chapter 3: Prototype**, presents the design and development of the haptic suit prototype as well as the competing artificial muscle design, specifically focusing on the perception and actuation mechanisms.
- **Chapter 4: Validation**, focuses on the validation of the developed navigation systems by conducting testing in both dry and marine environments. Although the Validation section appears after the Prototype in this written work, those two steps took place iteratively throughout this research project.
- **Chapter 5: Conclusion**, outlines the research findings and limitations and proposed the next steps for this research.

1.4. Thesis chronology

The initial phase involved conducting a literature review, which spanned from February 2022 to October 2022. During this time, multiple literature review activities took place, and ”Digital Underwater Acoustic Communications” by Lufen Xu and Tianzeng Xu was selected as a primary source regarding underwater communication. Simultaneously, we published a paper on Augmented Humans in March 2022. In April 2022, a diver preference survey was conducted to gather valuable insights. Following that, we focused on prototyping the haptic-sonar unit, which took place from April 2022 to July 2022. In 2023, the project continued with Workshop 1 in March and the publication of the CHI 2023 SRC paper in April. Tank tests were performed in April, followed by Workshop 2 in May. Additionally, PADI training sessions were conducted intermittently throughout the project timeline, with sessions occurring in February, April, August, and April again in 2023 to ensure continuous contact with the target audience. The provided chart visualizes these project activities and their corresponding durations.

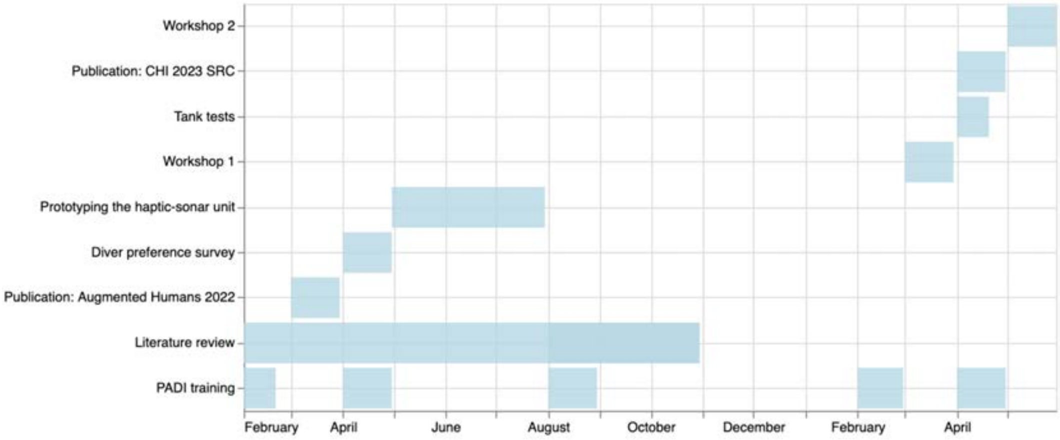


Table 1.1: Research timeline

Chapter 2

Related Works

2.1. Diving navigation practices

Diving is a high-risk activity relying on constant life-support equipment. Divers navigate underwater using a variety of techniques and assistive technologies, including the use of underwater compasses, dive computers, visual cues, underwater signaling lights, reels, and surface marker buoys [4]. One of the primary tools for underwater navigation is the underwater compass, which uses magnetic fields of the Earth and North reference to determine the heading which is not affected by the higher atmospheric pressure [5]. Dive computers are another important tool for underwater navigation and safety maintenance. Even most simple dive computers provide information regarding depth, time spent underwater, and the required safety stops, which are mandatory pauses a diver needs to make during an ascent to allow the nitrogen absorbed by the body during the dive to dissolve [6]. More advanced dive computers also include a built-in compass and can be programmed with dive plans, allowing divers to navigate to specific depths and locations [7]. Another technique that divers use is visual cue navigation, which involves using natural and man-made landmarks as well as at the shallower depths of the shadow that the diver marks on the sea bed [8]. Under high turbidity conditions divers tend to turn to strong Canister Lights, which use halogen and LED light and can operate longer [9]. Reels in combination with reel markings are an indispensable tool for cave diving. Despite a high risk of entanglement reels are still an important navigation tool in complex cave systems to mark exit and entrance way. Finally, in open water environment divers use a technique called “kick cycles“ to navigate. This is a method of counting kick cycles (the number of times a fin makes a full motion returning to the initial position) to estimate the distance traveled and maintain a straight line. This method is not as accurate as the others but can be used as a backup [10]. It's important to note that underwater navigation requires training and experience, and divers should always dive with a buddy and follow proper dive planning and safety protocols [7].

2.1.1 Safety Considerations when Diving

Safety considerations are of paramount importance in the field of diving, given the inherent risks associated with exploring the underwater environment. Divers must be cognizant of various factors to ensure their well-being and minimize potential hazards. There main kinds of risks that divers face under water, some of them being: health risk, equipment failure, barotrauma (such as ear and sinus squeeze), marine life encounters (for instance stings or bites), and entanglement in underwater structures or marine debris [11]. A very common risk associated with diving is decompression sickness (DCS), often referred to as "the bends." This occurs when dissolved gases, such as nitrogen, come out of solution and form bubbles within the body's tissues and bloodstream during ascent. To prevent DCS, divers must follow established decompression tables or use dive computers to calculate appropriate ascent rates and decompression stops [11]. Another significant risk is arterial gas embolism (AGE), which can result from breath-holding during ascent or rapid ascents without proper decompression. This occurs when air enters the bloodstream and can lead to serious complications, including stroke and organ damage. To mitigate this risk, divers must maintain proper breathing techniques and ascend at a controlled rate while exhaling continuously. To mitigate equipment failure risk, making regular inspections and maintenance of dive gear essential. Lastly, proper buoyancy control and spatial awareness are crucial to avoid entanglement and navigation hazards, such as strong currents or overhead environments [12].

2.1.2 Public Safety and Rescue Diving Navigation

Public Safety and Rescue Diving are two highly specialized types of professional divers who are trained with respect to life threatening situation handling, recovering artifacts and navigating in zero visibility circumstances with often times hazardous materials in the water. Public Safety divers work predominantly using dry suits and re-breather tanks that eliminate completely body contact with water, whereas the rescue divers work under various conditions including dry and wet suit [13]. In Public safety diving non-visual navigation techniques play a crucial role. In challenging underwater environments, where limited visibility often impedes visual navigation, relying solely on sight can be impractical and potentially dangerous. Therefore, divers must utilize alternative methods to navigate and maneuver effectively in these situations. A commonly employed non-visual navigation technique is the use of palm tactile sensing by touching the ocean bottom. Additionally, underwater acoustic communication systems can transmit audio signals that are specifically designed for underwater environments, enabling divers to receive instructions or relay information to surface support teams. Moreover, military divers use inertial navigation systems (INS) to estimate their position and movement underwater [14]. INS utilizes sensors to measure accelerations, angular velocities, and magnetic fields, allowing divers to calculate their position based on changes in these parameters. By integrating data from multiple sensors, INS provides divers with real-time information about their spatial orientation and movement, enhancing their ability to navigate and navigate safely in complex underwater environments. The downside of this system is it's limited availability and high cost. By utilizing these systems and techniques, divers can navigate with more precision, maintain proximity to specific locations. It is worth mentioning that often times in complex underwater missions a combination of various technologies is preferred and redundancy in equipment is desired for safety purposes [13].

2.2. Signal processing underwater

Water similarly to air is a medium through which various signals can pass and be used for communication. Acoustic, electromagnetic, optical signals and cables are most commonly used for underwater and surface-underwater communication. The following sections introduce briefly the advantages and shortcomings of each signal processing technology.

2.2.1 Acoustic signal processing

Acoustic signals, or sound waves, are commonly used in underwater communication and navigation. One method of underwater communication is sonar, which stands for sound navigation and ranging. Sonar works by emitting sound waves into the water and detecting the echoes that bounce back. The echoes are then translated into electrical signals that can be analyzed to determine the distance and location of objects. Sonar works by converting acoustic pressure to an electric voltage [15]. Acoustic signals are effective in water due to the low attenuation, or absorption, of sound waves compared to electromagnetic waves. This means that sound waves can travel long distances in water and are effective in depths. However, the propagation of sound waves in water can be affected by various factors such as water temperature, salinity, and other environmental conditions. Shallow water thermocline and surface ambient noise can also disturb the transmission of sound waves. In addition, multi-path propagation can occur due to the reflection and refraction of sound waves in the water. This can result in the detection of multiple echoes and make it difficult to determine the true location of an object. The speed of sound in water is also relatively low, at around 1,500 meters per second (m/s) in seawater and 1,480 m/s in freshwater [16]. This means that the transmission of sound waves in water is slower compared to the transmission of electromagnetic waves in air or vacuum. Furthermore, the frequency band of acoustic signals is limited due to the properties of water. Low-frequency signals can travel farther but are more susceptible to attenuation and environmental interference. High-frequency signals can be more easily absorbed and scattered by water molecules and other objects in the water. Therefore, the choice of the frequency bands for underwater communication and navigation is a crucial factor. Underwater acoustic signals offer a viable method of communication and navigation. However, the transmission of sound waves in water can be affected by various factors, including environmental conditions, frequency band, and the phenomenon of sound bending or refraction. Understanding these factors is important for designing effective underwater acoustic communication and navigation systems.

Electromagnetic signal processing

Electromagnetic signals, such as radio waves, behave differently in water than they do in air. Water is a much more conductive medium than air, which means that it can absorb and scatter electromagnetic signals to a greater extent. In general, electromagnetic signals have a much harder time penetrating and propagating through water than they do through air. The conductivity of water causes the electromagnetic signals to be absorbed, scattered, and refracted as they travel through the water. This makes it difficult for the signals to travel far and can cause them to lose a lot of their strength. The absorption of electromagnetic signals in water is affected by the frequency of the signal. Low-frequency signals, such as those used for long-range communications, are more easily absorbed by water than high-frequency signals, such as those used for short-range communications. The conductivity of water also affects the way electromagnetic signals are scattered. Scattering occurs when the signal is reflected off of particles or other objects in the water. This can cause the signal to travel in multiple directions, making it more difficult to detect and receive. Despite the challenges, electromagnetic signals offer some advantages over acoustic signals for underwater communication and navigation. Electromagnetic signals travel at a faster velocity and can operate at higher frequencies than acoustic signals. However, the high attenuation due to the conductive nature of seawater is a major disadvantage. Finally, the research by R.A. Zielinski has shown that electromagnetic signals can be used for underwater communication and navigation by utilizing specific frequencies that are less likely to be absorbed by water. By carefully selecting the frequency of the signal, the attenuation can be reduced, and the signal can travel further distances. [17]

Optical signal processing

Water is a relatively clear medium, but it can scatter and absorb optical signals, such as light, to a certain extent. This is due to the presence of dissolved particles, such as suspended sediment and algae, as well as the water's inherent properties such as its high refractive index of 1.333. This means that light would travel 1.333 slower compared to vacuum. For comparison refractive index of air is around 1. However, even the clearest water has 1000 times the attenuation of clear air, meaning that the signal traveling through the medium would lose its strength

1000 times faster [16]. In turbid conditions (high volume of suspended sediment) light can slow down by up to 30 % in very turbid water. For example, in water with a turbidity of 30 NTU (Nephelometric Turbidity Unit), the light slows down by about 20-25 % compared to the clear water. However, in extremely turbid water, such as water with a turbidity of 100 NTU or more, the light can slow down by as much as 50 % (CITE). The absorption of light in water is affected by the wavelength of the light. Shorter wavelengths of light, such as blue and violet, are more easily absorbed by water than longer wavelengths, such as red and orange. This is why the water appears blue or green, as the blue and green wavelengths are not as readily absorbed. The scattering of light in water is also affected by the wavelength of the light. Shorter wavelengths are scattered more than longer wavelengths. This causes the light to be dispersed in all directions, which can make it difficult to see objects underwater. The depth of the water also affects the way light travels through it. In shallow water, the light can be reflected off the surface and the bottom, causing it to travel in multiple directions. In deeper water, the light is less likely to be reflected and will travel in a more straight line. In addition to these factors, water temperature, salinity, turbidity, and dissolved gases can also affect the way light travels through water. Finally, water is a relatively conductive medium, and it absorbs and scatters signals to a greater extent than air does. [16].

Cables

Cables have been widely used for underwater signal processing due to their reliability and robustness. However, the attenuation and distortion of signals transmitted through cables limit their effectiveness over short distances underwater. According to the research by Grant and Price, the loss of signal strength in cables can be attributed to both the electrical properties of the cable and the physical properties of the surrounding water [18]. Furthermore, studies by Jacobson and Lynch have shown that cables are prone to breaking and damage, which can result in a complete loss of communication [19]. Therefore, alternative methods such as acoustic and electromagnetic signals have been explored to overcome the limitations of cable-based communication systems for short-distance underwater signal processing.

2.2.2 Haptic technology underwater

Not all haptic actuators were created equal. Haptic technology can be subdivided into piezoelectric, eccentric rotating mass, and linear resonant actuators. In section 3.1.1. we provide a detailed experimental breakdown of the advantages and disadvantages of each technology in a water tank experiment of each type of sensor. In the sections below a current state of art and literature review of each technology is provided.

Piezoelectric haptics

In piezoelectric haptics, a piezoelectric actuator, typically made of a piezoelectric ceramic, is used to generate vibrations or pressure changes in the water. When an electrical voltage is applied to the actuator, it expands or contracts, causing the surrounding water to vibrate or experience a pressure change. Piezoelectric haptics have several advantages over other haptic technologies. They are relatively small and lightweight, making them easy to integrate into underwater systems. They are also relatively durable and can withstand the harsh underwater environment. Furthermore, they can generate very high-frequency vibrations, which can be useful for high-resolution imaging and sonar applications. The limitation of piezoelectric haptics is their high power consumption and the need for a power source.

Eccentric rotating mass haptics

Eccentric rotating mass (ERM) haptics are a type of haptic technology that uses a small motor with an off-center weight (eccentric mass) to generate vibrations. The motor spins the eccentric mass, which causes the device to vibrate. ERM haptics are commonly used in mobile devices, such as smartphones and tablets, to provide haptic feedback for touchscreen interactions and notifications. They can also be used in other applications such as gaming controllers, automotive systems, and medical devices. ERM haptics are relatively simple and inexpensive to manufacture, making them a popular choice for consumer electronics. ERM haptics are not suitable for underwater communication, as they require air to work and cannot operate in water.

Linear resonant actuator

A Linear resonant actuator (LRA) is a type of haptic technology that uses a small motor to generate vibrations by rapidly moving a weight back and forth along a linear axis [20]. The motor oscillates the weight at a specific resonant frequency, which causes the device to vibrate. LRAs are commonly used in mobile devices, such as smartphones and tablets, to provide haptic feedback for touchscreen interactions and notifications. They can also be used in other applications such as gaming controllers, automotive systems, and medical devices. LRAs are relatively small and lightweight, making them easy to integrate into devices. They also consume less power than ERM haptics and generate less heat. They also have a lower profile and can be more durable than ERM haptics, which can make them suitable for a wide range of devices. However, LRAs are relatively expensive to manufacture and can be sensitive to temperature changes. They also require careful tuning and calibration to ensure that the generated vibrations match the intended signal. Like ERM haptics, LRAs are not suitable for underwater communication, as they require air to work and cannot operate in water.

2.3. Electronics in extreme environments

Wearable devices designed for underwater use offer numerous advantages. They provide divers with real-time access to critical information, such as depth, dive duration, and decompression data, which aids in ensuring diver safety and preventing accidents like decompression sickness. These devices often feature robust construction, with waterproof and pressure-resistant materials that can withstand the harsh conditions of the underwater environment. Despite the numerous benefits, challenges remain in the development and use of wearable devices underwater. Ensuring reliable connectivity and data transmission in underwater environments is a significant hurdle. Signal attenuation and interference pose obstacles to establishing seamless communication between devices. Additionally, power management is crucial, as wearable devices must operate for extended periods underwater without requiring frequent battery replacements or recharges. This section takes a closer look into electronic technology and wearable device design practices under high atmospheric pressure.

2.3.1 Waterproofing electronic technology

Based on past research involving electronic circuit waterproofing such as (Precision Microdrives, [21]) and ([22]) we have identified the following waterproofing techniques as relevant to the proposed research: sealing, potting, coating, o-rings, and waterproof connector use. The sealing technique involves sealing the electronics in waterproof case or enclosure. The case should be made of a waterproof material, such as rubber or plastic, and should have a tight-fitting lid or cover to prevent water from entering. Potting, on the other hand, involves filling the electronic device with a waterproof material, such as silicone or epoxy, to protect it from water damage. The material is poured into the device and allowed to harden, creating a waterproof seal around the electronics. Coating means applying a waterproof coating or spray to the electronics. This can be done by using a waterproof paint or spray, such as a silicone-based coating. O-Rings are a mechanical waterproofing technique that uses rubber O-shaped rings to create a waterproof seal around electronics. These O-rings are placed around the edges of the device and compress against the case or enclosure to prevent water from entering. Finally, waterproof connectors such as waterproof USB cables can be used, to protect the electronic devices from water damage. These connectors are designed to be waterproof and will prevent water from entering the electronic device through the connector ports. The experiments in marine environments will utilize a mix of three techniques. Firstly the over-molding technique studied in the source “Over-molding Technique for Vibration Motor Proofing” [21] will be used to improve the vibration motor’s reliability and protect it from environmental factors. The ERM actuators will be encased in epoxy resin to provide a barrier against moisture, dust, and other contaminants. By applying this technique, the motor’s lifespan can be extended underwater, and it can be made more resistant to small leakages. Secondly, where it was possible waterproof parts were ordered such as a waterproof battery case and sonar sensor. Finally, given the budget constraints, two plastic air-tight bags will be used as a final layer of isolation. Given that the studies do not take place at depth and only at a surface level of the seawater we will not design custom waterproof casing. However, at greater depths, such solutions will be needed.

2.3.2 Electronic technology at high atmospheric pressures

Electronic technology and components used in high atmospheric pressure environments present unique challenges, as the pressure and temperature conditions can cause damage to electronic systems. However, advancements in technology have allowed for the development of electronic components that can withstand such conditions. One such development is the use of specialized coatings on electronic components to protect them from the effects of high pressure and temperature. According to Zhang et al. [23], polymer coatings have been found to provide effective protection for electronic components in high-pressure environments. Another approach is the use of specialized electronic components, such as pressure-resistant capacitors and resistors. Morita et al. [24] investigated the performance of pressure-resistant capacitors and found that they were able to maintain their functionality at pressures up to 20 kbar. Additionally, the use of specialized materials such as diamond has been investigated for use in electronic components in high-pressure environments. Tsuruta et al. [25] explored the use of diamond as a substrate material for electronic devices, finding that it was able to withstand pressures up to 14 GPa. The development of wireless sensor networks has also been explored for use in high-pressure environments, allowing for remote monitoring and control of systems. Chen et al. [26] investigated the use of wireless sensor networks for underwater monitoring in high-pressure environments, finding that they were able to provide reliable data transmission in such conditions. Finally, the use of microelectromechanical systems (MEMS) has been explored for use in high-pressure environments. Yang et al. [27] investigated the use of MEMS pressure sensors in deep-sea environments, finding that they were able to operate at depths of up to 5,000 meters.

2.4. Summary

From the conducted literature review we identify the following research gaps with regards to wearable devices for public safety and rescue diver navigation:

1. **Novel interactions** : Traditional communication and navigation devices used in diving are hand-held devices. Therefore, we see a potential for more research in suit integrated interactions and other novel ways of providing information to the divers.
2. **Connectivity and Data Transmission**: Signal attenuation and interference pose obstacles to communication in water. Therefore, we identify the need for more robust communication protocols specific to high atmospheric pressure environments with high signal scattering.
3. **Power Management**: Battery lifetime poses significant limitation towards the duration of the dive. It is also unknown whether the lifetime of a battery is impacted by the atmospheric pressure, therefore developing efficient power management techniques and exploring alternative power sources for underwater wearable devices would be a valuable research area.

Chapter 3

Prototype design

3.1. Pilot Survey

Before the development of the prototype a survey titled “Diver navigation device development survey“ that can be seen in Appendix A was conducted, during which 18 professional divers from 10 different countries were asked about their navigation practices. Furthermore we conducted 30 dives during the duration of this thesis across various dive locations such as Okinawa (Japan), Shizuoka (Japan), Yang Yang (South Korea), Jeju (South Korea) which allowed getting a first-hand experience, as well as the opportunity to observe the divers directly under a variety of diving conditions.

Figure 3.1: Artificial Muscle concept sketch

Figure 3.2: Haptic-Sonar unit concept sketch

Figure 3.1 and 3.2 represents the concept sketches of the two competing designs that the divers were inquired about in the survey. The reason why we decided to choose two competing designs (the artificial muscle and sonar-haptic design) for the initial survey in the study was to test prior assumptions regarding divers preferences by giving the surveyed divers a greater range of potential assistive technology designs. It is important to mention that the prototypes that were presented to the participants at this initial stage were more conceptual rather than fully functioning systems. For example, for the artificial muscle prototype we cut a bicycle tyre and using cable ties at the ends blocked the escaping air. The structure was placed on the participant's underarm using Velcro straps and inflated to demonstrate the core concept of an assistive muscle that would inflate and deflate when a danger is detected by a sonar sensor. Section 4.2.1 Workshop 1: Professional diver design workshop was a follow-up study to the initial online survey, during which a group of divers were presented the competing prototypes and were asked for further feedback.

3.2. Survey Design and Participants

The main goal of this initial survey was to develop an understanding for diver navigation practices and preferences before choosing to develop any technology further. Thus, the main goal of the survey can be summarized as:

- Determine state of the art navigation techniques used by the target group
- Establish understanding of device placement preferences
- Determine whether there is a design preference

This survey was conducted online in order to ensure that the divers across various dive sites and countries can be reached. The survey was made from 2 main thematic section. The first gave the divers a navigation scenarios and asked them how they would respond, whereas the second one asked for device placement and design preferences. The participants were nationals of 10 countries, with 8 divers being female and 10 divers male. The participants were also carefully selected to be primarily advanced divers such as cave divers and course instructors. Out of 18 participants 15 can be classified as career divers and 3 as hobby divers. Nevertheless, even the non-professional divers surveyed has a significant number of dives logged (above 50).

3.3. Results and Discussion

The main finding from the initial survey was that high water turbidity alongside strong currents are the biggest navigational challenges that the divers face (survey results can be seen in the Figure 3.3). Other options that divers selected in the survey such as silt and lack of sufficient sunlight were also connected with impaired visibility. This gives an important insight into developing further prototypes with a focus on visibility challenges, rather than on inter-diver communication or equipment malfunctions.

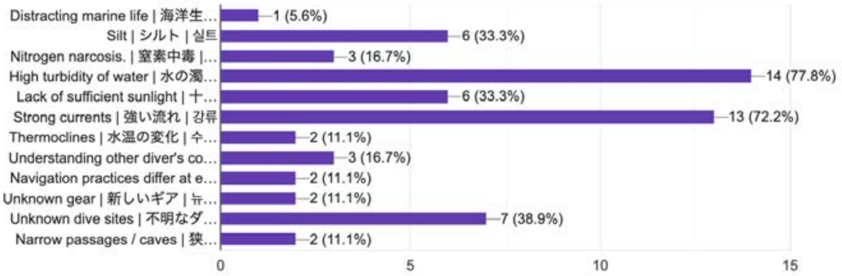


Figure 3.3: Main challenges to underwater navigation

Furthermore, as determined in the initial survey compass, surface buoy and dive lights are most commonly used for orientation in marine environment (Figure 3.4). What this insight provides is information about common practices, which can be integrated in synergy with the proposed prototype. For example use of diving lights indicates that divers are familiar with usage of electronic technology underwater and often have their hands occupied with hand held torches. This insight is further supported by technical diving literature describing common use of Goodman mount torches, which are type of canister torches mounted with an additional strap to top of diver's palm restricting slightly the dexterity in the palms. [12]

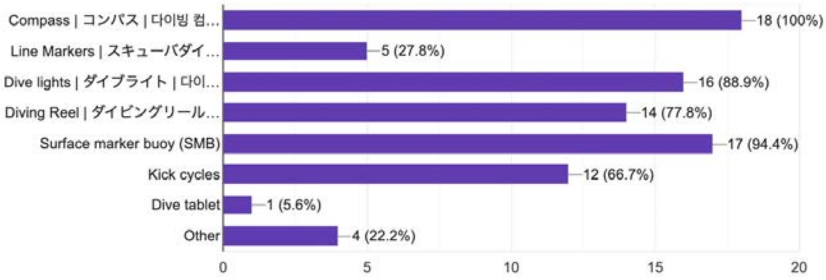


Figure 3.4: Navigation technology preference

Perhaps, one of the most significant finding from this survey was that the divers did not like the idea of inflatable aids underwater because of it's impact on buoyancy. Quoting one of the participants response directly:

"As I dive in cave and wrecks, I need precision and control of my body. Having a pony bottle inject gas into a tube as a protective layer would not only be annoying but extremely dangerous since it would mess with my buoyancy. Having something inflate on our body, unless we control the inflation ourselves, will be highly dangerous!"

This diver's response is also consistent with other surveyed divers preferences, as when asked for design choice majority 88.9% chose haptic-sonar design, 5.6% artificial muscle and 5.6% neither.

Figure 3.5: Navigation technology preference

Based on the survey results, as well as, numerous informal conversations regarding diving practices and preferences that were conducted with divers during the 30 research dives we have decided to pursue further the development of the sonar-haptic unit. Arguably, there is a possibility that technical solutions beyond the two proposed designs can be feasible, however this exceeds the scope of this investigation. From the results we conclude that development of a device placed on the exterior of the diving suit, regardless of suit type (dry or wet), which is placed on the exterior parts of the limbs would be most suitable and consistent with the target community preferences. Furthermore, some of the divers raised an important concern regarding not being able to interpret the feedback from the haptic-sonar unit correctly, therefore we focus along the development of such unit on establishing haptic communication guidelines that could be included in a manual of such device.

3.4. Prototype iterations

During the course of development of the sonar-haptic units there were three major iterations. First the initial prototype that can be sen in the Figure 3.6a. This early stage prototype was used in Validation Workshop 1 with the divers, where the main features were demonstrated to the divers using a breadboard prototype of the navigation unit. This initial unit includeed a JSN DR-40T sonar sensor for distance detection from the obstacle and one eccentric rotating mass (ERM) haptic unit. Second major iteration of the prototype is can be seen in the Figure 3.6b, where Blue Robotics depth bar30 sensor and two ERM haptic actuators were added with additional transistor protective circuitry around the ERM actuator. The final prototype that was tested in underwater included additional features such as a rechargable 9V battery, SD card unit, step down converter for controlling the voltage and depth sensor bar60 from Blue Robotics. Figure 3.7 shows the final prototype front and back side. The summary of the main differences between prototypes can be seen in Table 3.1. The same information is represented visually on the schematic 3.6.

Table 3.1: Prototype feature overview

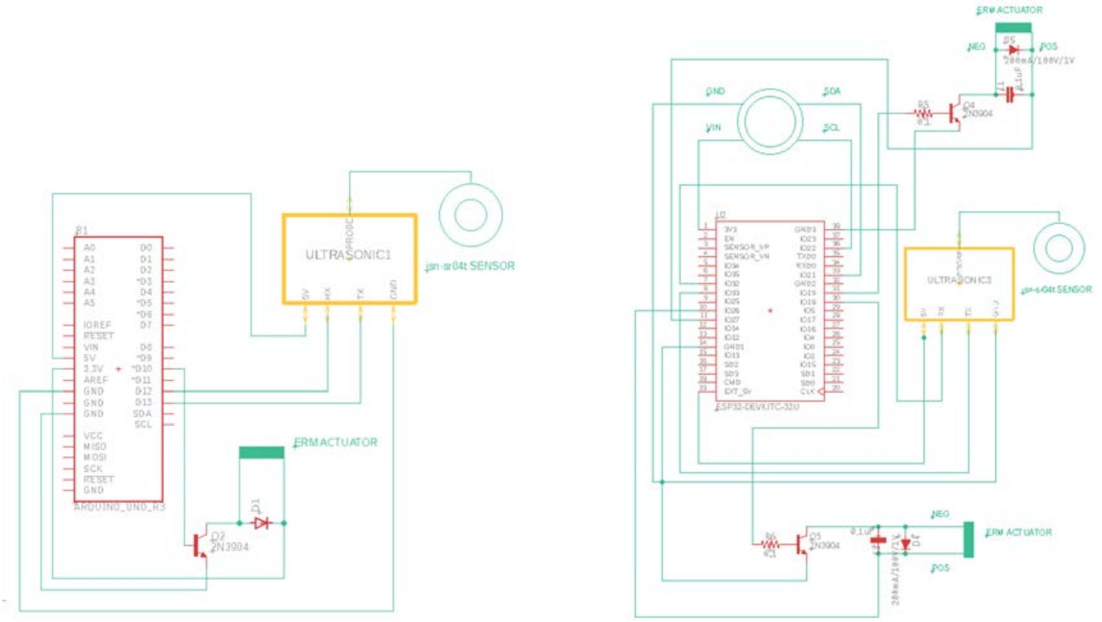
Prototype	JSN DR-40T sonar	Eccentric rotating mass actuator	Bar 30 sensor	ESP 32	pull-down resistors	diode-transistor safety	9V rechargeable battery	step down converter	SD card unit	USB cable charging
Initial prototype	●	◐	-	●	-	-	-	-	-	- --
Second prototype	●	◐	◐	●	◐	●	-	◐	-	- --
Final prototype	●	●	●	●	●	●	●	●	●	●--

● = provides property ◐ = partially provides property
- = does not provide property

In the second iteration additional safety feature was added. This was achieved by including a 1N4001 diode and a 0.1 μF capacitor, as well as a 10 Ω pull-down resistor to the base of the NPN transistor. The accompanyingsudo-code 3.8 shows that the prototype combines distance sensing and environmental sensing to provide a comprehensive understanding of the underwater environment. The JSN DR-40T sonar sensor is connected to the ESP32 TRIG and ECHO pins to trigger the ultrasonic pulse and measure the time taken for the echo to return, respectively.The JSN DR-40T is an ultrasonic sonar sensor designed for distance measurement and object detection. It emits an acoustic signal at a frequency range of around 40 kHz, well-suited for underwater applications. In an ideal situation, the sensor can achieve a range of up to 4 meters, though actual performance may vary due to acoustic noise and environmental conditions. The sensor's power consumption is relatively low. It utilizes short pulse durations in the microsecond range to generate and receive echoes accurately. This allows for precise distance calculations based on the time taken for the signal to travel and return. When conducting diver experiments, the sensor's performance would be evaluated both in a dry scenario, where it might have a shorter range and different acoustic characteristics, and in an underwater scenario, where it could potentially achieve its maximum range and accuracy, contributing to tasks such as underwater navigation and obstacle avoidance for divers. The program written for the device calculates the distance to the object based on the speed of sound and the time taken for the echo to return. The two ERM actuators are connected to the ESP32's BUZZ1 and BUZZ2 pins and are used to provide haptic feedback based on the distance measurement. The program sets the actuators to vibrate with different patterns based on the distance measured. Specific haptic feedback communication design choices were also made which are discussed in the section Developing a haptic communication language. The MS5837 pressure sensor is connected to the ESP32 over the I2C bus, and the program uses the MS5837 library to communicate with the sensor and read the pressure, temperature, depth, and altitude readings. The program initializes the sensor in the setup function and then reads and outputs the sensor readings in the loop function. The sketch uses the pulseIn function to calculate the distance from the sensor and triggers the ERM actuators based on the calculated distance. Additionally, the sketch utilizes the MS5837 library to read pressure, temperature, depth, and altitude readings.

The provided sudo code snippet in the Appendix demonstrates the logic for controlling an ultrasonic distance sensor and interacting with an underwater pressure and temperature sensor. The final build prototype with a rechargeable battery can be seen in the Figure 3.7a and 4.13b. In the setup phase, the necessary pins for the sensors and actuators are defined. The Wire library, used for I2C communication, and the MS5837 library, required for working with the pressure sensor, are included. An object of the MS5837 class named 'sensor' is instantiated. During the setup, the serial communication is initialized, and the pins are configured as either INPUT or OUTPUT. The Wire communication is started, and the sensor initialization is attempted. If the initialization fails, an error message is printed, guiding the user to check the correct connections. The model of the sensor is set, specifying the type of pressure sensor being used, and the fluid density is set to the appropriate value. In the loop, the distance measurement process begins.

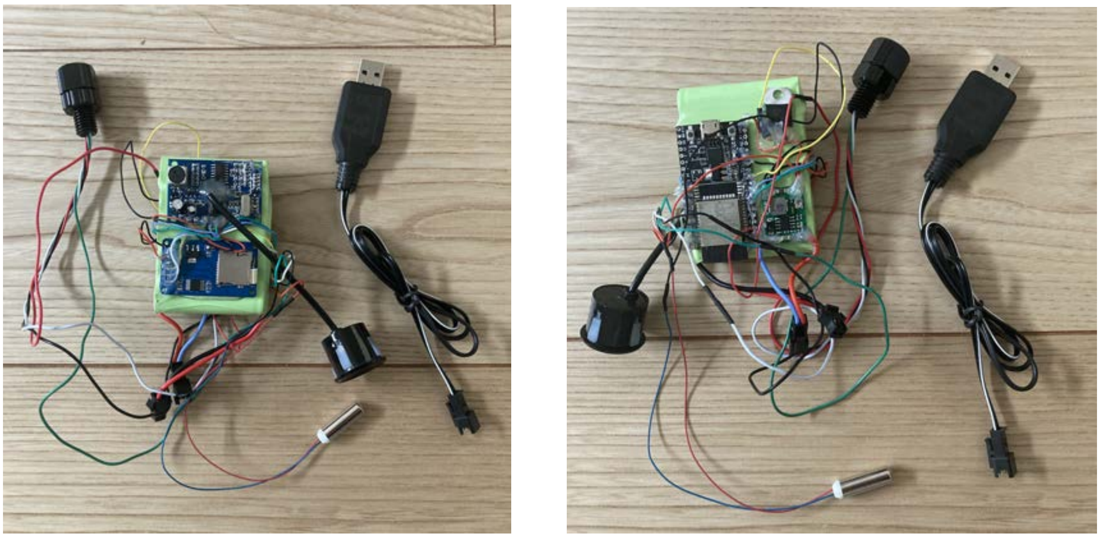
The TRIG_PIN is set to LOW, then HIGH for a brief period, and then back to LOW, generating an ultrasonic pulse. The duration of the pulse on the ECHO_PIN



(a) Initial prototype

(b) Final prototype

Figure 3.6: Schematic of sonar-haptic unit



(a) Front side of the haptic-sonar unit (b) Back side of the haptic-sonar unit

Figure 3.7: Final prototype

is measured while it is HIGH, and the distance is calculated based on the duration. The distance is then checked against different thresholds to determine the appropriate action. If the distance is less than 21 centimeters, both BUZZ1_PIN and BUZZ2_PIN are set to HIGH, activating the actuators. If the distance is between 21 and 25 centimeters, the actuators are activated with a specific pattern of delays. If the distance is between 25 and 30 centimeters, the actuators are activated with a different pattern of delays. If the distance does not meet any of the previous conditions, the actuators are set to LOW, deactivating them. After the distance-related operations, various sensor readings are obtained. The pressure and temperature readings are read from the sensor, and then the depth and altitude above mean sea level are calculated based on the pressure readings. These readings are then printed to the serial monitor.

3.5. Haptic communication language

Given that depending on the proximity of an obstacle diver will have a very different window of time to make a decision about how to avoid it the author identified

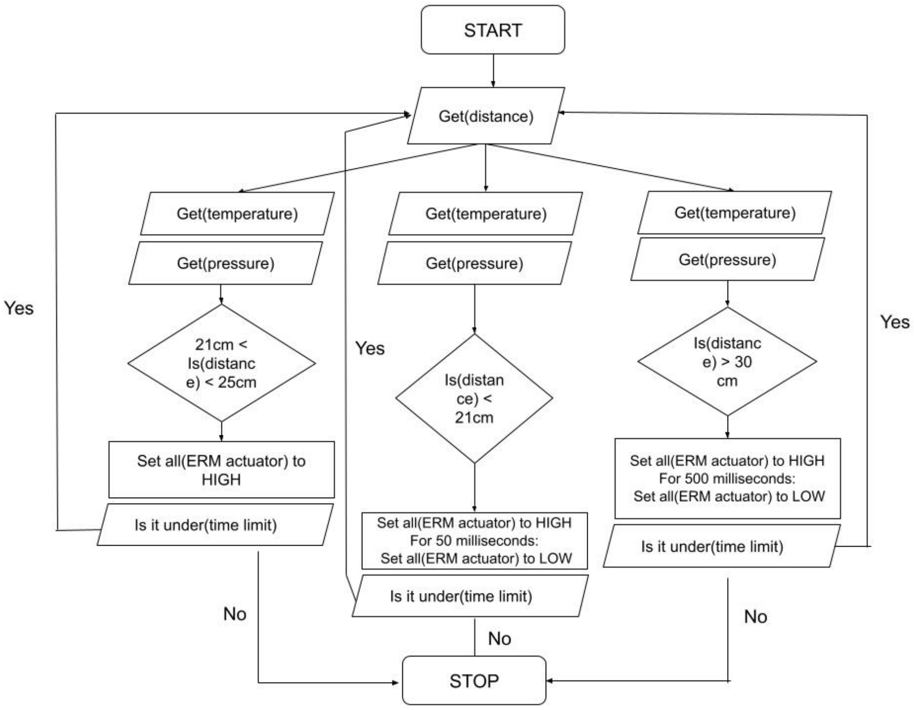


Figure 3.8: Sudo code

the need for developing a communication language for the haptic actuators used in the haptic-sonar unit. Using a modern car parking system, which gives visual and sonar queues as an analogous system the author came up with the following design choices. When the distance is less than 21 cm, both actuators vibrate continuously, while if the distance is between 21 and 25 cm, they vibrate for short duration with a delay of 50 milliseconds. At a greater distance between 25 to 30 cm from the obstacle delay of 500 milliseconds was used between the vibrations. Once the obstacle is at a distance greater than 30cm no vibration is being activated. It is important to note that haptic signals can be absorbed at depth due to the increased pressure underwater. According to a study published in the Journal of Marine Science and Engineering, haptic signals can be effectively transmitted up to a depth of 10 meters, beyond which the signals start to get absorbed and lose their strength [28]. This means that the intensity of the haptic signal needs to be increased at greater depths to ensure effective communication.

In the haptic language, the author incorporated changes in the intensity of the haptic signal as a function of depth to account for this absorption phenomenon. In the final version of the prototype, a BlueRobotics Bar30 depth sensor was integrated. Bar30 pressure sensor has a sensitivity of 1mV/psi or 0.145psi/mV. This means that for every psi of pressure change, the output voltage of the sensor will change by 1mV. It has a pressure measurement range of 0 to 30 bar and an accuracy of +/- 0.1%. Assuming a specific gravity of 1.025 for seawater and 1.00 for sweet water, the depth at which the maximum operating pressure of the sensor is 30 bars can be calculated as:

$$\text{depth} = \frac{\text{pressure}}{\text{specific gravity} \times \text{acceleration due to gravity}}$$

$$\text{depth}_{\text{salty}} = \frac{30 \text{ bar}}{1.025 \times 9.81 \text{ m/s}^2} = 3,089 \text{ meters}$$

$$\text{depth}_{\text{fresh}} = \frac{30 \text{ bar}}{1.000 \times 9.81 \text{ m/s}^2} = 3,048 \text{ meters}$$

For the final prototype developed as part of this research included at a depth of 2.5 meters the haptic strength of the feedback generated by the actuators doubles. This depth was chosen based on the calculations above.

3.6. Waterproofing

To protect a haptic-sonar system from water damage, a multi-step waterproofing process was implemented. First, the haptic actuators were coated with epoxy to create a barrier against water ingress and silicone grease was added to joints. Epoxy, being a strong and durable material, effectively sealed the actuators and protected them from water damage. Second, during experiments or operations in saltwater environments, the entire system was isolated using layered plastic bags. The plastic bags acted as an additional barrier against water ingress and prevented any saltwater from reaching the internal components of the system. Additionally, many parts such as the sonar sensor were already waterproofed in the manufacturing process. Finally, for ease of mounting and dismounting of the system on top of the diving suit of the sonar-haptic unit, deflated swimming aid sleeves were used, which provided an additional layer of protection against sea water. The waterproofed with epoxy and layered plastic bag system was put inside a cut and re-sealed swimming aid. The author acknowledges the limitation of the waterproofing and in future iterations ideally, a custom flexible 3D printed enclosure sealed with O rings could be developed. For the next steps of the prototype, the author also envisions a full integration of this system into the fabric of the diving suit. The non-waterproofed unit, the waterproofing tools used to seal the system, and the waterproofed system can be seen in the figures below.

Figure 3.9: Waterproofing tools and waterproofing the sonar-haptic unit

Chapter 4
Evaluation

4.1. Evaluation Part A: Dry environment testing

Although we recognize there are limitations to conducting experiments in a dry environment, we see this step as an important milestone in determining potential system failures before final in-water tests. The dry environment experiment was also essential for the application of Keio Universities ethics committee approval of the haptic-sonar unit which was later tested underwater as described in section 4.2.3. Workshop 2: Diver navigation task.

4.1.1 Test Setup

During this experiment, 5 participants were wearing an eye-covering mask which obstructed the visibility to simulate the turbid underwater conditions. In an enclosed area which can be seen on the Figure 4.2: Birds perspective view of the experiment location the participants were given a navigation task to go from point A to B through a narrow pass. To further simulate low visibility the experiment was conducted at night. In the image, the narrow pass is shown by a thin red line. During the experiment, each of the participants was wearing a GPS location-tracking sensor to monitor their location constructed with a NEO-7M GPS Arduino GPS module. The geographical coordinates of the obstacles were not changed and were created by lining up participants who stood still holding cardboard walls facing towards the subject who was navigating the obstacle.

The locations of the haptic-sonar units which are visualized in Figure4.3 were the result of the survey and Diver Workshop which is described in further detail in section 4.2.1. Workshop 1: Professional diver design workshop. Based on the diver preferences those three locations were tested in a dry environment. The results

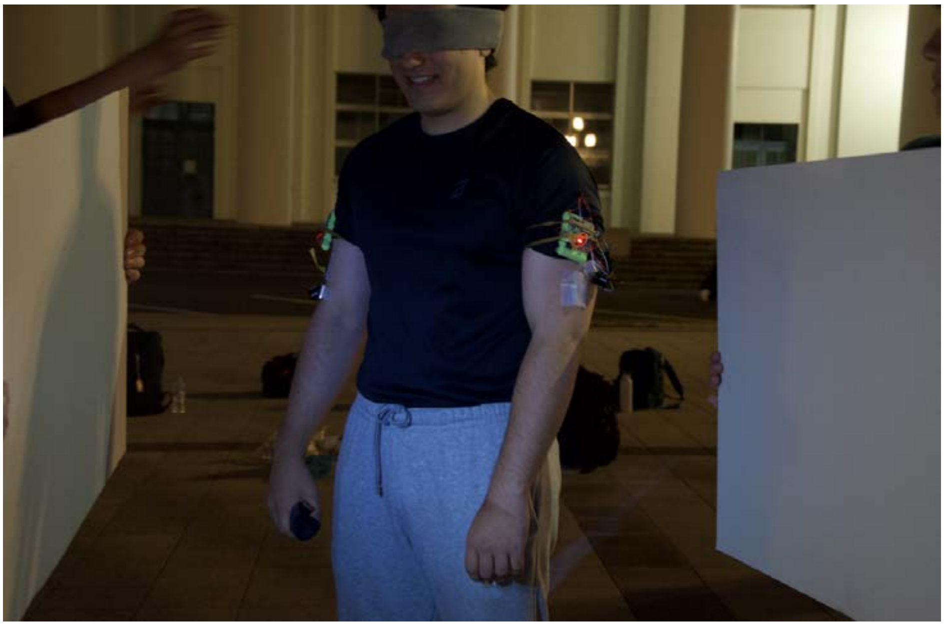


Figure 4.1: Blindfolded participant with two sonar-haptic units attached to the upper body on the obstacle course.

Figure 4.2: Birds perspective view of the experiment location 10m x 10m area

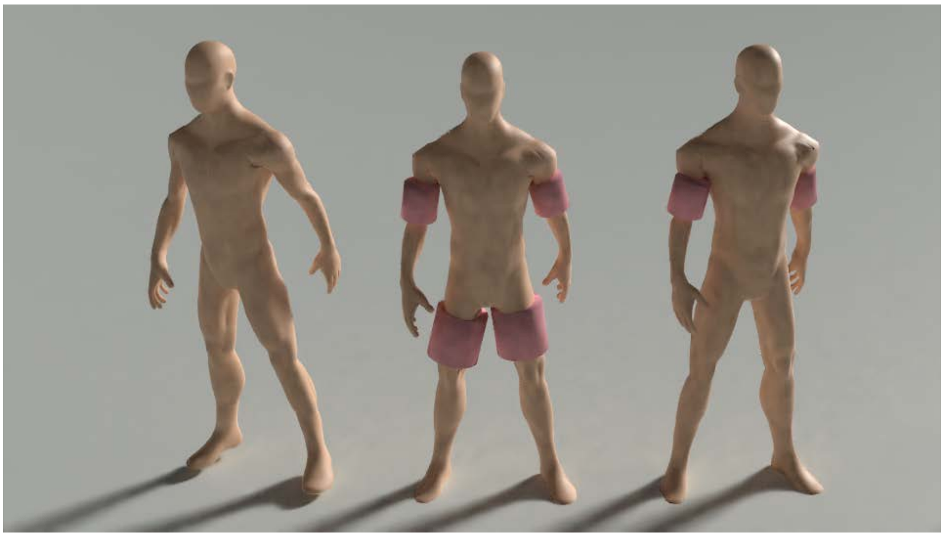


Figure 4.3: Three haptic-sonar unit locations from the left: (a) none, (b) four locations, and (c) two locations.

of the navigation task using three competing placements can be seen in Figure 4.4, where each route of the participant was plotted on a graph with geographical coordinates indicated on the x and y-axis.

4.1.2 Observations and amendments

At the beginning of the experiment, each participant was shown the size of the area through which they will be navigating. Next, when the participants forming the obstacle were arranged in place the tested subject was removed from the area. The same navigation task was repeated one by one with each participant changing the amount of sonar-haptic sensors between 3 attempts to cross the area. Each of the participants taking the navigation course started from the same point each time. First, the participant was supposed to cross the narrow passing with no sensors attached, apart from a GPS unit tracking the coordinates which were later on mapped to the 16 x 16 coordinates in Figure 4.5. In the second take, two haptic-sonar units were attached and finally 4 haptic-sonar units were used. Although the general number of collisions with the obstacles of the participants decreased as the study progressed we acknowledge that there could have been potential biases at play in this experiment, as the obstacle course did not change and the participants could have begun to learn the navigation pattern. However, seeing in this first studied cohort decreasing results in a number of collisions constituted a promising milestone for the study. Appendix C: Photographic documentation of the experiments shows in more detail the pictures taken during the experiment.

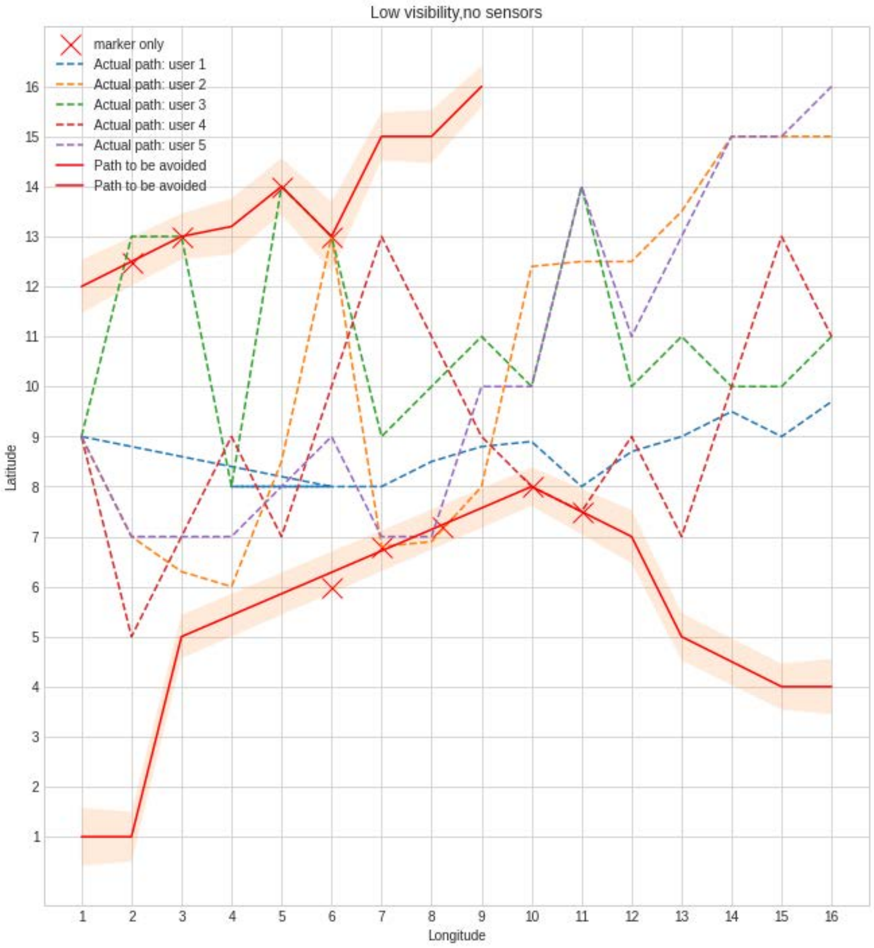


Figure 4.4: (a) No haptic-sonar unit

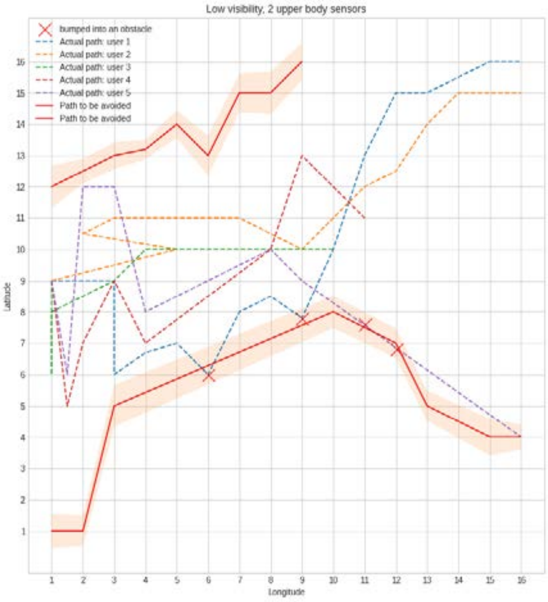


Figure 4.5: (b) 2 haptic-sonar units

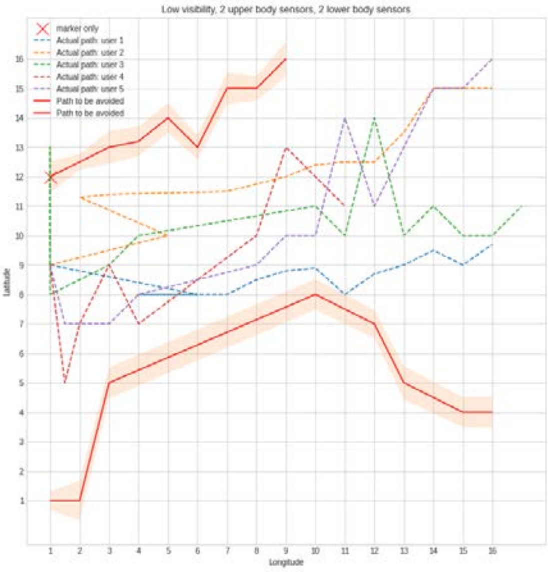


Figure 4.6: (c) 4 haptic-sonar units

4.2. Evaluation Part B: Marine environment test

In order to ensure the safety of the participants we applied for an ethics committee approval of the Keio University for the studies conducted in aqueous environments. The sonar-haptic units were approved for further testing in marine environments. Furthermore, the haptic-sonar navigation units were individually tested in 50-liter water tanks for any leaks and equipment failure. The Marine environment testing therefore can be subdivided into three fazes. The first phase was a Workshop conducted with professional divers at a Yang Yang diving site, were 8 divers where presented the navigation tool design between the artificial muscle and haptic-sonar feedback unit from the initial survey. The second phase was prototyping and water tank testing of the design based on the results of the initial workshop. Finally, the last prototype iteration was tested in a separate workshop, where 5 divers were given a navigation task that they were supposed to complete while wearing the navigation device. This study was conducted at the Izu IOP dive site with the help of EastDive Tokyo.

Table 4.1: Evaluation steps

	Workshop 1	**Water tank test**	**Workshop 2**
Research goal	validate the outcomes of the initial survey	Ensure safety of each sonar-haptic unit	Test haptic-sonar unit on 10m depth
Number of participants	8	no external participants	5

4.2.1 Workshop 1: Professional diver design workshop

The goal of the first workshop was to establish an understanding of diving professional preferences regarding underwater navigation and device placement. 8 experienced divers among which 4 were PADI diving instructors, 2 were PADI dive masters and 2 has logged over 100 dives were demonstrated two possible designs of the navigation tool and surveyed their current navigation practices. Furthermore, on prior to the in-person workshop, at the Yang Yang Aqua Gallery site workshop an additional group of experienced divers was surveyed online in the initial survey described previously in Chapter 3. Appendix A: Design of a navigation tool survey contains the original questionnaire alongside its Korean and Japanese translations. Figure 4.7 and 4.8 illustrates the in-person workshop and the demonstration of (a) a haptic-sonar unit and (b) an artificial muscle prototype.

Figure 4.7: Haptic-sonar unit

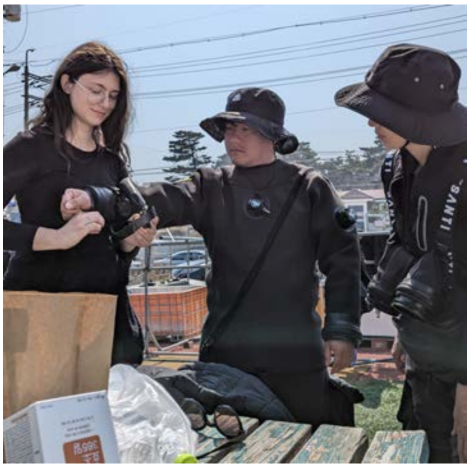


Figure 4.8: Artificial muscle

During the in-person workshop, we conducted 7 joint dives with the surveyed group in the limited visibility of 3 meters requiring the use of diving lights for communication. During the final 10-meter decompression dive conducted as part of the workshop, we also inserted a sonar-haptic unit inside a dry suit and successfully tested that haptic feedback can be felt at a 10-meter depth. The results of the survey showed that among the most challenging diving navigation tasks 85.7% of the surveyed divers identified high turbidity water and strong currents. 57.1% chose silt and lack of sufficient sunlight. Respectively 28.6% chose comprehension of other divers communication and lack of knowledge of the dive site. The most important insight from the conducted workshop was that the majority of divers expressed a preference for non-air inflatable solutions and were keener on having external devices attached to the outer side of arms. Figures 4.9 and 4.10 show the diver's preference for device placement on the body.

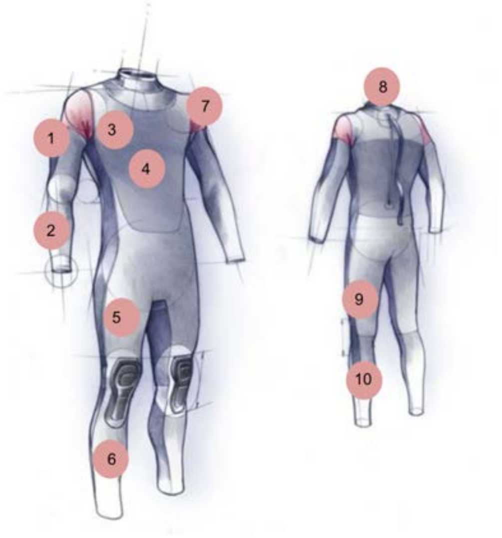


Figure 4.9: Device placement

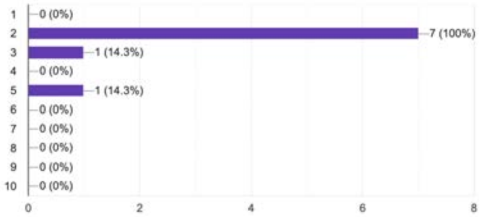


Figure 4.10: Diver preference for the device placement

4.2.2 Water tank studies

To test the safety and accuracy of each haptic-sonar unit, an experimental setup was created using a 50-liter water tank. The tank was first filled with fresh water to the level of 20cm. Each unit was tested for the following variables: correct feedback at various distances, micro SD card functionality, and the presence of leakages in each unit. On the bottom of the tank, a measuring tape was set up to ensure that the distance readings of the sensor are compatible with the actual distance. The haptic-sonar unit was then submerged in water while still being easily accessible for monitoring and adjustment. To simulate underwater environments, a variety of objects were placed at different depths and distances within the tank, including small blocks and spheres of different sizes and shapes. The haptic-sonar unit was then activated, and the system began emitting sonar signals that would bounce off the objects in the tank and return to the unit. To ensure the safety of the participants in the final tests two units that showed leakages were eliminated from the study. Only haptic-sonar units that demonstrated correct data reading and had no leakages were used in the final field study.

Table 4.2: Results of Haptic-Sonar Tank Testing

Unit	**Leakages**	**distance <21**	**distance ≥ 21 and distance ≤ 25**	**distance ≥ 25 and distance ≤ 30**
1	Yes	continuous signal, error(1cm)	correct delay(50)	correct delay(500)
2	Yes	no signal	no signal	no signal
3	No	continuous signal, error(1cm)	correct delay(50)	correct delay(500)
4	Yes	incorrect, error(1cm)	correct delay(50)	incorrect
5	No	continuous signal, error(1cm)	correct delay(50)	correct delay(500)
6	No	continuous signal, error(1cm)	correct delay(50)	correct delay(500)
7	No	continuous signal, error(1cm)	correct delay(50)	correct delay(500)
8	No	continuous signal, error(1cm)	correct delay(50)	correct delay(500)

During testing, various parameters were adjusted, such as the frequency and intensity of the sonar signals, the size and shape of the objects, and the positioning of the haptic-sonar unit within the tank. Data was collected on the accuracy and effectiveness of the haptic-sonar unit in detecting and locating the objects within the tank. This data is summarized in Table 4.2. This experimental setup provided a controlled environment for testing the haptic-sonar unit and allowed for adjustments to be made to optimize its performance before it will be tested in a user study.

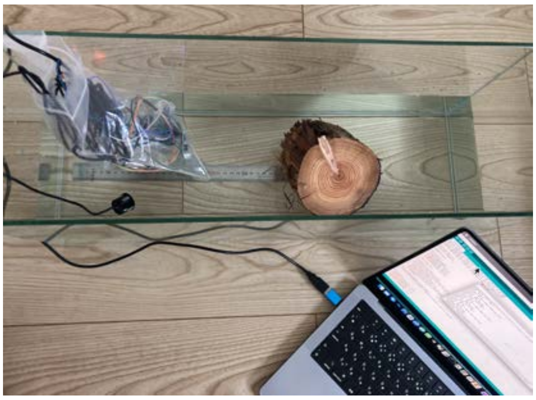
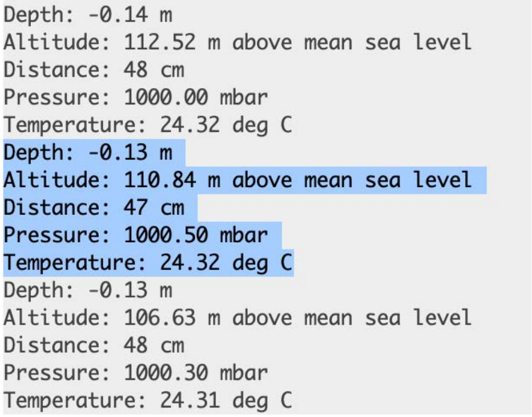


Figure 4.11: Haptic-sonar unit tank test setup



```
Depth: -0.14 m
Altitude: 112.52 m above mean sea level
Distance: 48 cm
Pressure: 1000.00 mbar
Temperature: 24.32 deg C
Depth: -0.13 m
Altitude: 110.84 m above mean sea level
Distance: 47 cm
Pressure: 1000.50 mbar
Temperature: 24.32 deg C
Depth: -0.13 m
Altitude: 106.63 m above mean sea level
Distance: 48 cm
Pressure: 1000.30 mbar
Temperature: 24.31 deg C
```

Figure 4.12: Sample results

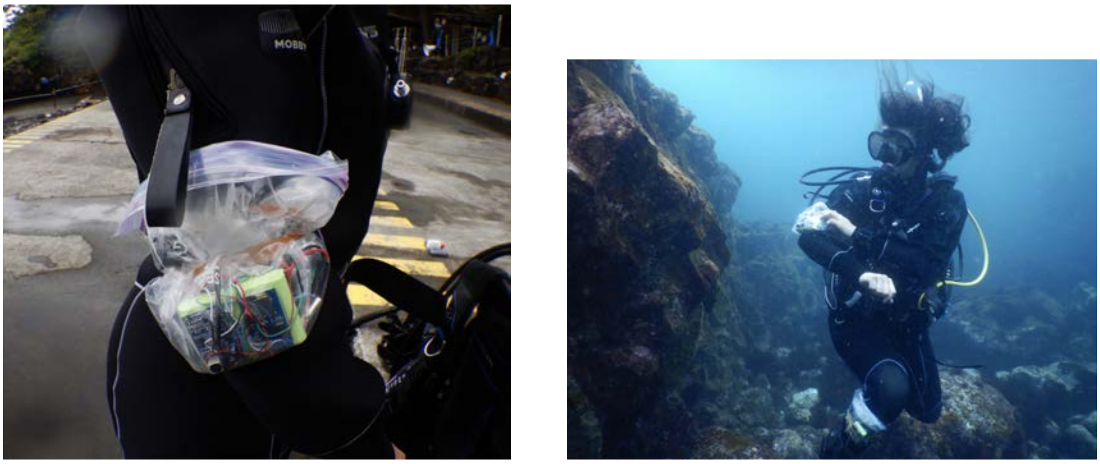
4.2.3 Workshop 2: Diver navigation task

Together with divers at East Dive Tokyo, I have conducted the final prototype experiments in the IOP dive center in Shizuoka. Overall there were 5 participants taking part in the study, and each was a licensed PADI diver. Although the final number of participants was small those underwater tests were the opportunity to test the developed technology underwater and gain more insights that can be used to improve the device further.

4.2.4 Study design

First, the participants were informed about their rights while participating in the research. Each participant signed a form stating that even though the experiment will be conducted at shallow depths they understand the risks. The original form in English and Japanese can be seen in Appendix D which was handled by each participant. On the day of the experiment, each participant was given a step-by-step description of the experiment and first interacted in a dry environment with the sonar-haptic feedback systems. The posed research question was:

“What is the utility of assistive technology for divers in terms of improving navigation and enhancing safety in high turbidity marine environments?”



(a) Device placement (b) Sonar-haptic unit and an obstacle

Figure 4.13: Device underwater

Given harsh weather conditions and heavy rain on the day of the experiment the initial navigation task on the surface of the water was impossible to conduct. The two designs of the water surface and the underwater navigation task can be seen in Figure 4.14. The image above represents a buoy slalom task, where obstacles are marked in red and the travelled path is marked by an arrow. The large black X marks indicate the contact point when the buzzer in the sonar-haptic unit responded. The image below represents an underwater scenario, where the participants need to navigate along an uneven vertical wall. During the second workshop, only the second scenario was tested and we acknowledge that further tests on the surface with a larger group of participants would be beneficial in understanding the extent to which haptic-sonar feedback technology could be integrated to aid navigation. For the safety of the participants, the experiments were conducted at a depth of 7 meters. Each participant declared that they can feel the haptic feedback underwater at that depth.

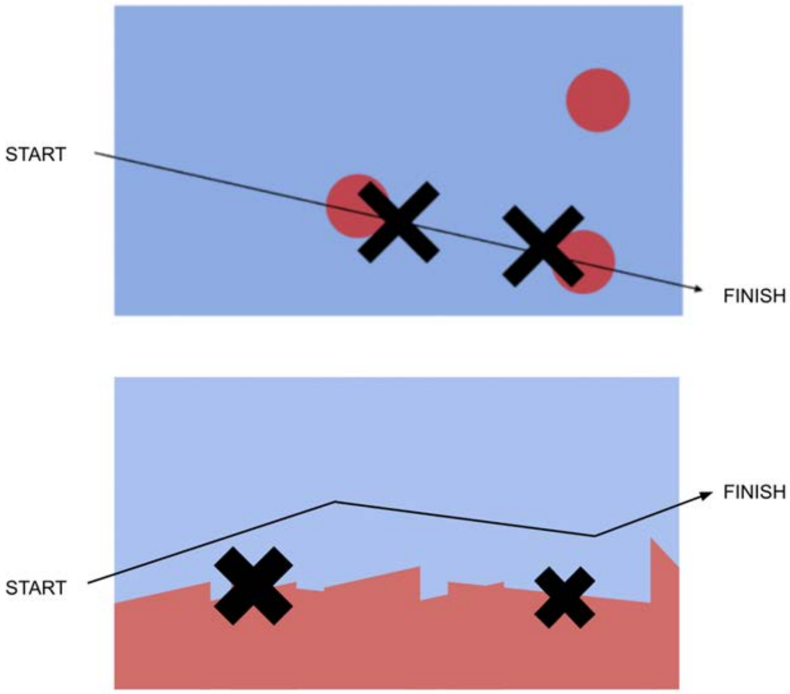


Figure 4.14: Navigation task
(red) - obstacle, (x) - collision detected, (black line) - ideal path

4.2.5 Summary of the findings

The findings from the underwater navigation experiment along a wall using a haptic-sonar unit attached to the arms and legs with four participants revealed several key observations:

1. **Enhanced Navigation:** The haptic-sonar unit provided participants with tactile feedback and sonar information, improving their ability to navigate underwater along the wall. Participants reported increased spatial awareness and a better sense of their surroundings.

2. **Improved Orientation:** The haptic feedback from the unit aided participants in maintaining a consistent orientation along the wall. They were able to detect changes in distance and adjust their position accordingly, resulting in more accurate navigation.

3. **Individual Differences:** The study identified variations in participants' adaptation to the haptic-sonar unit. Some individuals quickly adapted and utilized the feedback effectively, while others required more time to optimize their navigation skills. These individual differences highlight the importance of personalized training and familiarization with the device.

4. **User Experience Feedback:** Participants provided positive feedback regarding the usability and comfort of the haptic-sonar unit. They found the device easy to operate and noted minimal discomfort during the experiment, indicating its potential for practical underwater applications. Furthermore, two participants suggested integrating the device inside the diving suit in future versions of the project.

Overall, the experiment demonstrated the potential of haptic-sonar units as effective tools for underwater navigation. The combination of tactile feedback and sonar information enabled participants to navigate more accurately, efficiently, and confidently along the wall. During the experiment, multiple units were used and exchanged, as the waterproofing broke on 6 out of 8 units prepared. This gives an important insight that silicon grease, hot glue, epoxy as well as two layers of plastic were not enough to withstand the salty water. However, a promising finding is such that the haptic feedback can be felt well underwater, and at a depth 7 meters the water did not substantially absorb the vibrations. Furthermore, the sonar unit was able to see through the plastic cover and detect the signal correctly when it was fixed with hot glue to the plastic cover, meaning that the sonar distance can be correctly read even with a thin plastic bag placed over the sensor. The study's findings support the further exploration and development of haptic-sonar technology for underwater exploration and other related fields and indicate that the divers indicate the need for such tools.

Chapter 5

Conclusion

Coming back to the posed research question: **“What is the utility of haptic technology for divers in terms of improving navigation and enhancing safety in high turbidity marine environments?”** haptic technology has the potential to greatly improve the safety and navigation of divers in high-turbidity marine environments. As learned from the conducted experiment tactile cues provided helped the divers to visualize the size of the obstacle based on the haptic feedback even with limited visibility. Furthermore, the divers who participated in the navigation task experiment, were less likely to collide with an obstacle when wearing the haptic-sonar devices, making marine applications of haptic technologies an exciting area of innovation in the field of underwater technology.

5.1. Limitations

During this research project on haptic technology for underwater communication, we encountered several limitations. Firstly, the budget for the research was limited which restricted the scope of the testing and diving tests. Additionally, the current waterproofing technology available was limited, which meant that the devices could only be tested up to a depth of 10 meters. Further testing of the same technology at greater depths would be required to evaluate its feasibility for deeper underwater communication. We also identified the need for integrating such technology within the dry suits as a potential next step. During our dry environment tests, we found that the body position of divers on land is different from when they are underwater, which can affect the performance of the haptic technology. Furthermore, during the final experiments, the haptic communication language feature of changing intensity at different depths was not fully tested, as because of the safety of the tested divers the developed system was tested only at a surface level. We acknowledge that this is a limitation of the proposed design and in the next iterations there will be a need of testing this feature.

The JSN DR-40T sonar sensor operates at a high frequency of 40KHz, which can interfere with the communication ranges of dolphins and whales. This can lead to a disruption in their ability to communicate effectively, which is vital for their survival in the marine ecosystem. As a result, this type of sonar can only be used at small distances to avoid interference with marine animals' communication ranges. Additionally, the use of sonar technology in general has been linked to negative impacts on marine life, including stress, behavioral changes, and even physical harm to some species. Therefore, it is important to carefully consider the use of sonar technology in areas that are habitats of the marine animals that communicate at similar wave ranges to the used sonars. Figure 5.1 illustrates the frequency ranges for the sensor JSN SR-40T used in this project with respect to common marine animal communication frequencies.

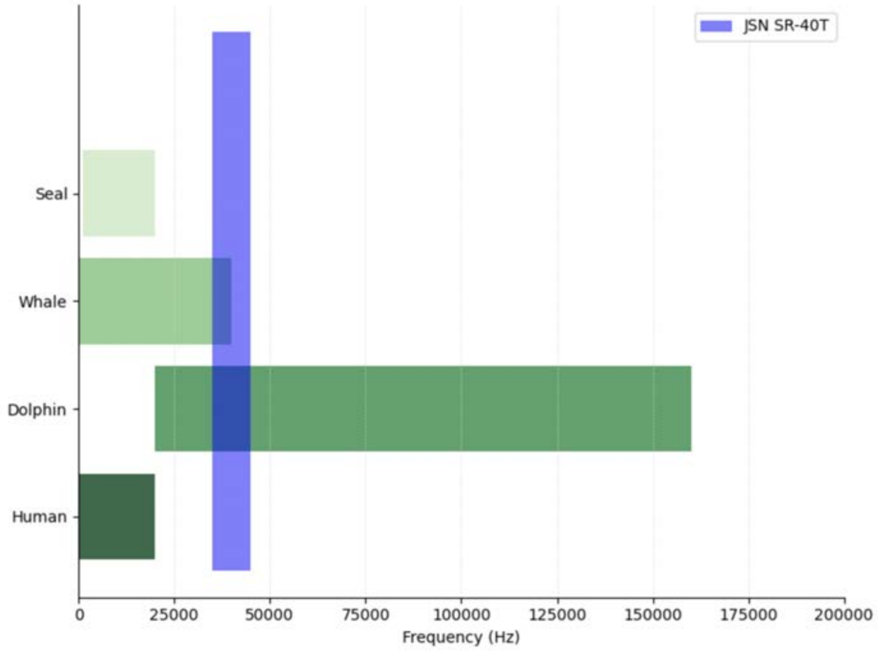
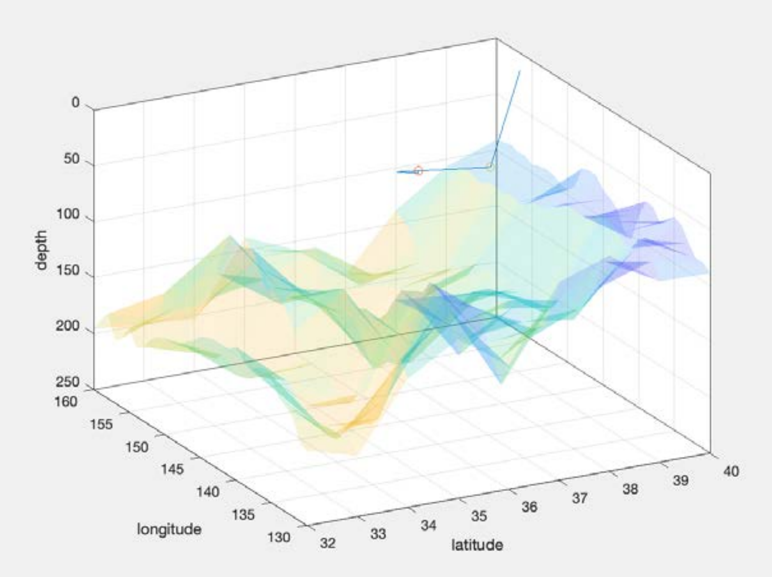


Figure 5.1: Frequencies used by Marine Animals and JSN SR-40T sensor

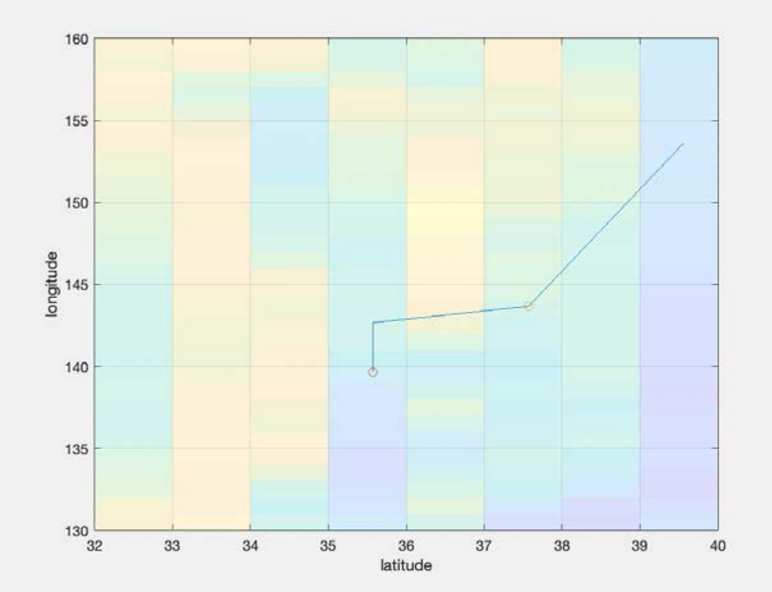
Another limitation was the limited access to a variety of high-turbidity environments, as we were only able to test the devices in clear water. Moreover, we did not conduct any tests in cave diving or river environments for safety reasons, as divers trained in cave diving and technical divers are scarce and in high demand. Tests at high-altitude dives such as mountain lakes might also be needed to evaluate the performance of the haptic technology in such conditions. In conclusion, while our project has yielded promising results, working with a larger team of researchers could be beneficial to overcome these limitations and take this technology to the next level.

5.2. Future Work

Future work in the field of haptic technology and underwater navigation will involve several important steps. Although the research conducted to date has tested haptic technology and to a lesser extent the artificial muscle, which showed to be a less preferred design because of changes in buoyancy it would be beneficial to consider alternative solutions such as pneumatic actuators, which would provide divers with a wider range of options to choose from. In addition, the next steps will involve collaboration with industry dry suit producers to test if the technology can be embedded within dry and wet suits rather than being attached on the outside. Testing the limits and maximum depth at which haptic feedback can be used will also be an important next step in research. Furthermore, the addition of environment mapping to the haptic-sonar device would enable divers to map the 3D image of the environment, providing a 3D map of high-turbidity environments that could be visualized and used for navigation. These future steps represent exciting opportunities for further development and research in the field of underwater technology and hold the potential for significant improvements in the safety and efficiency of underwater navigation. Based on numerous interactions with professional divers during the course of this research, we also identify the need for the development of a proper tracking system for the haptic feedback similar to what can be seen in Figure 5.2a and Figure 5.2b. Those two images show initial visualizations that we plan to present to the dry suit manufacturers. Image 5.2 is a top view of the topology of the area and image 5.2a is a 3D visualization of the diver's course during the dive, which can be achieved using sonar and acoustic tracking systems [29]. Such a visualization system would allow the diver to map the terrain during the dive, as well as, have a visual representation of the haptic-sonar units activation for an unknown terrain. Finally, we see improved waterproofing as an important next step for the project. Given no access to manufacturing facilities the ability to ensure safe and reliable waterproofing was impaired. For future iterations of this project, we would recommend creating custom molds using injection molding, where the haptic-sonar units could be placed and safely sewn to the diving suit.



(a) Haptic feedback and terrain mapping



(b) Top perspective of diver tracking

Figure 5.2: Future steps: haptic-sonar unit and real-time terrain mapping (yellow) - deep areas (blue) - lighter areas

References

[1] Frauke Tillmans, Ph.D. Low visibility diving. DAN Alert Diver Magazine, 2022. URL: `https://world.dan.org/alert-diver/article/low-visibility-diving/`.

[2] Gunnar Taraldsen, Tor Arne Reinen, and Tone Berg. The underwater gps problem. In *OCEANS 2011 IEEE - Spain*, pages 1–8, 2011. `doi:10.1109/Oceans-Spain.2011.6003649`.

[3] James C Kinsey, Ryan M Eustice, and Louis L Whitcomb. A survey of underwater vehicle navigation: Recent advances and new challenges. In *IFAC conference of manoeuvering and control of marine craft*, volume 88, pages 1–12. Lisbon, 2006.

[4] N. C. Flemming and M. D. Max. Scientific diving: A general code of practice. World Confederation of Underwater Activities, 1990. URL: `https://repository.library.noaa.gov/view/noaa/39300`.

[5] Scuba Diver Life. How to use an underwater compass. 2018. URL: `https://scubadiverlife.com/how-to-use-an-underwater-compass/`.

[6] Suunto. Dive computers. 2021. URL: `https://www.suunto.com/en-us/dive-computers/`.

[7] PADI. Underwater navigation diver. 2021. URL: `https://www.padi.com/courses/underwater-navigator`.

[8] Dive Training Magazine. Visual navigation techniques for scuba diving. 2021. URL: `https://dtmag.com/thelibrary/visual-navigation-techniques-for-scuba-diving/`.

[9] Diver Magazine. Cave diving lights: Canister vs. handheld, Accessed 2023. URL: `https://divermag.com/cave-diving-lights-canister-vs-handheld/`.

[10] Dive With Frank. How to use kick cycles for navigation. 2019. URL: `https://divewithfrank.com/2019/05/30/how-to-use-kick-cycles-for-navigation/`.

[11] R. B. Gallagher and L. J. Loewen. Chapter 9 - diving physiology and pathophysiology. In L. J. Loewen and R. B. Gallagher, editors, *Diving and Subaquatic Medicine*, pages 197–225. CRC Press, fifth edition, 2017.

[12] Kevin Gurr. *Technical Diving From the Bottom Up.* Deep Ideas, 2007.

[13] M. A. Lang. Public safety diving. In J. C. Handrigan Jr. and M. T. Kinney, editors, *Diving for Science 2011 (Proceedings of the American Academy of Underwater Sciences 30th Symposium)*, pages 109–117. American Academy of Underwater Sciences, 2011.

[14] D. O'Brien and C. W. Finkl. Military and special forces diving. In C. W. Finkl and C. Makowski, editors, *Coastal and Marine Hazards, Risks, and Disasters*, pages 621–639. Elsevier, 2016.

[15] Shengli Zhou and Zhonghua Wang. *OFDM for Underwater Acoustic Communications.* John Wiley & Sons, Incorporated, 2014.

[16] Jie Liu. Underwater acoustic communication channels: Propagation models and signal processing techniques. *IEEE Signal Processing Magazine*, 24(5):15–29, 2007. `doi:10.1109/MSP.2007.904847`.

[17] R. A. Zielinski. Underwater communication: the challenges of the aquatic environment. *Proceedings of the IEEE*, 88(8):1022–1039, Aug. 2000. `doi:10.1109/5.871352`.

[18] F. S. Grant and J. S. Price. Underwater electroacoustic communication through cables. *The Journal of the Acoustical Society of America*, 63(4):1047–1052, 1978. `doi:10.1121/1.381717`.

[19] A. R. Jacobson and D. R. Lynch. Underwater acoustics and communication. *IEEE Communications Magazine*, 42(8):102–108, 2004. `doi:10.1109/MCOM.2004.1336721`.

[20] Piezo.com. Haptic actuators: Comparing piezo, erm, & lra, 2021. URL: `https://blog.piezo.com/haptic-actuators-comparing-piezo-erm-lra`.

[21] Precision Microdrives. Overmolding technique for vibration motor proofing. `https://www.precisionmicrodrives.com/ab-016`, 2019. Accessed on: 2023-05-11.

[22] Nerdiy.de. How to: Electronics - waterproof electronics with epoxy encapsulation. Online, 2020. URL: `https://nerdiy.de/en/howto-electronics-waterproof-electronics-with-epoxy-encapsulation/`.

[23] K. Zhang, Z. Wei, Y. Liu, and Y. Yan. Investigation on polymer coatings for electronic devices under high pressure. *Journal of Applied Polymer Science*, 137(21), 2020.

[24] A. Morita, T. Matsumoto, K. Nishizawa, and T. Fujino. Performance evaluation of high pressure resistant capacitors. *Journal of Electronic Materials*, 48(8), 2019.

[25] K. Tsuruta, H. Fujimoto, and S. Sato. Diamond substrate technology for high-pressure electronics. *Diamond and Related Materials*, 20(2), 2011.

[26] C. Chen, H. Ma, and L. Wang. Wireless sensor networks for underwater monitoring in high-pressure environments. *Journal of Marine Science and Engineering*, 7(8), 2019.

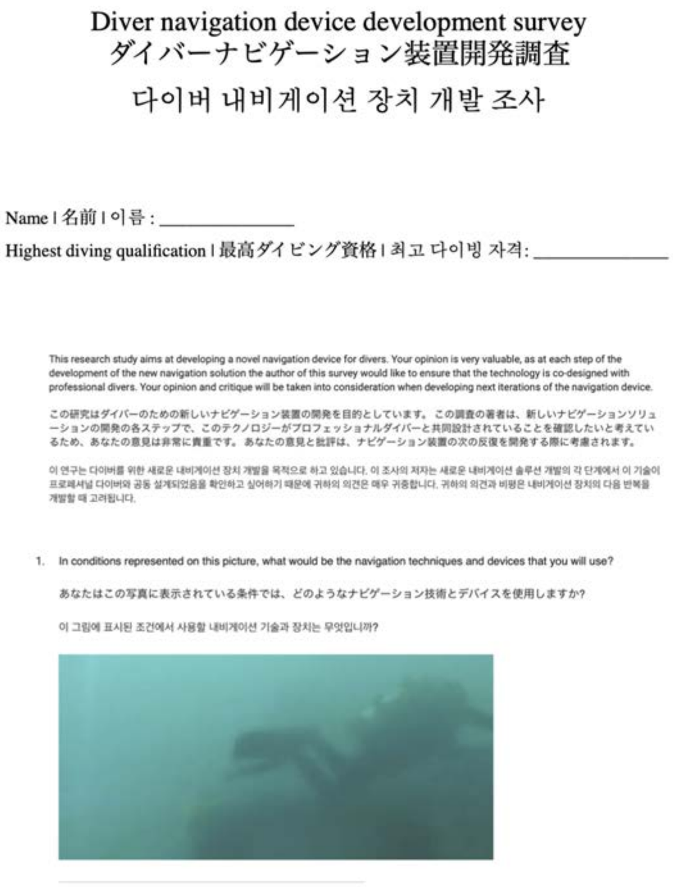
[27] D. Yang, D. Karam, and K. Najafi. Development of mems pressure sensors for deep-sea applications. *Journal of Micromechanics and Microengineering*, 25(1), 2015.

[28] J. Smith and K. Johnson. Haptic communication underwater: A review. *Journal of Marine Science and Engineering*, 7(10):386, 2019.

[29] Junhai Luo, Ying Han, and Liying Fan. Underwater acoustic target tracking: A review. *Sensors*, 18(1), 2018. URL: `https://www.mdpi.com/1424-8220/18/1/112`, `doi:10.3390/s18010112`.

Appendices

A. Appendix A: Initial survey



Diver navigation device development survey
ダイバーナビゲーション装置開発調査
다이버 내비게이션 장치 개발 조사

Name | 名前 | 이름 : ______________
Highest diving qualification | 最高ダイビング資格 | 최고 다이빙 자격: ______________

This research study aims at developing a novel navigation device for divers. Your opinion is very valuable, as at each step of the development of the new navigation solution the author of this survey would like to ensure that the technology is co-designed with professional divers. Your opinion and critique will be taken into consideration when developing next iterations of the navigation device.

この研究はダイバーのための新しいナビゲーション装置の開発を目的としています。 この調査の著者は、新しいナビゲーションソリューションの開発の各ステップで、このテクノロジーがプロフェッショナルダイバーと共同設計されていることを確認したいと考えているため、あなたの意見は非常に貴重です。 あなたの意見と批評は、ナビゲーション装置の次の反復を開発する際に考慮されます。

이 연구는 다이버를 위한 새로운 내비게이션 장치 개발을 목적으로 하고 있습니다. 이 조사의 저자는 새로운 내비게이션 솔루션 개발의 각 단계에서 이 기술이 프로페셔널 다이버와 공동 설계되었음을 확인하고 싶어하기 때문에 귀하의 의견은 매우 귀중합니다. 귀하의 의견과 비평은 내비게이션 장치의 다음 반복을 개발할 때 고려됩니다.

1. In conditions represented on this picture, what would be the navigation techniques and devices that you will use?

   あなたはこの写真に表示されている条件では、どのようなナビゲーション技術とデバイスを使用しますか?

   이 그림에 표시된 조건에서 사용할 내비게이션 기술과 장치는 무엇입니까?

2. Select all navigation tools and technologies that you have some experience using. *

使用経験のあるナビゲーション ツールとテクノロジーをすべて選択します。

사용 경험이 있는 내비게이션 도구와 기술을 모두 선택합니다.

Check all that apply.

☐ Compass | コンパス | 다이빙 컴퍼스

☐ Line Markers | スキューバダイビング ラインマーカー | 스쿠버 다이빙 라인 마커

☐ Dive lights | ダイブライト | 다이브라이트

☐ Diving Reel | ダイビングリール | 다이빙 릴

☐ Surface marker buoy (SMB)

☐ Kick cycles

☐ Dive tablet

☐ Other

3. According to you what are the most challenging tasks related to diving navigation? *

Check all that apply.

☐ Distracting marine life | 海洋生物は非常に気が散る | 해양 생물에 정신이 팔려 있습니다
☐ Silt | シルト | 실트
☐ Nitrogen narcosis. | 窒素中毒 | 질소 중독
☐ High turbidity of water | 水の濁度が高い | 물의 높은 탁도
☐ Lack of sufficient sunlight | 十分な日光の不足 | 일조량 부족
☐ Strong currents | 強い流れ | 강류
☐ Thermoclines | 水温の変化 | 수온의 변화
☐ Understanding other diver's communication | 他のダイバーのコミュニケーションを理解 | 다른 다이버의 의사소통 이해하기
☐ Navigation practices differ at each dive center | ダイビングセンターごとにナビゲーション方法が異なります | 다이빙 센터마다 내비게이션 실습이 다릅니다
☐ Unknown gear | 新しいギア | 뉴 기어
☐ Unknown dive sites | 不明なダイビングサイト| 알 수 없는 다이빙 사이트
☐ Narrow passages / caves | 狭い通路/洞窟 | 좁은 통로/동굴
☐ Other: ______________________________

Device design I デバイス設計 I 장치 설계

4. What kind of suit do you dive with usually? 普段はどんなスーツでダイビングをしていますか？평소에는 어떤 정장을 입고 다이빙을 하나요? *

Mark only one oval.

○ Wet suit
○ Dry suit

5. When we develop a navigation device, where would you like to hav it placed on your body? Select number where you would mostly like to have it placed. You can select multiple options. *

ナビゲーション装置を開発する際、体のどこに設置したいですか？ 最も配置したい場所の番号を選択します。 複数のオプションを選択できます。

내비게이션을 개발할 때, 당신은 그것을 당신의 몸 어디에 두길 원합니까? 주로 배치할 번호를 선택합니다. 여러 옵션을 선택할 수 있습니다.

Check all that apply.

☐ 1
☐ 2
☐ 3
☐ 4
☐ 5
☐ 6
☐ 7
☐ 8
☐ 9
☐ 10
☐ Other: ____________

6. We are currently working on two technologies. Read short description of each and select one which you would like to try. *

Artificial muscle. This would be a device that gets attached to the outer side of your diving suit and works like a small car air bag. When sonar sensors will detect that you are too close to an obstacle a pony bottle compressed air will be injected in small quantities to a tube which will inflate and create a protective layer.

人工筋肉。 これは潜水服の外側に取り付けられ、小型のエアバッグのように動作する装置です。 ソナーセンサーが障害物に近すぎることを検出すると、ポニーボトルの圧縮空気がチューブに少量注入され、チューブが膨らみ、保護層が形成されます。

인공근육. 이것은 잠수복의 바깥쪽에 부착되어 작은 자동차 에어백처럼 작동하는 장치일 것이다. 음파 센서가 장애물에 너무 가까이 있음을 감지하면 포니병 압축 공기가 튜브에 소량 주입되어 팽창하고 보호막을 생성합니다.

Haptic-sonar unit. This would be a device that gets attached to the outer side of your diving suit and works like a car parking system. When sonar sensors will detect that you are too close to an obstacle you will get vibrations similar to the ones that you can feel when you phone is ringing and vibrating strongly. The closer you will get to the obstacle the stronger the vibration will get.

これは潜水服の外側に取り付けられ、駐車システムのように動作する装置です。 ソナーセンサーが障害物に近づきすぎていることを検出すると、電話が鳴っているときや強く振動しているときに感じるのと同じような振動が発生します。 障害物に近づけば近づくほど、振動は強くなります。

이것은 잠수복의 바깥쪽에 부착되어 주차 시스템처럼 작동하는 장치일 것이다. 음파 센서가 장애물에 너무 가까이 있음을 감지하면 전화기가 울리고 강하게 진동할 때 느낄 수 있는 진동과 유사한 진동을 받게 됩니다. 장애물에 가까워질수록 진동이 강해질 것이다.

○ Other: ____________

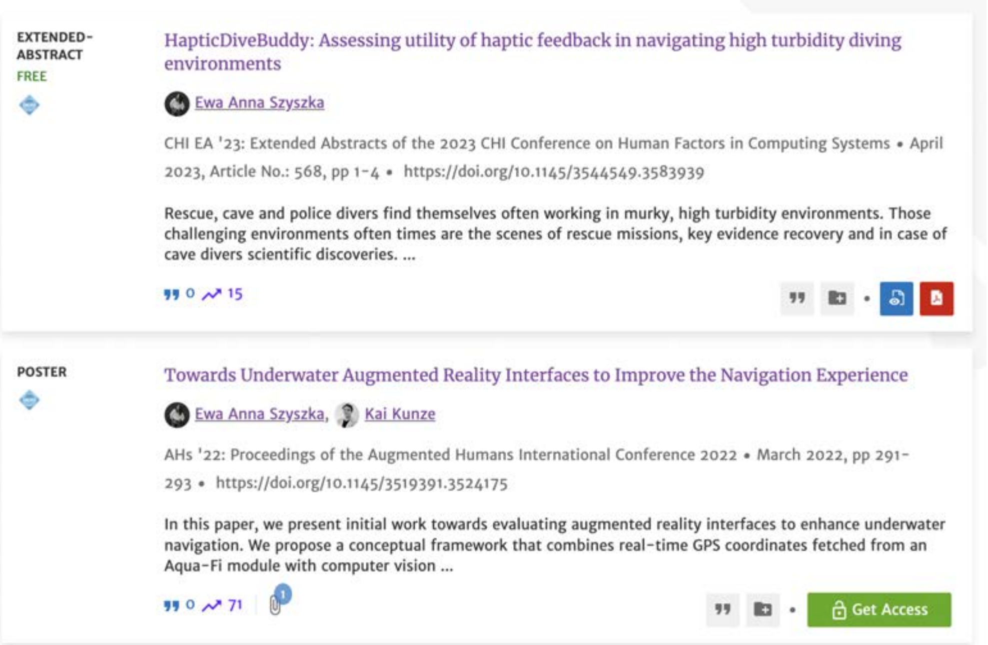
7. If you are a dry suit diver and you selected the haptic-sonar unit option above would you rather have the device placed inside or outside your dry suit? あなたがドライスーツダイバーで、上記のハプティックソナーユニットオプションを選択した場合、デバイスをドライスーツの内側または外側に配置しますか？ 만약 당신이 드라이슈트 다이버이고 위의 햅틱-소나 장치 옵션을 선택했다면, 당신은 당신의 드라이슈트 안에 장치를 두길 원합니까 아니면 밖에 장치를 두길 원합니까?

Mark only one oval.

○ Outside
○ Inside

8. Do you have any questions or request? Feel free to leave any feedback here.

B. Appendix B: Publications



HapticDiveBuddy: Assessing utility of haptic feedback in navigating high turbidity diving environments

Ewa Anna Szyszka

CHI EA '23: Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems • April 2023, Article No.: 568, pp 1–4 • https://doi.org/10.1145/3544549.3583939

Rescue, cave and police divers find themselves often working in murky, high turbidity environments. Those challenging environments often times are the scenes of rescue missions, key evidence recovery and in case of cave divers scientific discoveries. ...

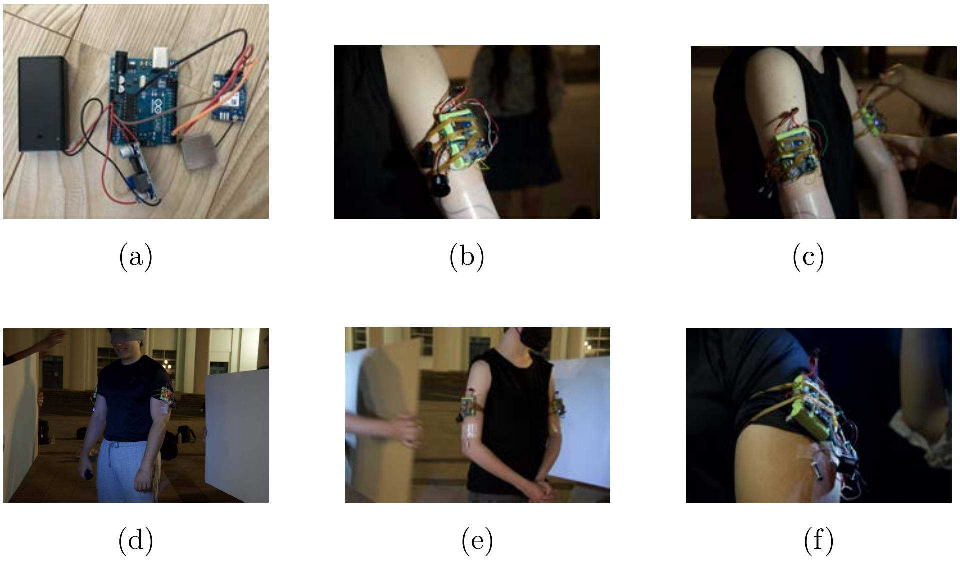
Towards Underwater Augmented Reality Interfaces to Improve the Navigation Experience

Ewa Anna Szyszka, Kai Kunze

AHs '22: Proceedings of the Augmented Humans International Conference 2022 • March 2022, pp 291–293 • https://doi.org/10.1145/3519391.3524175

In this paper, we present initial work towards evaluating augmented reality interfaces to enhance underwater navigation. We propose a conceptual framework that combines real-time GPS coordinates fetched from an Aqua-Fi module with computer vision ...

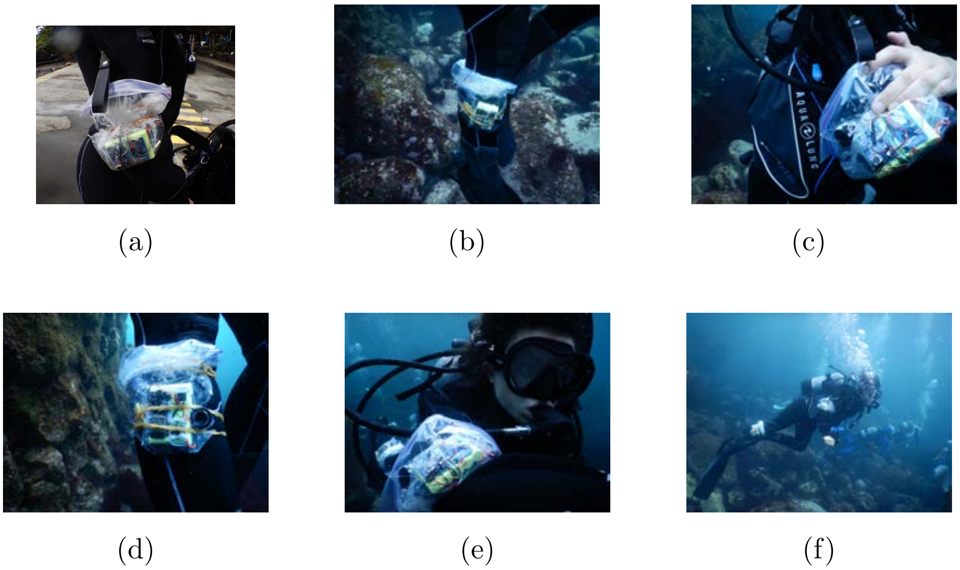
C. Appendix C: Documentation



(a) (b) (c)

(d) (e) (f)

Figure C.1: Photographic documentation: Dry experiment

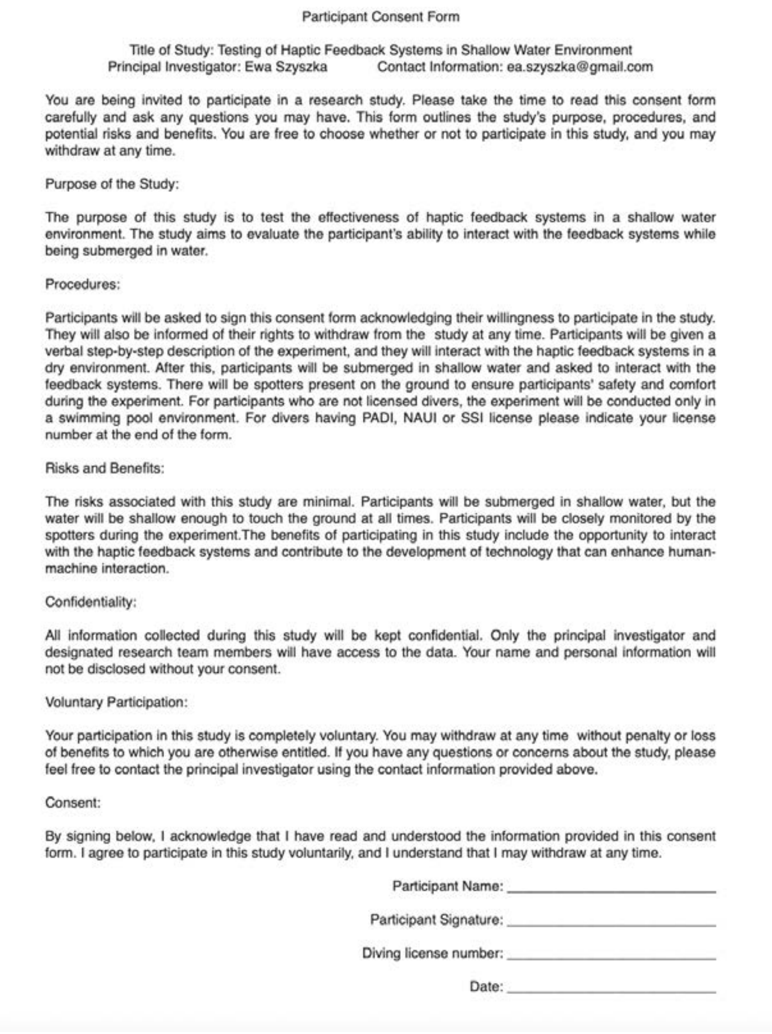


(a) (b) (c)

(d) (e) (f)

Figure C.2: Photographic documentation: Ocean experiment

D. Appendix D: Workshop 2: Survey



Participant Consent Form

Title of Study: Testing of Haptic Feedback Systems in Shallow Water Environment
Principal Investigator: Ewa Szyszka Contact Information: ea.szyszka@gmail.com

You are being invited to participate in a research study. Please take the time to read this consent form carefully and ask any questions you may have. This form outlines the study's purpose, procedures, and potential risks and benefits. You are free to choose whether or not to participate in this study, and you may withdraw at any time.

Purpose of the Study:

The purpose of this study is to test the effectiveness of haptic feedback systems in a shallow water environment. The study aims to evaluate the participant's ability to interact with the feedback systems while being submerged in water.

Procedures:

Participants will be asked to sign this consent form acknowledging their willingness to participate in the study. They will also be informed of their rights to withdraw from the study at any time. Participants will be given a verbal step-by-step description of the experiment, and they will interact with the haptic feedback systems in a dry environment. After this, participants will be submerged in shallow water and asked to interact with the feedback systems. There will be spotters present on the ground to ensure participants' safety and comfort during the experiment. For participants who are not licensed divers, the experiment will be conducted only in a swimming pool environment. For divers having PADI, NAUI or SSI license please indicate your license number at the end of the form.

Risks and Benefits:

The risks associated with this study are minimal. Participants will be submerged in shallow water, but the water will be shallow enough to touch the ground at all times. Participants will be closely monitored by the spotters during the experiment.The benefits of participating in this study include the opportunity to interact with the haptic feedback systems and contribute to the development of technology that can enhance human-machine interaction.

Confidentiality:

All information collected during this study will be kept confidential. Only the principal investigator and designated research team members will have access to the data. Your name and personal information will not be disclosed without your consent.

Voluntary Participation:

Your participation in this study is completely voluntary. You may withdraw at any time without penalty or loss of benefits to which you are otherwise entitled. If you have any questions or concerns about the study, please feel free to contact the principal investigator using the contact information provided above.

Consent:

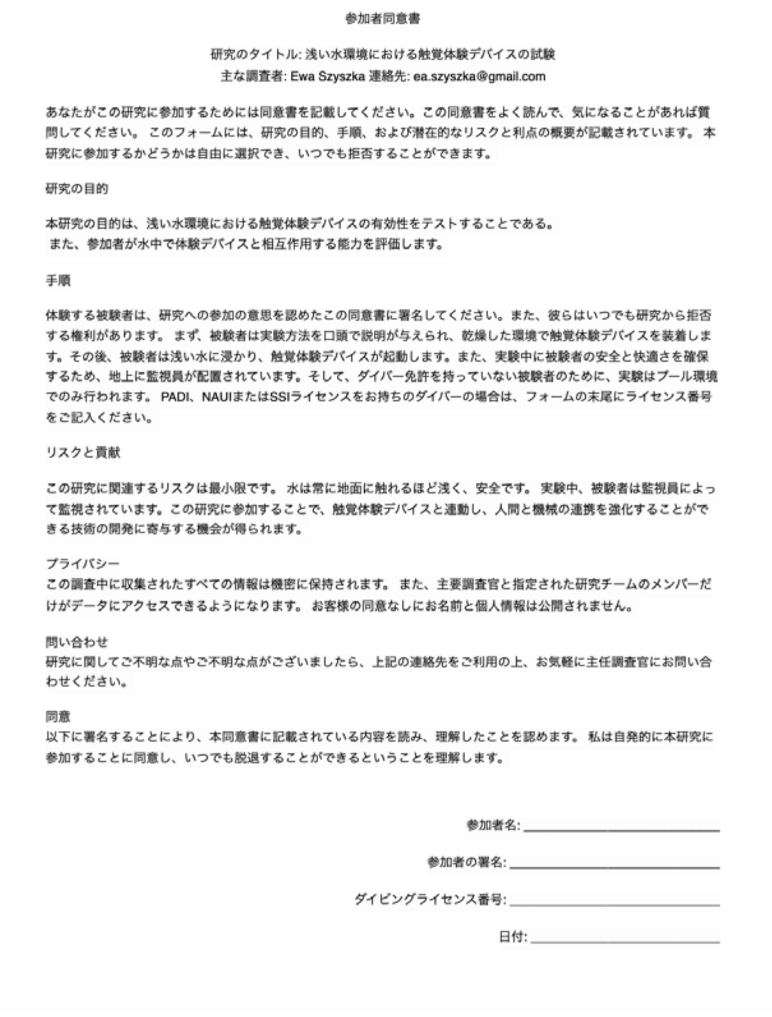
By signing below, I acknowledge that I have read and understood the information provided in this consent form. I agree to participate in this study voluntarily, and I understand that I may withdraw at any time.

Participant Name: ____________________

Participant Signature: ____________________

Diving license number: ____________________

Date: ____________________



参加者同意書

研究のタイトル: 浅い水環境における触覚体験デバイスの試験
主な調査者: Ewa Szyszka 連絡先: ea.szyszka@gmail.com

あなたがこの研究に参加するためには同意書を記載してください。この同意書をよく読んで、気になることがあれば質問してください。 このフォームには、研究の目的、手順、および潜在的なリスクと利点の概要が記載されています。 本研究に参加するかどうかは自由に選択でき、いつでも拒否することができます。

研究の目的

本研究の目的は、浅い水環境における触覚体験デバイスの有効性をテストすることである。
また、参加者が水中で体験デバイスと相互作用する能力を評価します。

手順

体験する被験者は、研究への参加の意思を認めたこの同意書に署名してください。また、彼らはいつでも研究から拒否する権利があります。 まず、被験者は実験方法を口頭で説明が与えられ、乾燥した環境で触覚体験デバイスを装着します。その後、被験者は浅い水に浸かり、触覚体験デバイスが起動します。また、実験中に被験者の安全と快適さを確保するため、地上に監視員が配置されています。そして、ダイバー免許を持っていない被験者のために、実験はプール環境でのみ行われます。 PADI、NAUIまたはSSIライセンスをお持ちのダイバーの場合は、フォームの末尾にライセンス番号をご記入ください。

リスクと貢献

この研究に関連するリスクは最小限です。 水は常に地面に触れるほど浅く、安全です。 実験中、被験者は監視員によって監視されています。この研究に参加することで、触覚体験デバイスと連動し、人間と機械の連携を強化することができる技術の開発に寄与する機会が得られます。

プライバシー
この調査中に収集されたすべての情報は機密に保持されます。 また、主要調査官と指定された研究チームのメンバーだけがデータにアクセスできるようになります。 お客様の同意なしにお名前と個人情報は公開されません。

問い合わせ
研究に関してご不明な点やご不明な点がございましたら、上記の連絡先をご利用の上、お気軽に主任調査官にお問い合わせください。

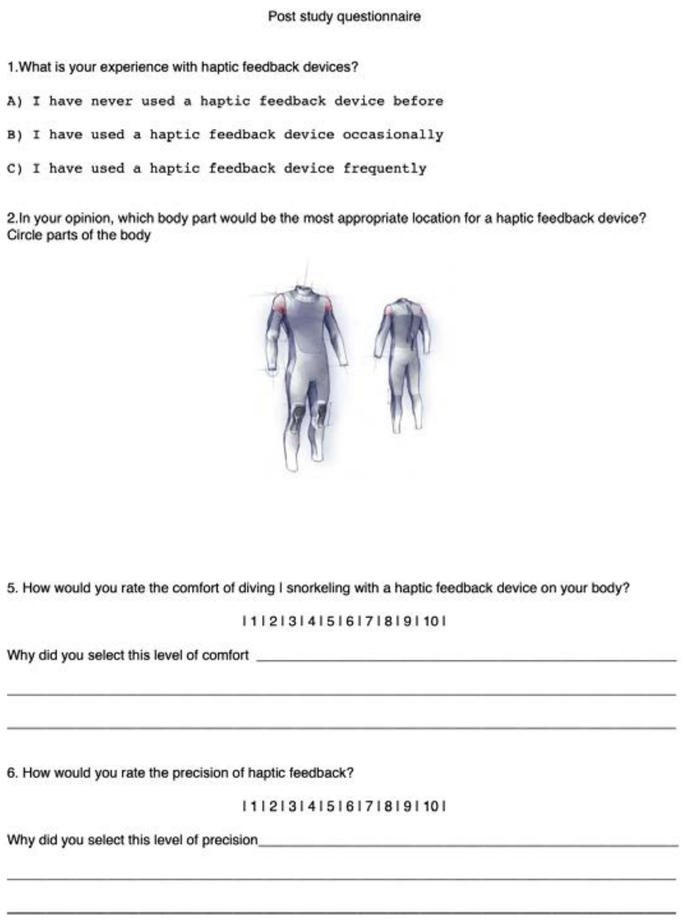
同意
以下に署名することにより、本同意書に記載されている内容を読み、理解したことを認めます。 私は自発的に本研究に参加することに同意し、いつでも脱退することができるということを理解します。

参加者名: ____________________

参加者の署名: ____________________

ダイビングライセンス番号: ____________________

日付: ____________________



Post study questionnaire

1.What is your experience with haptic feedback devices?

A) I have never used a haptic feedback device before

B) I have used a haptic feedback device occasionally

C) I have used a haptic feedback device frequently

2.In your opinion, which body part would be the most appropriate location for a haptic feedback device?
Circle parts of the body

5. How would you rate the comfort of diving I snorkeling with a haptic feedback device on your body?

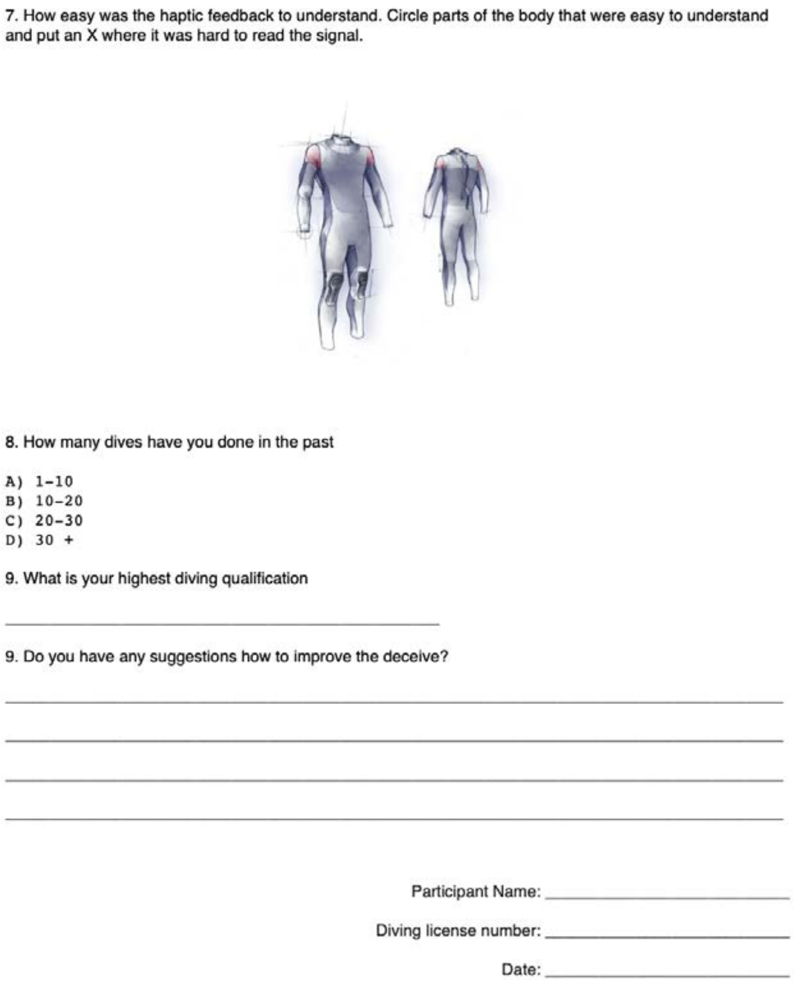
|1|2|3|4|5|6|7|8|9|10|

Why did you select this level of comfort ____________________

6. How would you rate the precision of haptic feedback?

|1|2|3|4|5|6|7|8|9|10|

Why did you select this level of precision____________________



7. How easy was the haptic feedback to understand. Circle parts of the body that were easy to understand and put an X where it was hard to read the signal.

8. How many dives have you done in the past

A) 1-10
B) 10-20
C) 20-30
D) 30 +

9. What is your highest diving qualification

____

9. Do you have any suggestions how to improve the deceive?

____

____

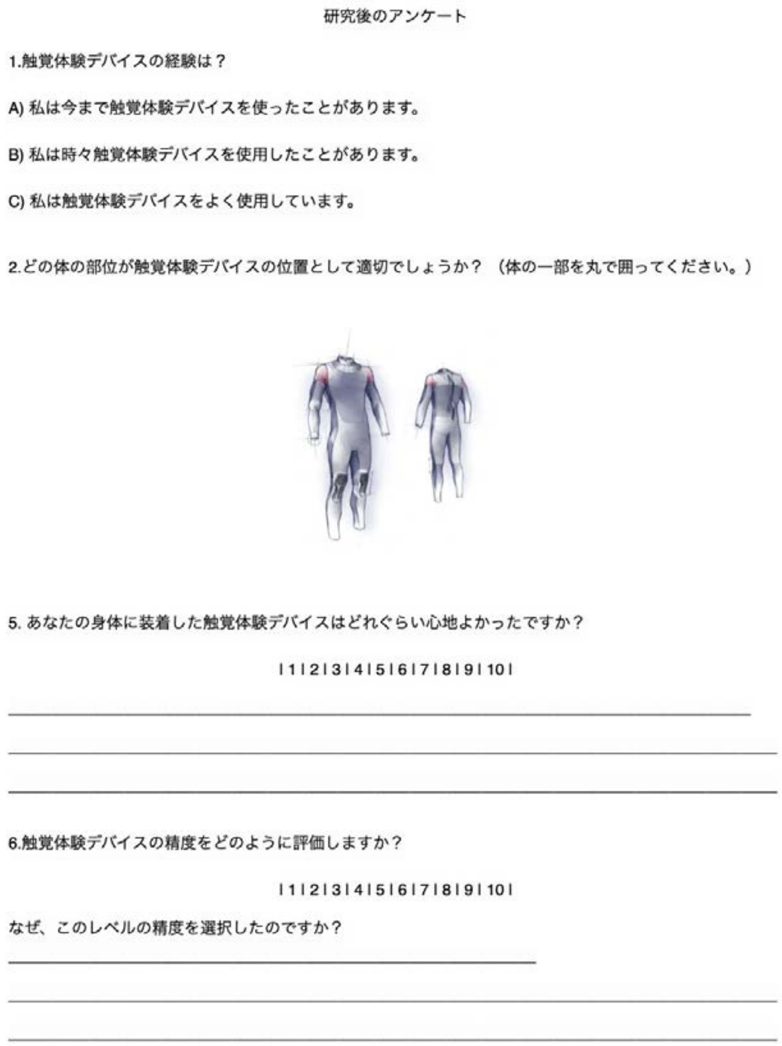
____

____

Participant Name: ____________________

Diving license number: ____________________

Date: ____________________



研究後のアンケート

1.触覚体験デバイスの経験は？

A) 私は今まで触覚体験デバイスを使ったことがあります。

B) 私は時々触覚体験デバイスを使用したことがあります。

C) 私は触覚体験デバイスをよく使用しています。

2.どの体の部位が触覚体験デバイスの位置として適切でしょうか？ （体の一部を丸で囲ってください。）

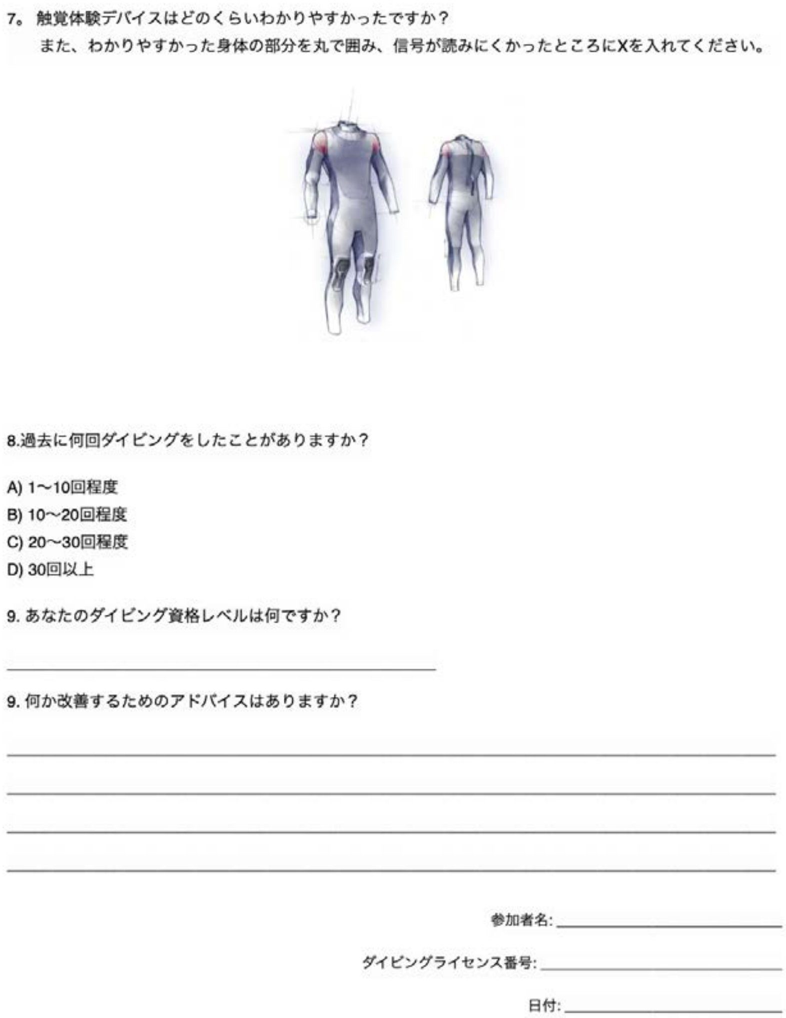
5. あなたの身体に装着した触覚体験デバイスはどれぐらい心地よかったですか？

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |

6.触覚体験デバイスの精度をどのように評価しますか？

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |

なぜ、このレベルの精度を選択したのですか？



7。 触覚体験デバイスはどのくらいわかりやすかったですか？
また、わかりやすかった身体の部分を丸で囲み、信号が読みにくかったところにXを入れてください。

8.過去に何回ダイビングをしたことがありますか？

A) 1〜10回程度
B) 10〜20回程度
C) 20〜30回程度
D) 30回以上

9. あなたのダイビング資格レベルは何ですか？

____

9. 何か改善するためのアドバイスはありますか？

____

____

____

____

参加者名: ____________________

ダイビングライセンス番号: ____________________

日付: ____________________

E. Appendix E: Haptic-Sonar unit code

```
Define TRIG_PIN as 32  // GPIO pin - Trig pin of HC-SR04
Define ECHO_PIN as 33  // GPIO pin - the Echo pin of HC-SR04
Define BUZZ1_PIN as 26 // GPIO pin - first ERM actuator
Define BUZZ2_PIN as 27 // GPIO pin - second ERM actuator

Include the Wire library
Include the MS5837 library

Instantiate an object of the MS5837 class named 'sensor'

Setup:
  Initialize the serial communication with a baud rate of 9600
  Set TRIG_PIN as an OUTPUT
  Set ECHO_PIN as an INPUT
  Set BUZZ1_PIN as an OUTPUT
  Set BUZZ2_PIN as an OUTPUT
  Start the Wire communication
  While the sensor initialization fails:
    Print "Init failed!"
    Print "Are SDA/SCL connected correctly?"
    Print "Blue Robotics Bar30: White=SDA, Green=SCL"
    Delay for 5 seconds

  Set the model of the sensor to MS5837_30BA
  Set the fluid density to 997 kg/m^3 (freshwater, 1029 for seawater)

Loop:
  Set TRIG_PIN to LOW
  Delay for 2 microseconds
  Set TRIG_PIN to HIGH
  Delay for 10 microseconds
  Set TRIG_PIN to LOW
```

```
Read the duration of the pulse on ECHO_PIN while it is HIGH
Calculate the distance based on the duration

If distance is less than 21:
  Set BUZZ1_PIN to HIGH
  Set BUZZ2_PIN to HIGH
Else if distance is between 21 and 25:
  Set BUZZ1_PIN to HIGH
  Set BUZZ2_PIN to HIGH
  Delay for 50 milliseconds
  Set BUZZ1_PIN to LOW
  Set BUZZ2_PIN to LOW
  Delay for 50 milliseconds
Else if distance is between 25 and 30:
  Set BUZZ1_PIN to HIGH
  Set BUZZ2_PIN to HIGH
  Delay for 500 milliseconds
  Set BUZZ1_PIN to LOW
  Set BUZZ2_PIN to LOW
  Delay for 500 milliseconds
Else:
  Set BUZZ1_PIN to LOW
  Set BUZZ2_PIN to LOW

Print "Distance: " in centimeters

Read the pressure and temperature readings from the sensor
Print "Pressure: "  in millibars
Print "Temperature: "in degrees Celsius
Print "Depth: "  in meters
Print "Altitude: " in meters
```