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Comparing feedback techniques for underwater navigation

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Abstract

A lot of research is going into underwater global positioning systems since radio waves do not propagate underwater. However, the few underwater navigation approaches out there use bulky screen devices which are held in hand. This leads to constrained movement, is rather distractive, and prone to varying brightness conditions. In this master thesis we describe the construction of a prototype, which incorporates several feedback methods, and its evaluation. We implement a vibration motor, a red LED, and a thermoelectric cooler in diving goggles and a headband. Additionally waterproof in-ear headphones are used for auditory feedback. Since these devices are worn on the head they allow an unintrusive way to give low level directional cues. In a user study we evaluate the feedback methods ashore as a baseline and compare it to their performance underwater and gather additional qualitative feedback of the participants.

Überblick

Global Positioning Systeme für Navigation unter Wasser ist ein aktuelles Forschungsgebiet, da Radiowellen unter Wasser nicht übertragen werden. Die wenigen Systeme, die Unterwassernavigation zu einem gewissen Level umsetzen, nutzen Bildschirme, die in der Hand gehalten werden. Das schränkt die Bewegungsfreiheit ein, ist eher ablenkend und die Sichtbarkeit ist beeinflusst durch die sich ändernden Lichtverhältnisse. In dieser Masterarbeit wird die Konstruktion eines Prototypen beschrieben, der verschiedene Feedbackmethoden beinhaltet und deren Auswertung. Wir benutzen einen Vibrationsmotor, eine rote LED und ein Peltier Element in einer Taucherbrille und Stirnband. Zusätzlich verwenden wir wasserfeste In-Ohr-Kopfhörer für akustisches Feedback. Da diese Geräte direkt am Kopf getragen werden, ermöglichen sie einen unaufdringlichen Wege Richtungsangaben auf niedrigem Level zu vermitteln. In einen Benutzerstudie werten wir die verschiedenen Feedbackmethoden an Land aus und vergleichen die Leistung mit der unter Wasser. Zusätzlichen sammeln wir qualitatives Feedback der Teilnehmer.

Acknowledgements

First of all, I would like to thank Prof. Dr. Jan Borchers for supervising my thesis and Dr.-Ing. Ulrik Schroeder for being my second examiner. Secondly, I would like to thank Jan Thar for her feedback and guidance. Furthermore, thanks to everyone who participated in the time-consuming user study.

Conventions

Throughout this thesis we use the following conventions.

Text conventions

Definitions of technical terms or short excursus are set off in coloured boxes.

EXCURSUS:
Excursus are detailed discussions of a particular point in a book, usually in an appendix, or digressions in a written text.

Definition:
Excursus

Source code and implementation symbols are written in typewriter-style text.

`myClass`

The whole thesis is written in Canadian English.

Download links are set off in coloured boxes.

File: myFile[a]

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Chapter 1

Introduction

Today navigation systems are a natural part of our everyday life. They are used in vehicles and every smart phone has GPS and map information as well. GPS uses 29 satellites in the atmosphere where at least four of them are in view from any spot on the earth at any time. The satellites are synchronized by control stations around the globe using atomic clocks. The receiver triangulates the position with the distance information of the satellites. Most of the time this navigation information is conveyed visually by a screen or auditory with precise instructions.

Underwater navigation can be as crucial as it is outside the water. From novice snorkellers to experienced scuba (self-contained underwater breathing apparatus) divers navigation information can lead to a better experience or is essential for the task. Novice divers have no knowledge of the area and are not used to the orientation via certain landmarks. GPS underwater can help to navigate the user to points of interest, save locations to share them later, find back to the start, or view the route later on the computer.

GPS underwater is a complex topic since the signals of GPS satellites do not propagate below the water surface. Current research investigates different approaches to provide GPS underwater not only for divers but submarines and autonomous underwater vehicles (AUV). A few systems are out there which already use a floating GPS antenna wired to a screen held by the diver [Nehowig, 2014]. Another system uses an initial GPS position before submerging and switches to inertial sensor measurements while submerged [Ariadna Tech, 2016]. Using acoustic waves in analogy to the radio waves of the GPS satellites is locally used in WaterLinked [WaterLinked, 2018] and researched [Taraldsen et al., 2011].

These systems, partly commercially available, focus on their realization of the GPS problem. All of them use waterproof encapsulated screens and controls which are held by the user all the time. On one hand, screens are a rich solution and can provide detailed information not only for navigation. On the other hand it can be tedious to carry a screen device all time, including the wires and high power consumption. Other solutions which focus more on the interaction part of underwater navigation systems propose augmented reality diving goggles [N. Smith, 2015]. It is an all in one system which is most likely expensive and not suitable for everyone.

Since underwater GPS is hard to deploy without a proper test environment we decide to focus on the interaction aspect. Following the concept of ubiquitous computing we aim to make the technology invisible to achieve high acceptance and less distraction [Weiser, 1993]. Therefore, we focus on low level feedback which can give directional cues using more affordable electronics.

In this thesis we present our prototype comprising an LED, a vibration motor, a Peltier cooling element, and waterproof headphones. We describe how it is built and what consideration it implies. Furthermore we conduct a user study with 10 participants testing the system underwater and one participant outside the water for comparison. We evaluate for the time it takes the participants to perceive the feedback by and ask for qualitative feedback via a questionnaire and comments.

The results show that light, vibration, and sound achieve rather similar reaction times. Thermal feedback performs poorly underwater and is not even recognized by all participants. Additionally, the power consumption of the thermoelectric cooler is not reasonable in mobile environments. Qualitative feedback supports the data of the study that vibration feedback is recommended to convey low level directional cues underwater since it unobtrusive, well recognizable, and comfortable.

Chapter 2

Related work

In this chapter we give an overview of related work and research in the the fields of underwater navigation systems. It is divided into three parts. First we give an overview of currently used technology used for underwater position tracking and the issues in comparison with common GPS. Second it covers existing systems which incorporate position tracking and underwater feedback today and third research regarding several feedback modalities.

Military grade underwater navigation

It is commonly known that radio signals do not propagate underwater. Current state of the art solutions consists of large and expensive inertial measurement units. Those are for example used in submarines and take the last known position in combination with military grade accelerometer and diving depth to interpolate the current location [Meyer, 2016].

Inertial Data Fusion

Rossi et al. [2014] presented a data fusion algorithm for inertial navigation with focus on performance. It is based on the idea of data fusion which measures and combines values from several inertial sensors.

Acoustic GPS

Taraldsen et al. [2011] technology relies on acoustic waves as an analogy to the GPS radio waves. They discuss different approaches of Dilution Of Precision (DOP) which differ from the classical GPS setting. Using statistical methods, they estimate the accuracy of positioning and try to correct errors.

2.1 Underwater Navigation Systems

Navimate

Shb Instruments [2009] developed Navimate which uses a floating radio antenna for GPS and several underwater transducers to communicate with a wrist-worn device via acoustic signals. The device receives the signals and uses the information of the GPS and the transducers to determine its location and presents the information on the screen.

NavDive

Nehowig [2014] built NavDive which uses a floating GPS receiver wired to a mobile receiver held by the diver. It shows the direction to previously set locations and positional information in text form. A desktop application lets the user inspect their diving path and add landmarks for locations of interest.

Ariadna Tech

Ariadna Tech [2016] developed a system which uses an initial GPS location from the wrist unit before submerging and switches to inertial sensors afterwards. The sensors track the divers real-time position, speed, heading, and distance information using a navigation transmitter worn on the leg. It calculates the information in and sends it wirelessly to to the wrist unit which displays it on screen.

WaterLinked

WaterLinked [2018] uses four hydro acoustic receiver in the water connected to a base station with access to a GPS antenna. The tracked object or diver is equipped with a locator which acts as an beacon sending acoustic pulses. These acoustic pulses are received be the four hydrophones and analysed with time-of-arrival and the GPS data. This system enables tracking of submerged ROVs and divers but not for the divers themselves.

Scubus S

N. Smith [2015] propose a system similar to featuring a head up display like Google Glass, a LED flash light, and a HD camera. All electronics including the battery are integrated into the smart diving goggles. The image is pro-

Figure 2.1: Scubus S smart diving goggles by Noah Smith.

jected into the eye of the user. The system is shown in figure 2.1

2.2 Feedback modalities

GentleGuide

Bosman et al. [2003] built and tested a system using two wrist worn vibration devices. Main findings were that vibration feedback on one wrist is confusing, vibrations are rather a beacon to follow than a correction of one's direction, and that direction is better encoded in the duration of the pulse than the intensity. Results are promising for non-disruptive, easy learnable, low level navigation cues.

MOVING

Kiss et al. [2018] present MOtorbike VIbrational Navigation Guidance, a smart kidney belt for motor cyclists that provides feedback through 12 vibration motors. Tactile feedback allows distraction free navigation cues which are more reliable and safe than visual based navigation systems used today.

HapticHead

Kaul and Rohs [2016] developed HapticHead a system for intuitive tactile 3D guidance. The use 20 vibration motors in 3 concentric ellipses around the head to give 3D directional cues in virtual or augmented reality environment. Vibration performed well compared to direct visual guidance and significantly better than 3D auditory cues.

IrukaTact

IrukaTact by Chacin and Oozu [2016] is a a glove which uses water propulsion on the fingertips and a sonar to assist in the location of objects underwater. The sonar detects the topography of the ground and sends the information to the system which uses micro-pumps to convey these information via varying water jets on the fingertips.

ThermoVR

Peiris et al. [2017] present ThermoVR, a VR headset with five thermal feedback modules. The thermal stimulation, hot and cold, were used to increase the immersion and give directional cues. They found that cold stimuli were perceived significantly better in providing directional feedback.

Cold vs hot stimuli

Wilson et al. [2011] discovered that cold stimuli are faster to detect and more comfortable for the user. They tested different changes of temperature per second and higher rates are better detectable. Also producing detectable cold stimuli are more power efficient than warm stimuli.

Effect of ambient temperature

Halvey et al. [2012b] investigated the environmental effects on thermal feedback recognition. They conducted an outdoor study over several month with varying conditions and showed that ambient temperature has a significant effect on the detection and perception of thermal stimuli. Humidity on the other hand has a negligible effect in mobile interaction. This result is supported by Givoni et al. [2006].

Effect of room and skin temperature

Hirosawa et al. [1984] looked into the effect of room and skin temperature on sensitivity. Their results show that the threshold values change with the room temperature for both, warm and cold.

Chapter 3

Hardware Prototype and Software

In this chapter we present the construction of the hardware prototype and development of the user study software. Furthermore we talk about the technical considerations regarding each component and their feasibility.

3.1 System Design

The aim of this thesis is to investigate the perception of several feedback modalities underwater and their feasibility for low level navigation cues. We include visual, auditory, and tactile feedback in form of a LED, waterproof in ear headphones, a vibration motor, and a thermoelectric cooling module. The prototype has to incorporate these methods as unobtrusive and comfortable as possible in particular when they are inactive. Electronic connections have to be waterproof, undisturbing, and fail safe. Furthermore all components should be affordable to provide an advantage over commercial solutions.

To investigate the recognition times and comfort of each technique we built a prototype composed of one LED in the diving goggles as well as a waterproof vibration motor and a Peltier cooling module in a stretchable headband. The headphones are provided separately.

Visual Feedback To provide visual low level feedback we use a common red 5 mm LED. An issue regarding luminous light emitted by an LED is its proneness to water reflections. These reflections change rapidly due to water undulation and exterior lighting. The color of the surroundings influence it as well. For example light blue tiles in a swimming pool render a blue LED almost undetectable. To provide clear recognizable feedback we tested several colors underwater and came to the conclusion that red LED is better recognizable than other common LED colors.

There are several ways to provide feedback with an LED. Depending on the way it is presented the user might not notice it fast enough if the brightness increases over time. However, this might be more comfortable than turning on the LED to full brightness instantly. Therefore we implement both. First we set the LED from zero to full brightness immediately. Second we increase the brightness from 0% to 100% and back to 0% over 5.1 seconds resulting in a slowly blinking pattern. We choose this interval arbitrarily after testing several duration. This can be further investigated but would go beyond the scope of this thesis since we aim to consider several modalities.

Auditory Feedback For auditory feedback we choose AGPTEK E11B IPX8 waterproof in-ear headphones. The headphones are worn separately from the other components and are connected to the operating MacBook Pro. Like visual feedback, the comfortableness of auditory feedback depends on the way it is presented to the user. The audio file played should start immediately and be clearly recognizable. Furthermore the pitch and loudness should be within an appropriate range. We use the sound of a sonar since it suits the underwater scenario.

Vibration Feedback To provide feedback using vibration actuators we choose waterproof 7 mm vibration motors.

They are working at 3.3 V with 2.45 g at 250 Hz. We tried to make smaller vibration motors waterproof. Using shrinking tubing and epoxy resin adhesive made them waterproof but running them over night underwater let them stop working regardless. Thus we have to stick to the larger motor.

We handle the vibration feedback similar to the visual feedback and set it to maximum power instantaneously as well as increasing it over time. Tests have shown that it requires a certain amount of voltage to feel a vibration even outside the water. Therefore we start at 1,18 V, where vibration is barely noticeable, and increase to 3.3 V over 5.4 seconds.

Literature suggests to place tactile feedback at the shoulders or the hips [Kiss et al., 2018]. Since we aim to build a compact prototype we implement the vibration motor in the headband instead of an separate belt which would include more wires. Additionally we think that especially while snorkeling the users want an unobtrusive experience.

Thermal Feedback For thermal feedback we choose a CUI CP6014 Thermoelectric Module. Peiris et al. [2017] have shown that users prefer cooling over heating. Cooling also performs better when it comes to recognition time. Previously we tested heating and cooling effects in water with 21 degrees and cooling was much faster perceivable than heating. Additionally heating effects were rarely recognizable. The theromelectric cooler has a maximum voltage of 2.1V and maximum current of 6 A. Therefore we use an external battery combined with a relay to operate it. There are specific circuit boards to control the temperature of theromelectric cooling elements. However, we considered that running it on full power is sufficient for our purpose since we are interested in the fastest possible reaction times underwater.

Figure 3.1: LED insulated and attached between the silicone and frame of the diving goggles using hotglue.

3.1.1 Hardware Prototype

As shown in figure 3.1 the LED is glued to the diving goggles between the silicone and the frame. There are three reasons to place the LED there. First, the LED is not in sight or noticeable when turned off and thus unobtrusive. Second, the light is diffused by the silicone leading to non-dazzling feedback. Third, the cable routing is easier compared to placing it within the silicone and still make sure no water gets in.

In addition to the stretchability of the headband it feature a pair of hook and loop fastener as shown in figure 3.2. Both parts of the fastener are 12 cm long allowing alignment of headband length from approximately 38 up to 62

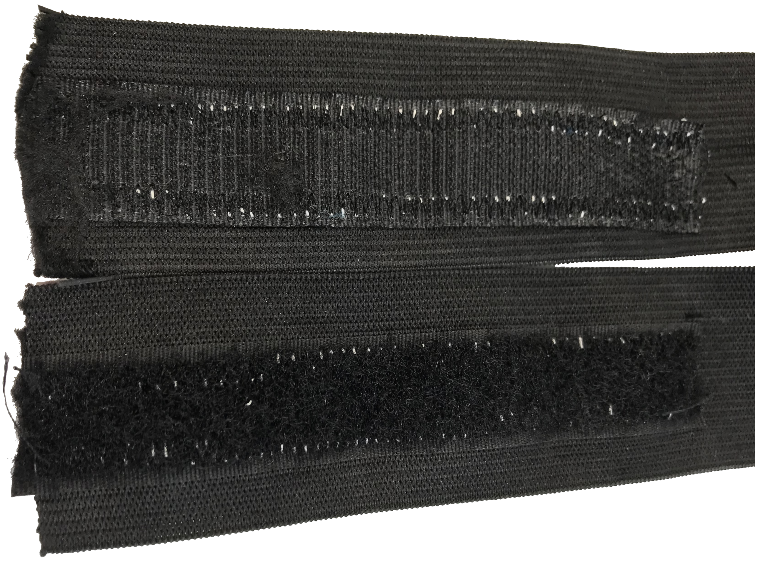

Figure 3.2: Stretchable headband with hook and loop fastener sewn to it. Allows comfortable adjustment on different head froms and sizes.

cm (stretching not included). This enables adjustable, tight, and still comfortable wear of the headband. The fasteners were sewn to the 40 mm wide elastic band using a Bernina 880.

To sense the cooling effect of the thermoelectric module it has to be placed directly onto the users skin. We achieve this by cutting two holes in the elastic band and put the VCC and Ground wires through it. Although the edges of the module seem to be uncomfortable, none of the users noticed it at all while it was not active. The heat produced by the theromelectric cooler is no issue underwater since the water naturally conducts the heat away.

As depicted in figure 3.4 a piece of the elastic band was sewn to the headband to house the vibration motor. Since we choose an already waterproof vibration motor the only challenge is to keep the motor in place and still provide as much tactile performance to the user as possible. Therefore the the piece of elastic band is sewn to the headband to be at maximum stretch when the motor is in the bag. The ki-

Figure 3.3: theromelectric cooler mounted to the headband to be placed directly on the users skin.

netic energy is better transferred by rigid objects. As for the theromelectric cooler, the motor is not perceived by the user wearing the headband while it is turned off.

To prevent the user form tangling up in the wires we sew pieces of the elastic material to the headband as shown in figure 3.5. These wireways, leading to one side of the headband, make wire management easier and prevent them from being damaged.

The user has to provide feedback if she notices one of the possible stimuli we present to her. Figure 3.6 shows the button we use for this purpose. We pick a large button used in arcade cabinets and a 3D printed case. The button features vertical lift to prevent accidental pressing by the user. Furthermore, the supervisor can hear a clearly recognizable click sound when the button was pressed which helps monitoring the functionality of hardware and software. A consequence of this button design is that the user has to press it outside the water. This is no issue since the user will stay at the pool edge anyway.

The wires of the LED, vibration motor, theromelectric

Figure 3.4: Piece of the stretchband sewn to the headband as a bag for the vibration motor.

Figure 3.5: Pieces of the stretchband sewn to the headband as wireway for better cable management.

Figure 3.6: The botton and the 3D printed case. To be pressed by the user when he recognizes feedback.

cooler, and botton are joined with a ribbon cable depicted in figure 3.7. All connections and soldering joints are made waterproof with glue and shrinking tube. The 3 m long ribbon cable leads to the breadboard shown in figure 3.8. The breadboard houses an Arduino Uno, the cables leading form the pins to the ribbon cable, a relay, and a battery case. The relay is connected to the Arduino Uno which controls when it connects the two AA batteries with the Peltier circuit. Figure 3.9 shows all prototype parts worn by the user.

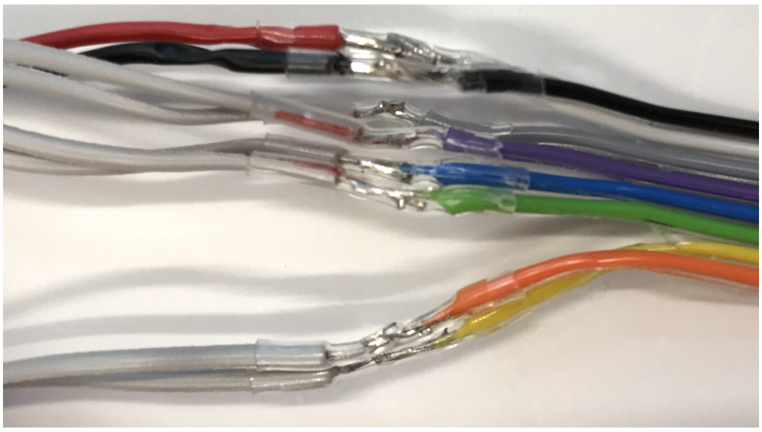

Figure 3.7: Waterproof join of wires from each actuator to the ribbon cable.

3.1.2 Safety

Since we operate electronics in an underwater test environment, safety concerns arise. In fact, the voltage and current are below critical values. Besides, all wired connections are waterproof and tested for three days in a box filled with water. The breadboard is always placed in some distance and above the water surface. During the operation of the prototype in underwater scenario the breadboard and batteries are loosely covered by a towel to protect it against splashing water.

In case the user leaves the pool edge the ribbon cable falls off the breadboard rather than pulling it down. We achieve this with shorter than usual pin header connections.

3.2 Software

The software for the prototype and the user study runs partly on the Arduino Uno micro controller and partly on a computer. The micro controller activates the feedback elements or signals the computer via processing to play a sound file. Furthermore it tracks the time a user needs to

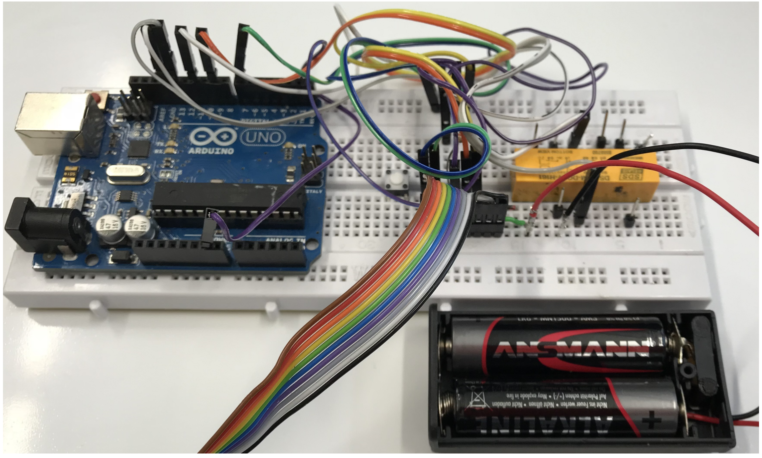

Figure 3.8: The Arduino controlling the relay and other components of the prototype via the ribbon cable. The batteries power the theromelectric cooler when the relay is set correspondingly.

press the button after the feedback was activated and sends that date to computer. Processing receives the data frames from the micro controller and creates a file to log the data for further analysis or plays the sound file and tracks that time.

Arduino Code Each stimulus (increasing LED, LED, increasing vibration, vibration, sound, theromelectric cooler) is exclusively encoded with a number from *0* to *5*. Six distinct arrays were randomly generated only limited by prohibiting occurrences of the same stimuli in a row more than two times and by making sure each stimuli is active exactly 8 times. This results in 48 stimuli per program run. The random generation of the arrays is used to prevent participants from recognizing the order of the stimulus which might influence the results. It has been done in a separate program due to an inefficient algorithm which would slow down the user study program unnecessarily.

The program iterates over the array and a *switch case* statement that triggers the corresponding actions. For each action the time is saved in milliseconds immediately before

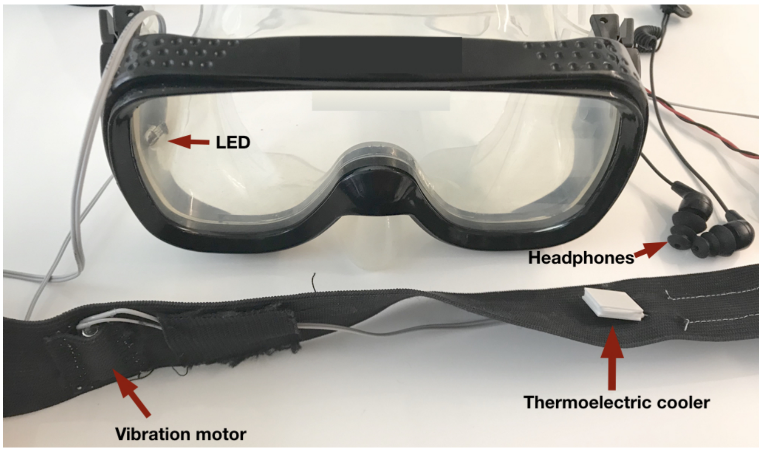

Figure 3.9: Headband, diving goggles, and waterproof headphones with the integrated LED, Vibration motor, and Thermoelectric cooling module.

the stimulus is activated. The program proceeds with the current action until the button is pressed and the start time is subtracted from the end time. Results are sent in a format which specifies whether data (*D*) follows, the sound file (*S*) has to be played, or an interrupt (*I*) via a button press was issued after the sound file was played. This is followed by the identification number of the action. Thereupon follows the time (*t*) in milliseconds and an *x* to terminate the frame or just the *x* if it is not data. Tracking the time of the sound is done on the computer. For example a data frame after the LED action is completed in 0.45 seconds looks like *D3t450x*, a play-sound frame like *S5x*, and when the button was pressed while the sound file is playing like *Ix*.

After each action is completed the program waits for two seconds and additionally a random number of seconds between zero and five before the next action triggers. This is done to further prevent adoption to a rhythm which influences the measurements. Once the 48 actions are completed *Fx* is sent and the program enters an infinite loop.

Processing Code In Processing we create a Writer which creates and writes to a text file for logging the user study data. Furthermore a sound file is loaded to be played when the corresponding signal from the micro controller arrives. Processing reads the incoming data from the micro controller per character and saves it in an array of characters. If *x* is read, the serial port is cleared and the data handling begins. In case of a data transmission for the LED, vibration motor, or theromelectric cooler, the identification number of the current stimulus and the corresponding time is written to the log file. If S is received the sound file is played and the time is saved. After pressing the button, playback of the sound file stops and the time taken is calculated and written to the logfile. After handling the data the buffer is cleared and the next data frame can be received. When the micro controller sends F to signal the end of the program the log file is saved.

3.2.1 Testing

Hardware testing To ensure the functionality of the prototype underwater and over a longer period of time testing is required. This is particularly important since the supervisor of the study can not tell if the prototype works properly while the participant is submerged. In advance of assembling the prototype we tested each component individually for several days. The corresponding modes for each modality were activated in intervals similar to the user study program. As mentioned in 3 we tested some vibration motors which were not suited for our needs. Repeated tests have shown that the small and cheaper vibration motors break after running them even outside the water. However higher quality vibration motors in the same small order of magnitude seem promising. Since the already waterproof vibration motors passed the test we went with those for the sake of convenience. All other components passed the testing without errors.

Measurement accuracy Since we measure in milliseconds and feedback is partly recognized in under one second we must ensure the measurements are correct. To ensure high accuracy we tested each modality and the communication latency itself. Communication latency is not measurable within the millisecond range. The sound file is cut such that it starts with a clearly audible noise level from the beginning. Measuring a single playback of the file reveals that there is a short delay of about 2 milliseconds. This delay can be considered redundant. Besides it is influenced by the hardware which reads and plays the file and the file size itself. To reduce the delay of the vibration motor to the same magnitude we let the vibration motor run with low rotation which is not noticeable. The increasing motor action starts precisely at an intensity which is barely noticeable outside the water. Activating the LED has no measurable delay in the millisecond range.

Chapter 4

Evaluation

In this chapter we will evaluate our prototypes with respect to the quantitative and qualitative aspects of the different feedback methods. We are interested to what extent the perception of feedback differs onshore versus underwater regarding time until the stimulus is perceived. We conducted a user study consisting of two parts: in the first part we measured reaction times between presentation of the feedback and it being perceived by the user. The second part was a questionnaire investigating preferences and experiences regarding the feedback types and their applicability for navigation under water.

4.1 User Study

The apparatus consists of a button at the edge of the pool, diving goggles with an *LED* on the right side, a headband with a vibration motor and a thermoelectric cooler (TEC), and waterproof in-ear headphones. These are encapsulated and connected to an Arduino Uno except for the headphones which are directly connected to the MacBook Pro. The Arduino measures the time between the activation of a feedback and the press of the button. For sound the Arduino sends the command to Processing which then plays the *Sound* file and measures the reaction time. Processing

Figure 4.1: A participant during the study in a local swimming hall.

logs the time in milliseconds and the corresponding feedback for further analysis.

4.1.1 Procedure

The participants took a shower and were asked to swim a few laps until they felt at ease. They put on the diving goggles and the headband first, and we ensured that the *peltier element* had direct contact to the skin of the forehead and that the headband was worn firmly and comfortably. Finally, participants put on the snorkel and the earphones. Then the participant was instructed to submerge, start the study by pressing the button for the first time, and press the button as soon as she perceives a stimulus. The prototype is shown in figure 4.1.

Every run included each stimulus eight times in random order with the same stimulus being repeated at most two times in a row. After the button was pressed the next stimulus was randomly delayed between two and eight seconds to prevent adaption. This was repeated at least four times per participant with some participants voluntarily doing more runs. Participants were allowed to emerge whenever they feel uncomfortable or had issues with the equipment. Afterwards, participants answered questions on a 5-point Likert scale regarding feedback recognition, feedback com-

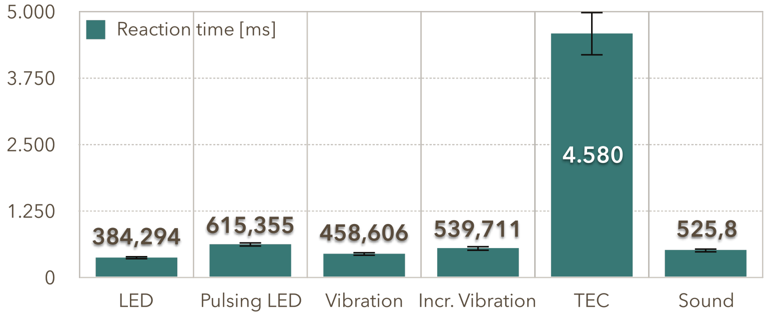

Figure 4.2: Results of the reaction time on different feedback types under water. Means and 95% confidence intervals.

fort, and imagining the feedback type for underwater navigation.

The equipment is cleaned with sanitizer after usage. When acquiring the participants the were allowed to bring their own snorkel if the have hygienic concerns.

4.1.2 Design

The independent variable was STIMULUS (*simple LED*, *pulsing LED*, vibration, increasing vibration, cooling, *Sound*). A sequence of eight stimuli of each type in random order for each run and at least 4 runs per user resulted in (6 x 8 x 4) 192 trials per user in a within-subjects design (48 trials for every additional run). The dependent variable is Time [ms] which denoted the time between a stimulus started and the button was pressed.

4.1.3 Results

A total of 10 users participated in the study (average age 24.1, 8 male), five of which had prior experience with diving or snorkeling. 391 outliers (results differed by more than 1.5 SD from the mean) were identified resulting in 2021 data points. The results of the reaction time are shown in figure 4.2. Only 4 participants recognized the *thermoelectric cooler* at all which led to the majority of outliers. The

		LED	Puls. LED	Vibration	Inc. Vibration	TEC	Sound
Reco-gnition	M	1.3	2.3	1	1.3	4.8	1
	SD	.483	1.059	0	.483	.422	0
Comfort	M	1.5	1.4	1.6	1.2	3.83	1.8
	SD	.707	.966	.513	.422	.983	.919
Navi-gation	M	1.4	1.8	1.5	1.8	4.7	1.7
	SD	.699	1.033	.707	1.033	.483	.675

Figure 4.3: Means and standard deviations (less is better) of the results from the questionnaire.

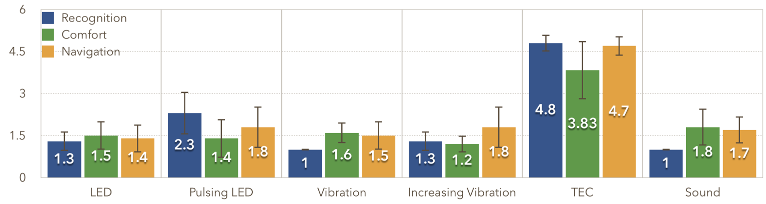

Figure 4.4: Rating of the feedback modalities by the users (less is better). Means and 95% confidence intervals of the results from the questionnaire.

remaining outliers are caused by issues with the equipment (e.g., water in the snorkel or goggles), forcing the participant to emerge. We log-transformed *Time* for a repeated measures ANOVA. STIMULUS had a significant effect on *Time* ($F_{1991} = 852.97, p < .0001$). Tukey HSD post hoc pairwise comparisons showed that the *thermoelectric cooler* (4580ms) was significantly slower compared to each other STIMULUS and pulsing *LED* (615 ms) was significantly slower than vibration (458 ms) and simple *LED* (384ms).

We used Friedman and Wilcoxon Signed Ranks tests to evaluate the questionnaire (cf. Figure 4.3). There was a significant difference in user rated recognition ($\chi^2(5)$ = 39.73, $p < .001$). Post-hoc pairwise comparison revealed that the *thermoelectric cooler* was perceived significantly less than all other stimuli ($p < .005$).
There was a significant difference in user rated comfort ($\chi^2(5)$ = 15.83, $p < .007$). Post-hoc pairwise comparison revealed that *thermoelectric cooler* was significantly less com-

fortable than all other stimuli ($p < .041$) and increasing vibration was significantly more comfortable than vibration ($p < .046$).
There was a significant difference in user rated navigation suitability ($\chi^2(5)$ = 28.77, $p < .001$). Post-hoc pairwise comparison revealed that only the *thermoelectric cooler* was rated significantly less suitable for underwater navigation ($p < .004$).

4.1.4 Discussion

The results and the tremendous power consumption show that the *thermoelectric cooler* is not suitable for underwater applications. Participants reported that it is hard to tell whether the *thermoelectric cooler* is active or if it is a cold flow of water. The skin adapts to thermal changes quickly and makes consecutive cooling events hard to detect [Halvey et al., 2012a].

Visual, vibrotactile, and auditory stimuli are suitable for underwater navigation regarding reaction time (384 - 615 ms). Even though the *LED* feedback was fastest (384 ms) the vibration (459 ms) was perceived to be recognized faster. Binary feedback using light and vibration was perceived as less comfortable than the fading counterparts. Therefore, in an underwater navigation scenario, instant feedback should be used for time critical events only. Otherwise the more comfortable stimuli suffice.

Participants commented that *LED* feedback can be mistaken for water reflections or to be obstructive and distracting. *Sound* was rated as being immediately perceivable (1.0), but some users felt uncomfortable wearing in-ear headphones under water. Vibration on the other hand uses a different sense which is not occupied while diving/snorkelling and provides clear and comfortable feedback. Moreover, the vibration feedback is not influenced by light reflection or water temperature. Furthermore vibration feedback acts like bone conductance *Sound*, and therefore, also includes additional auditory feedback.

4.1.5 Testing outside the water

We let one user test the prototype outside the water to get a rough estimate how the medium influences the results in general. This user is sitting on a table and wears the prototype including the diving goggles but without the snorkel. The relay we use makes a notable clicking noise which is audible through the headphones worn by the participant. Therefore we use a pillow and a wastebin to make it infrasonic. Again we let the user do as many trials as she was willing to do. 210 trials are carried out by the user. Other than that the procedure and the user study program remain the same as described above.

The results of the participant is shown in figure 4.5. It is immediately notable that the visual stimulus is on average faster received in the under water condition (*LED*: 69.285 ms, *Pulsing LED*: 81.708 ms). Contrarily to the visual modality on average the haptic feedback of the vibration motor is faster perceived outside the water (*Vibration*: 28.822 ms, *Increasing Vibration*: 109.135 ms). The most preeminent difference between the two mediums is measured when it comes to thermal feedback. Not only is the cooling effect of the thermoelectric cooler recognized reliably by the participant, but also 3152.580 ms faster with 1427.657 ms. *Sound* was perceived negligibly faster underwater with 19.339 ms difference.

A reason for the slightly better performance of the *LED* underwater can be explained by the fact that underwater the participants is facing the pool edge where the participant testing the system outside the water has more objects in the room to possibly look at. However, the differences for *LED*, *Vibration*, and *Sound* might adjust when testing with more users ashore. In contrast, the water has a significant influence on the sensibility of the cooling effect provided by the *thermoelectric cooler*.

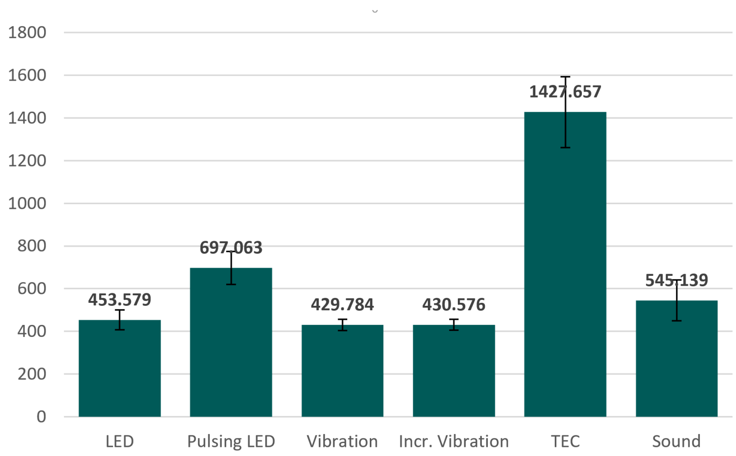

Figure 4.5: Results of the reaction time on different feedback types ashore. Means and 95% confidence intervals.

Chapter 5

Summary and future work

5.1 Summary and contributions

We built and tested a prototype to investigate the applicability of four feedback modalities for the low-level underwater navigation context. The prototype consists of diving goggles with an LED glued to it, a stretchable headband with a thermoelectric cooling element and vibration motor, a snorkel, and the electronics including an Arduino Uno. Visual, tactile, thermal, auditory feedback was investigated for their perceptibility and comfort in underwater scenario.

Results have shown that thermal feedback is not well suited for underwater application since it was not recognizable by a large amount of participants in the first place. It is heavily influenced by the water and perceptibility varies depending on the water temperature. This, however, was not observed outside the water where only the technical limitations of the thermoelectric cooler prolongates the recognition by the user. Additionally the huge amount of power used by the peltier cooling element makes it impractical to use in mobile environment.

Visual, vibration, and auditory feedback was perceived well and technically suited to provide underwater navigation cues. Qualitative analysis via a questionnaire, answered by the participants, revealed that vibration feedback performs best on a subjective level. It does not occupy any of the senses which used for diving in contrast to the LED. Some users report that wearing the waterproof in-ear headphones was uncomfortable and that they are not used to wear those underwater.

5.2 Future work

Our study solely focused on how fast the respective feedback can be perceived underwater and how comfortable it is. We did not yet investigate how accurate the feedback methods can communicate navigation cues in the field. In the future we will drop the thermoelectric cooler due to its bad performance underwater and massive power consumption. Furthermore we will tweak our prototype to incorporate a symmetrical amount of LEDs and vibration motors. The exact amount has to be investigated with a separate user study.

Since the vibration feedback on the head might have an influence on the comfort in the long term, we suggest to implement the vibration motors directly in the diving equipment of scuba-divers. Well accepted locations were investigated by Kiss et al. [2018].

Accuracy of the navigation cues is the most interesting measurement after proving the perceivableness. To compare the performance of low level cues and more sophisticated approaches, like augmented reality diving goggles and precise auditory instruction via bone conduction headphones, further investigation in real world scenarios will be conducted.

To conduct studies in the field the prototype will be made wireless. The primary challenges will be the waterproof incorporation of the power supply and electronics as well as establishing precise measurements. The omission of real time observation and communication requires technology presented in chapter 2. Furthermore a reasonable way to provide 3D navigation cues has to be investigated with focus on comfort and accuracy similar to HapticHead by Kaul and Rohs [2016].

Appendix A

TITLE OF THE FIRST APPENDIX

File: Source Code and Results[a]

[a]http://hci.rwth-aachen.de/public/UnderwaterNavigation/Comparing Feedback Techniques for Navigation Underwater.zip

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