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DOCTORAL THESIS

UNDERSTANDING AND SUPPORTING WEARABLE TECHNOLOGIES FOR FREEDIVERS

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Abstract

In recent years wearables have evolved significantly both for mainstream wearables and wearables for freediving. While the very first wearables only provided functionality for displaying the time, wearables nowadays provide a rich variety of functionalities. Hardware and Software capabilities like new sensors, touch screens and new human-machine interaction methods gave rise to new use cases for wearables, such as navigation support, making payments or routing below the water surface. While wearable devices in general are currently being widely examined and researched, there is a clear lack in both commercial devices and scientific literature in regard to wearable devices for divers; especially freedivers. Thus, little to none support exists for freedivers to improve the general safety of the dive and all surrounding activities. The goal of this thesis is to contribute systems that support the freediver and to ground these systems‘ designs in an understanding of user behaviour. Furthermore, this work is intended to advance research in a scientific context and to identify gaps.

The contribution of this research work is twofold: First, this work aims to understand how divers and researchers use wearable devices and in which direction those are developing. Findings are based on published research collected through the most relevant databases available. The methodology and results are available in chapter 3 Wearables in Diving: A Scoping Review.

Second, this work aims to support freediver in providing a wearable freedive computer with communication capabilities to allow a huge enhancement in safety and to provide a system which is expandable in the future. This prototype was then extensively tested and evaluated in the water by freedivers in terms of feasibility and usability. The methodology and results are available in chapter 4 A Novel Wearable Communication Device for Freediver.

Based on this, another prototype was created with fully available hardware and software, which can be adapted to the respective needs of the desired study with a manageable amount of effort. The methodology and results are available in chapter 5 Low-Cost Wearable Dive Computer.

These two fields of contributions — understanding and supporting — are addressed throughout this thesis and is presented in this thesis to address the two fields according to the challenges and research questions stated in the chapter 1 Introduction.

Finally, we will give an outlook in chapter 6 into the future of what can and should happen in this young discipline.

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Benjamin Bube,

Gummersbach, Dezember 2023

Publications

Significant parts of this work are based on previously published material or material in preparation for publication during this thesis's writing, of which are all indexed in the Web of Science (WOS) citation database and published in journals with high visibility and rank.

The following in JCR and Scopus Q1 ranked journal articles and reviews are of significance:

- **Bube, Benjamin, et al. "Wearable Devices in Diving: Scoping Review." JMIR mHealth and uHealth 10.9 (2022): e35727.**
  This article is available at the JMIR mHealth and uHealth (JMU, ISSN 2291-5222; Impact Factor: 5.0) and is a leading peer-reviewed journal and one of the flagship journals of JMIR Publications. JMU has been published since 2013 and was the first mhealth journal indexed in PubMed. In June 2023, JMU received a Journal Impact Factor™ from Clarivate of 5.0 (5-year Journal Impact Factor™: 5.7) and continues to be a Q1 journal in the category of 'Healthcare Sciences and Services.' It is indexed in all major literature indices, including MEDLINE, PubMed, PubMed Central, Scopus, Psycinfo, SCIE, JCR, EBSCO/EBSCO Essentials, DOAJ, GoOA and others. JMU focuses on health and biomedical applications in mobile and tablet computing, pervasive and ubiquitous computing, wearable computing and domotics. The Journal JMIR mHealth and uHealth can be found on the Journal Citation Report database, within the category HEALTH CARE SCIENCES & SERVICES, is listed in the first quartile, based on its Journal Impact Factor (JIF) (Q1 JIF = 87.3). At the time the paper was published, the journal ranked 12th out of 106 with a Journal Impact Factor (JIF) of 5 and a Journal Impact Factor Without Self Citations of 4.8.
- **Bube, Benjamin, et al. "Wearable freedive computer with acoustic communication." IEEE Consumer Electronics Magazine 11.5 (2021): 94-100.**
  The IEEE Consumer Electronics Magazine covers the following areas that are related to "consumer electronics" and other topics considered of interest to consumer electronics: Video technology, Audio technology, White goods, Home care products, Mobile communications, Gaming, Air care products, Home medical devices, Fitness devices, Home automation & networking devices, Consumer solar technology, Home theater, Digital imaging, In Vehicle technology, Wireless technology, Cable & satellite technology, Home security, Domestic lighting, Human interface, Artificial intelligence, Home computing, Video Technology, Consumer storage technology.
  The Journal IEEE Consumer Electronics Magazine can be found on the Journal Citation Report database, within the category COMPUTER SCIENCE, HARDWARE & ARCHITECTURE, is listed in the first quartile, based on its Journal Impact Factor (JIF) (Q1 JIF = 80.6). At the time the paper was published, the journal ranked 11th out of 54 with a Journal Impact Factor (JIF) of 4.5 and a Journal Impact Factor Without Self Citations of 4.1.

Both journal articles are a contribution of the author under supervision of the Supervisors. The chapter 5 Low-Cost Wearable Dive Computer for Monitoring, Logging and Presentation of Large-Scale Freediving Studies is in a different form currently under review in the Springer Journal Wireless Networks[1].

The Journal Wireless Networks focuses on the networking and user aspects of this field. It provides a single common and global forum for archival value contributions documenting these fast-growing areas of interest. The journal publishes refereed articles dealing with research, experience and management issues of wireless networks. The Journal Wireless Networks can be found on the Journal

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[1] https://www.springer.com/journal/11276

Citation Report database, within the category COMPUTER SCIENCE, HARDWARE & ARCHITECTURE as well as ENGINEERING, ELECTRICAL & ELECTRONIC, is listed in both the second quartile, based on its Journal Impact Factor (JIF) (Q2 JIF = 55.98 and Q2 JIF = 60.37). At the time the paper is under review, the journal ranked 111th(140th) out of 251(352) with a Journal Impact Factor (JIF) of 3.0 and a Journal Impact Factor Without Self Citations of 2.9.

Additionally, there are two noteworthy contributions resulting from the thesis work included in open access repositories, that can be of interest for the scientific community:

- Additional materials consisting of the complete schematics of the second prototype presented in chapter 5 enabling the reader to build a copy of the device for further research efforts which is published under Bube, Benjamin, et al. "Low-cost Wearable Dive Computer for Monitoring, Logging and Presentation of Large-scale Freediving Studies." OSF, 26 June 2023. and accessible through the link: https://doi.org/10.17605/OSF.IO/PGU6T
- The second prototype presented in chapter 5 is centred on collecting diving data from divers for further analysis. This includes an android mobile app, that enables the connection of the wearable dive computer with the android app and further to a firebase server available in the cloud. The associated build files for the Android app as well as the corresponding wiki can be viewed at the following link and used, distributed and modified in accordance with the licensing mentioned there: https://github.com/bbube/FreediverAppAndroid

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Acronyms

Abbreviation	**Long Form**
AIDA	Association Internationale pour le Développement de l'Apnée
CCK	Complementary Code Keying
CFFF	Critical flicker fusion frequency
CMAS	Confédération Mondiale des Activités Subaquatiques
CO	Cardiac output
DA	Dynamic apnea
DAN	Divers Alert Network
DoF	Degrees of Freedom
ECG	Electrocardiogram
EM	Electromagnetic
EMI	Electromagnetic interference
FRV	Freediver Recovery Vest
GPS	Global positioning system
GSM	Global System for Mobile Communications
HCI	Human-computer interaction
HR	Heart rate
HUD	Head-up display
IMU	Inertial measurement unit
IoUT	Internet of underwater things
IoWT	Internet of Wearable Things
JCI	Journal Citation Reports
LiPo	Lithium-ion polymer battery
PB	Personal Best
PCB	Printed Circuit Board
PMMA	Polymethylmethacrylat
pO2	Oxygen partial pressure
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PRISMA-ScR	PRISMA extension for scoping reviews
RF	Radio frequency
RTC	Real Time Clock
RTT	Round Trip Time
SCUBA	Self-Contained Underwater Breathing Apparatus
SpO2	Peripheral oxygen saturation
SV	Stroke volume
UEQ	User Experience Questionnaire
VLF	Very low frequency
WADAC	Wearable Apnea Dive Computer with Acoustic Communication

1 INTRODUCTION

This first chapter motivates the work and provides an introduction into the topic of this dissertation. It will first briefly recap the evolution of wearables in freediving and discuss challenges that result from that evolution. Based on those challenges will derive the research questions. Finally, Chapter 1 will give an overview on the structure of this work, its different pieces and how they form a bigger picture towards understanding and supporting wearable technologies for freedivers.

1.1 THE EVOLUTION OF WEARABLE TECHNOLOGY IN FREEDIVING

The dive computer recently had its 70th anniversary: In 1951 the Scripps Institution of Oceanography in California, members of the US Navy Committee for Undersea Warfare and Underwater Swimmers discussed improvements to SCUBA diving gear: Top of their list was a fool proof way of monitoring nitrogen loading[1]. From that day until this thesis was written, 7 decades later, dive computer has evolved significantly. Parallel to the development, the use of a dive computer became more and more popular, so that now almost nobody goes diving without a dive computer[2]. We distinguish two aspects of this evolution:

(1) Dive computer (wearables) improved in terms of the technology.
(2) Dive computer (wearables) became ubiquitous in freediving worldwide.

The more functionality wearables provide and the better the technology is, the more likely people are to get themselves a new wearable [3]i.e., aspect (1) supports aspect (2). Inversely, the more people have a wearable dive computer the bigger the market grows, and the more likely it becomes that manufacturers of wearable dive computers will improve their devices to increase their market share (e.g., since people will be more likely to choose the model which has a SpO2 meter build in); i.e., (2) also leads back to (1). The relation between these two aspects has led to the evolution that finally resulted in the ecosystem of wearables in general as known today. This development could not prevail to this extent for divers, especially free divers, because the target group is too small and the barriers to enter are too high. Therefore, both aspects will be discussed— Freediving and technology — leading to the momentum of wearables as dive computer.

1.1.1 FREEDIVING

In ancient times freediving without technical equipment was the only possibility to go diving at all. Back in those days freediving had been used to gather food, harvest resources such as sponge, pearl and other valuable things beneath the surface of the water. Both, Plato and Homer, mentioned the sponge as being used for bathing. By using weights breath-holding divers descended up to 30 metres to collect sponges [4]. In several fights in the Peloponnesian War divers were used to pass enemy blockades to relay messages as well as supplies to allied troops that were cut off. In Japan, ama divers began to collect pearls about 2,000 years ago [5], [6]. Most of the gathered seawater pearls were retrieved by divers working in the Indian Ocean in areas such as the Persian Gulf, the Red Sea or in the Gulf of Mannar [7]. However, at this time such terms as freediving did not exist. Therefore, the term freediving referred historically to the today known SCUBA divers, due to the freedom of their movements compared with surface supplied diving [8]–[10].

While historically the freedivers only held their breath for as long as possible the freedivers today enhance their dive by using technical equipment [8]–[10]. The equipment the freediver is using varies depending on the chosen activity. To better understand the developments and thoughts in this thesis, an explanation of the respective application areas of freediving follows.

There are currently several freediving activities which are either commercial, competitive or just for fun. Each of these activities will be shortly described.

- Spearfishing
  Spearfishing is one, if not the, biggest activity of all the other activities. Everyone who has a speargun can basically go in the water for hunting. On the other hand, there is no limit for the equipment to the top like a boat, several spearguns for every kind of fish or only special fitted fins. However, only a spear is necessary for spearfishing. When the spearfisher is diving, he needs to find, give and shot at the target. Supposing the spearfisher caught the target he needs to resurface as fast as possible. Otherwise, based on the dive-length, he could blackout and thereupon drown. If the spearfisher re-enters the surface he immediately needs to bring the fish as well to the surface. Based on the weight and power of the target the spearfisher needs a huge effort. Considering that the spearfisher recently resurfaced and that he is maybe breathless, the fight will be difficult. The spearfisher than must kill the target with a knife, generally mounted at the ankle. After the successful hunt the spearfisher either puts the target to the buoy or in the boat, depending on what he is using.

- Photography
  A freediver who want to photograph the seaworld basically only needs a camera to record and capture pictures. This camera needs to be waterproof. However, as well as the other activities photography underwater can also be extended to a complete other level. Especially under water is the light not very strong, which needs to be handled by the camera. The camera needs to be, in most cases, a better one compared to the camera used for atmospheric camera. Additionally, the camera housing must be waterproof, which directly increases the price and value as well. The more expensive cameras are most of the time for a usage in both hands. This requires some skill to handle the camera while diving. To adjust the settings for the camera the photographer has generally to surface before changing them.

- Competitive Freediving
  Competitive freediving is currently governed by two world associations: AIDA International and CMAS [11]. Each of these organizations has its own rules on recognizing a record attempt which can be found on their respective websites. Both organizations offer different levels as certifications. The greater the amount of level the better and often experienced the freediver is. Each certificate must be a theoretical as well as a practical exam with each level increasing requirements for the athlete. To highlight one specific example from the AIDA first level certification the freediver needs to dive 8 meters deep with fins, hold their breath for at least 1,15 minutes in a pool and can dive 25 meters with fins in a pool. The fourth level certification requires a 32 meters deep dive with fins, at least 3,30 minutes of breath hold in a pool and 70 meters with fins in a pool to pass the practical exam.

- Recreational freediving
  Recreational Freediving is the most used activity among all others freediving options. While recreational freediving can be dangerous, it is less problematic or dangerous compared to the other types of freediving. But this is also since recreational freedivers range from snorkelers to professional freedivers. As an activity, recreational freediving can best be compared to recreational SCUBA diving, as both serve the same purpose of exploring and perceiving the underwater world.
  Compared to SCUBA diving, however, Recreational freediving has enormous advantages:
    - Cheaper, since in principle no equipment is required.
    - Faster and easier to setup and dive.

- Deeper and in total time longer stay in the water diving.
- No decompression time for deep dives.
- Better fusion and adaptation to the natural environment underwater.
- Quieter and smoother movements.

There are plenty of things and activities more for which freediving is used which can't be all listed here. To outline some of those other aspects an understanding needs to be established what freediving really means. Most of the freedivers chose freediving as their dedication for life. They try to find their personal and maybe humankind limits und even surpass them. Freediving also let the person who practice it find themselves in a completely new situation and learn to handle those situations. That's how people learn to find their inner peace and to control their emotions, feelings and body in a peaceful way. Therefore, freediving can be practiced gaining positive effects on both situational and stable psychological characteristics [12]. This circumstance is also used in business by offering special courses for leaders and companies in general. Concerning that most of the freedivers are not certified freedivers rather than just recreational freedivers a huge problem occurs, when those people do not know their actual limit and more importantly don't know when to stop. Therefore, the most important aspect while practicing freediving is the safety.

When a sport is exercised which can't be stopped or cancelled in this exact moment (because the diver is dozens of meters below the surface), one must think about several options to guarantee the safety of the divers. Otherwise, the accident rate would be very high. Unfortunately, beside the current safety standards, the diving fatalities are still high. Based on 763 incidents, collected through each individual who submit an accident while diving to the Divers Alert Network, 80% end fatal [13]. This chapter will not focus on why these incidents went fatal, rather than only to figure out which standards for safety exist and describe them. The safety standards are twofold:

Human related standards are those standards which are directly in correlation with the diver or the buddy[2] and their actions while diving. Those can be but are not exclusively:

- Never dive alone.
- Create a dive plan before the dive session.
- Never hyperventilate.
- Never dive after an LMC/samba or blackout[3]
- Preserve the correct interval between dives.
- Never dive when tired or cold
- Know yourself and your limits.

Technical related standards are those standards which can be defined with a Norm like ISO, DIN or similar. However, in this special case we will also consider those things which are technical but not defined. This has the reason, that the activity freediving is not very diversified and therefore a lot of the equipment is custom made. To outline the most important equipment parts:

- Dive computer (dive time, depth, recovery time, differentiated acoustic alarms, temperature, etc.)
- Heart Rate Monitor
- Mask, Snorkel, Fins, Belt, Weight, Wet suit, Gloves, Booties, etc.

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[2] A buddy, in case of freediving, is the person responsible for the safety. The buddy should be at the same level of performance.

[3] Samba or Loss of Motor Control is the name given to the uncontrolled movements that occur because of having very low levels of oxygen in the body. Blackout is the sudden loss of consciousness caused by oxygen starvation.

  - Buoy, Lanyard, Rope, Counterweight, etc.

This list is by far not complete. However, those are the most relevant technical related standards which are necessary to understand this thesis. Since Safety is the most fundamental part of freediving and this thesis, will take a deeper look at safety throughout this thesis with a more detailed look in Chapter 2. The next chapter focus on the age of wearable technology with a focus on freediving and diving in general. After this, the challenges and the authors motivation will be outlined.

1.1.2 THE AGE OF WEARABLE TECHNOLOGY IN FREEDIVING

Dive computers have revolutionized the way one explores and enjoy the underwater world. These devices have come a long way since their inception, blending technology and diving expertise to enhance safety and optimize dive planning.

In the early days of recreational diving, divers relied on dive tables and manual calculations to plan their dives. These tables provided guidelines based on time and depth limits, but they lacked the precision and flexibility that divers needed. As diving became more popular, there arose a need for a device that could simplify and streamline dive planning. Dive computers have made an enormous leap from the development from two researchers in 1955 to the arms of millions of people worldwide today. These two researchers published a paper outlining the functions needed for a decompression device back then. Such a device, they said, should calculate three things – the decompression during a dive, the nitrogen remaining in the human body from a previous dive, and based on this information, the optimal and fastest rate of ascent. Groves and Monk suggested using an electrical analog computer to measure pressure and air intake[14].

In the 1960s, the first dive computers for recreational diver emerged, marking a significant turning point in the history of diving. These early models were relatively simplistic and primarily focused on depth and time calculations. They utilized analog mechanisms to track the diver's descent, bottom time, and ascent rate. While limited in their capabilities, these dive computers were a major leap forward, offering real-time information and reducing the risk of human error.

The 1980s witnessed a significant leap in dive computer technology with the advent of digital displays and microprocessors. This breakthrough allowed for greater computational power and improved accuracy. Manufacturers started incorporating additional features such as ascent rate monitoring, nitrogen loading calculations, and decompression algorithms. These advancements not only enhanced dive planning but also increased diver safety by providing vital information to prevent decompression sickness.

In the 1990s, dive computers underwent a renaissance as new players entered the market, pushing the boundaries of functionality and design. Manufacturers introduced more intuitive user interfaces, multiple gas mix capabilities, and customizable dive algorithms to cater to different diving profiles. Dive computers became smaller, more compact, and integrated with other dive equipment, such as dive watches and wrist-mounted devices. This integration eliminated the need for additional gear and simplified the diving experience.

As technology continued to advance, dive computers embraced wireless connectivity features while above the surface of the water. Divers could now connect their devices to smartphones or dive log applications, enabling them to log and analyse their dives in greater detail. These wireless capabilities also allowed for firmware updates, ensuring that divers had access to the latest algorithms and features, further enhancing safety and performance during their dives.

Furthermore, advancements in materials, display technologies, and sensor miniaturization will continue to make dive computers more compact, lightweight, and durable. Integrated heads-up displays, voice command modules integrated into full face masks, and augmented reality overlays may become common features, offering divers an immersive and intuitive experience.

As we reflect on the rich history of dive computers, it becomes evident that these devices have significantly transformed the diving landscape. From simple analog devices to sophisticated AI-powered companions, dive computers have evolved to empower divers with valuable information and enhance their underwater adventures. The future holds immense potential for further innovation, ensuring that divers can explore the depths with greater confidence and safety.

A closer look at the last years in the development of both dive computers and wearables in general is examined in detail in Chapter 2.1 State of the Art.

1.2 CHALLENGES AND MOTIVATION

With an increasing rate of freedivers and an increasing rate of accidents which happen in freediving, safety comes more and more into focus. However, both the accidents itself and the reasons for those accidents are in most accident cases the same. Indeed, the technology has changed a lot, which gives the opportunity to think and create completely new things to help and improve the safety for every freediver further.

A Thought Experiment:

People can have different reasons why they want to freedive. Basically, the reasons are twofold. People either want to dive to find inner peace, silence and enjoy the underwater world or they want to know their limits, possibilities and human restrictions. Of course, not only one of those reasons need to apply. Many people are practising freediving because of both parts. If we focus on the people who are practicing freediving who want to figure out their limits, possibilities and human restrictions we can assume followed listing:

- People want to find limits and to surpass them if possible.
- People who want to surpass those limits can easily lose control about their actions and close their mind for the obvious dangerous situation and can enter a state of euphoria.
- Actions and Reactions done by those people are not anymore in a logical order. Therefore, their behaviour is not controllable anymore.
- As soon as this occurs to a freediver he is in tremendous danger, because as we already outlined nearly 80% of the accidents end fatal[13].

Challenges:

Since the affected freediver can’t act rationally anymore in this state, we need to find another solution to guarantee the safety for the participating freedivers. Since the buddy of the freediver can still act rationally he should carry the control and possibility to react to the freedivers danger. From the highly experienced buddys and freedivers covering other freedivers, we can derive two challenges worth investigating to work towards this optimal safety independently from the freedivers and their buddys experience.

- Constant monitoring
  For a step towards the optimal safety of the freediver he needs to know how he feels and how his condition is. If he feels good, but he is maybe in trouble than he can react based on the given Information done by the constant monitoring.
- Communication
  The optimal safety can be reached when the buddy can directly see the same information and data as the freediver itself. Then he can completely rationally decide whether he acts or not.

Beyond the scope of the presented work:

This work has its background in human-computer interaction (HCI) and aims to understand and support people — especially freedivers — regarding their freediving activities under a smart device aspect to improve the safety, fun and experience while freediving.

However, for this thesis are several aspects by far too complex to be handled. Therefore, only a few steps in some specific directions will be made throughout this thesis. This thesis rather paves the way for future research done on those fronts. Parts which are crucial but too complex and time consuming to be handled and already mentioned are the following:

- Analysing the behaviour and critical points where freediver lose control.
- Usability and User Experience for the smart device (both for freediver and buddy)

Personal Motivation:

The Author's very personal motivation results from his over 10 years of experience in freediving. Before he even started to study and research in computer science, he became an AIDA 4* freediver, the highest level of freediver someone can reach. Over the last year's spending freediving almost every time the question comes up, how inexperienced freedivers can guarantee the safety of their buddies. Over the many dives done, he experienced this knowledge by observing others freediving, attending courses and conversations with other freedivers. However, he still tries to answer the question, how inexperienced and sometimes even experienced freedivers can be helped by a significantly improvement for the safety and therefore a more relaxed and enjoyable dive with no significantly disadvantages.

1.3 RESEARCH QUESTIONS

The overarching research question that we address in this work is:

How do freedivers use wearables, and how can we build systems to support freedivers in making effective and efficient use of wearables?

This question will be answered more by specifically addressing the challenges of the three fields of understanding, developing, and advancing wearable technology for freedivers. In particular, we can break down this research question into more specific questions, which this work sets out to answer, as by assigning them either an (U) for understanding or (S) for supporting:

(U1) What use cases do wearables cover, besides a depth logger dive computer, and in which directions are they developing?

(U2) Which communication technologies and seals are the most forward-looking for wearables and up to what depth have they been used and evaluated?

(U3) To what extent have wearable devices been evaluated and what results have been attained?

(U4) Are there important topics that have only been covered to an exceedingly small extent in scientific literature?

(S5) How can we build a system to support freedivers achieve one of the crucial goals aforementioned?

(S6) How can we further enhance such a system for further studies in this field?

The goal of this thesis is to contribute with systems that support the use of wearables and to ground these systems' designs in an understanding of user behaviour gained through empirical observations tailored for freedivers.

1.4 THESIS OUTLINE

The core contributions of this work are twofold: The first part, understanding, is on gaining insights into how people, while diving or researching in this field, focus and use their wearables to inform an understanding of wearable technology for freediver. Results of these sections are, for instance, descriptions of fields of application. As such, the first part of this thesis makes contributions the conceptual design through research on previous contributions to the topic. Based on this understanding, we present the second part of this thesis, which aims to support people during diving and make handling wearables more effective and efficient. The results of this second, more systems-oriented part is, for instance, applications and systems that provide communication between several divers. As such, this second part of this thesis makes technical contributions to engineering. These two fields of contributions — understanding and supporting — are addressed throughout this thesis and is presented in the following chapters to address the two fields according to the challenges and research questions stated above:

- Chapter 3 Wearables in Diving: A scoping Review
- Chapter 4 A Novel Wearable Communication Device for Freediver
- Chapter 5 Low-Cost Wearable dive Computer

The first part mainly written in Chapter 3 contributes to our understanding of how divers and the scientific community use wearable technology, while the latter chapters contribute to the part of supporting people with new devices, building on the findings of the previous study. In order to take a first step in this direction of development, the key point for a smart wearable device was built and tested as a prototype in the chapter 4 A Novel Wearable Communication Device for Freediver: probably the first wearable diving computer with wireless data transmission. We also underline the relevance and necessity of this prototype through an extensive test with the help of test subjects in the water.

2 FOUNDATIONS, BACKGROUND AND RELATED WORK

This chapter provides the foundations, background, and related work for this thesis and introduce the notion of context as it relates to the field of wearable technologies, describe the research methodology, and provide a literature review on works that are related to the two fields of contributions — understanding and supporting — of this thesis, as well as on fundamental work to frame this thesis.

2.1 STATE OF THE ART

In the previous chapter we defined the research questions of this thesis. Work related to these questions can be found in four different areas: First we will provide an overview on literature for 2.1.1 Underwater Communication, since this is the backbone of every smart device for an underwater use case. After this well go into more detail and explain 2.1.2 Wearable Computing followed by 2.1.3 Wearable Computer Usage, taking a deeper look into the different electronic user-device interactions and finally to ground these in the context of context-aware sensor systems as they apply to the three areas of this thesis: Chapter 3 Wearables in Diving: A Scoping Review, Chapter 4 A Novel Wearable Freedive Computer with acoustic communication and 5 Low-Cost Wearable Dive Computer. Further an overview of the applied methodology is given and explained why they were used.

2.1.1 UNDERWATER COMMUNICATION

The term underwater communication is covering a great range of applications and definitions, since both wired and wireless communication principles are covered. However, in this thesis it is generally about the wireless underwater transmission. If this is not the case, this will be explicitly mentioned. Further improvements and the addition of more use cases to the capabilities of the wearable systems will likely increase the usage in the future. There are many submarines, submersibles, exploration robots, etc. floating in the water. All of these are related to science, business or the military. In all of these disciplines, communication plays one of the most important roles, not just above but also below the water. In the following sub-section we will go into more detail and explain the three most relevant communication options: radio frequency, optical and acoustic communication.

2.1.1.1 OPTICAL COMMUNICATION

Optical communication uses light to transmit information. Light is an electromagnetic wave and therefore has the same properties as Radio Frequency (RF) waves, but at a higher frequency (430-790 THz). As shown in Figure 2.1, visible light frequencies are the least attenuated in all electromagnetic radiation. Wavelengths in the 470 nm range are generally attenuated the least, always depending on the properties of the water in question, as absorption and scattering are influenced by the chemical and biological composition of the water [5]. The low attenuation at these frequencies and the high propagation speed of electromagnetic waves offers optical systems the ability to communicate at data rates that are far superior to acoustic systems. Figure 1 shows that the blue light is the least attenuated and is therefore used by many commercial systems and research experiments.

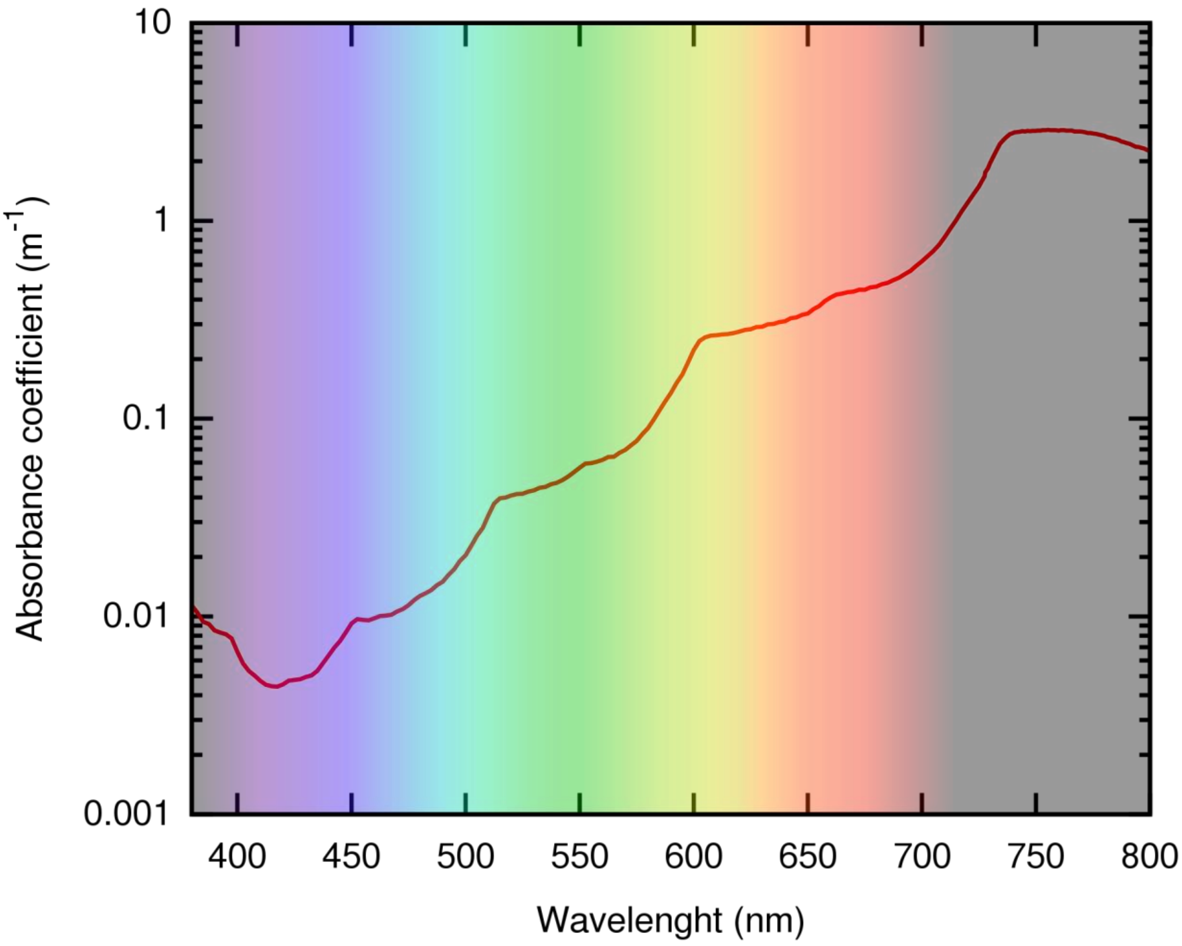

FIGURE 1. VISIBLE LIGHT ABSORPTION SPECTRUM OF PURE WATER[15]

Its limitations stem from the fact that light, as an electromagnetic wave, is strongly attenuated in water, affecting the transmission range. A key limitation of optical systems is the heavy reliance on a direct line-of-sight, which can be challenging when viewing an underwater environment especially lakes. Current improvements in LED technology [16] has enabled the development of low-cost, energy-efficient optical transmitters that provide high light intensity, fast switching speeds, high efficiency, and optimal wavelengths for underwater light transmission. Using lasers instead of LEDs can improve the quality of transmission even further as it provides a much better collimated beam of light than LEDs. However, it is much more prone to misalignment and is therefore not always considered [16]. Nevertheless, the need for line-of-sight and the strong reduction of performance caused by scattering, makes these systems impossible to apply in some scenarios.

2.1.1.2 RADIO FREQUENCY COMMUNICATION

Radio frequency waves are electromagnetic (EM) waves in the frequency band below 300 GHz. An electromagnetic wave is a wave of energy with a frequency within the electromagnetic spectrum (Figure 2) and propagates as a periodic disturbance of the electromagnetic field when an electric charge oscillates or accelerates[17]. Due to the high conductivity of water, few underwater RF systems have been developed, although these systems have been studied since the early days of radio and had received significant attention in the 1970s.

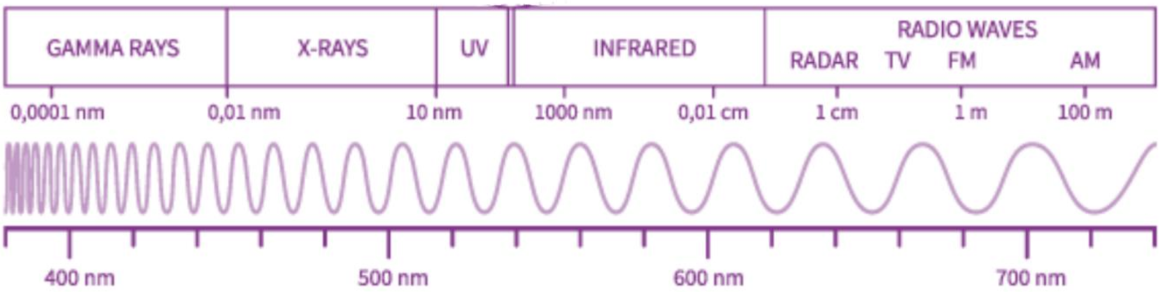

FIGURE 2. ELECTROMAGNETIC SPECTRUM[4]

Unlike acoustic waves, EM waves can be used in shallow water. EM transmissions are tolerant of turbulence caused by tidal waves or human activities, unlike acoustic and optical waves which are not[18]. They are insensitive to turbidity and pressure gradients and immune to acoustic noise [19]. Furthermore, they are not affected by multipath and effects on marine animals have not been identified so far[20]. Underwater communication based on EM waves is faster and can be used at higher operating frequencies (resulting in higher bandwidth). However, they are susceptible to electromagnetic interference (EMI)[19]. Their main problem is the high signal attenuation due to the conductivity of the water. This fact implies short communication distances between devices, so EM is never selected for long-distance communication.

When it comes to RF-based underwater communications systems, the number of commercially available systems has declined, largely due to the lack of research, and investment in this area's theoretical models show pessimistic scenarios. In fact, there isn't too much documentation about radio frequency in underwater communications, as most work is designed for low frequency.

$$\alpha_{\text{sea water}} \approx \sqrt{\pi f\, \mu\sigma}, \qquad (1)$$

The absorption coefficient of sea water is related to the conductivity where α is the absorption coefficient, f the operating frequency, μ the permeability and σ the conductivity. This is the reason why most of the work carried out for long range communication is in the low frequencies.

Therefore, researchers work with very low frequency (VLF) in RF communications and reduce the frequency to achieve a more effective communication range. Lloret et al. performed their simulations at 3 kHz with distances between nodes of about 40 meters[21]. In [19] there is also reference to an article in which the authors determined the maximum ranges for low frequencies and found around 6 m at 100 kHz, 16 m at 10 kHz and 22 m at 1 kHz. When using high frequencies around 2.4 GHz, [19] evaluated RTT and packet loss at different frequencies and modulations depending on distance.

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[4] Source: https://byjus.com/jee/electromagnetic-spectrum-and-electromagnetic-waves/

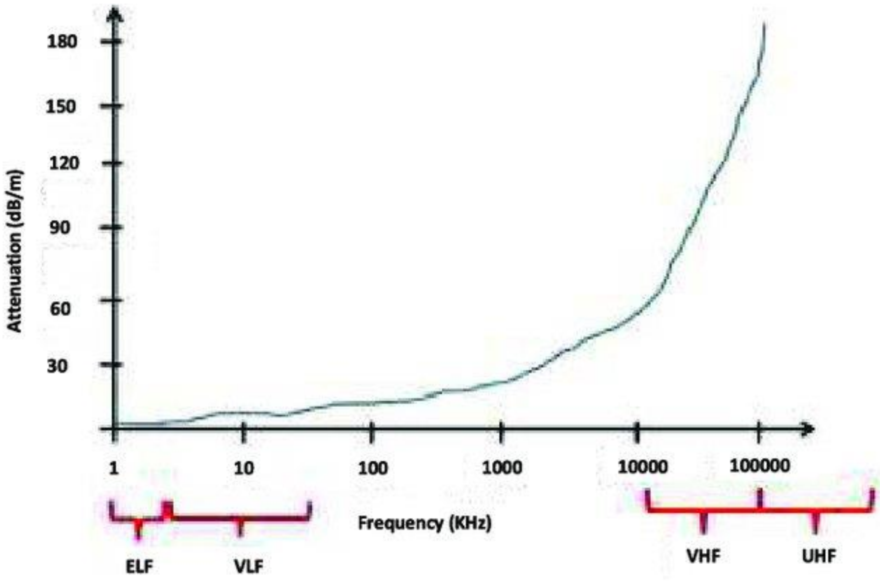

FIGURE 3. RF ATTENUATION IN SEA WATER[22]

Their results show the best-case scenarios in the frequencies 2,412 GHz, 2,437 GHz and 2,472 GHz. In the 2,412 GHz frequency range, they achieve the best results with a transmission rate of 11 Mbit/s (CCK modulation) at a maximum distance of approx. 15 cm.

Average conductivity in sea water is 4 mhos/m which is almost two orders higher than the conductivity in fresh water. This increases the absorption loss at high frequencies in sea water as shown in Figure 3. Rf Attenuation in Sea Water[22]. RF wave communication is good in fresh water. However, this requires huge antennas to work reliable (the wavelength is 10 km at 30 kHz).

2.1.1.3 ACOUSTIC COMMUNICATION

Acoustic channels associated with a sonar system can be used in seabed navigation and special features leading to underwater applications, such as fishing sonar systems or hunting sonars for mines[22]. This technology contributes to underwater navigation and information gathering, since this communication technology doesn't suffer in the water penetration as the electromagnetic attenuation in water does. It is a technology that uses the propagation of sound underwater to navigate, communicate with, or detect objects (e.g., submarines and mines) on or below the surface of the water by projecting sound and the Detects echoes of objects[23]. However, the physical properties of the underwater environment such as temperature, pressure, salinity and water density have a major impact on the propagation of sonar waves underwater, as these physical properties change drastically across the air-water interface. The density of water is much larger compared to the density of air, and obviously the density of the medium at the air-water interface changes accordingly. Therefore, the sonar wave is strongly attenuated as it propagates across the air-water boundary. Consequently, it is completely impractical to establish a communication system that uses sonar waves to cross air-water boundaries[24]. The sonar system uses a hydrophone as a transducer to send and receive acoustic signals in the water. Sound travels in water at a higher speed than air (around 1500 m/s in water compared to around 340 m/s in air), making seawater a favourable medium for sound transmission[25]. The propagation of sound underwater is influenced by temperature, salinity, hydrostatic pressure and other factors; its speed in the ocean varies between 1450 and 1540 m/s[23]. The speed of sound as a function of these three parameters became available in the 1920s. After improvisation, a simple formula from Medwin from 1975 states that the speed of sound c (in meters per second) is as in Eq. which can be expressed as (2)[26]:

$$c(S,T,z) = 1449.2 + 4.6T + 0.016z - 0.055T^2 + [(1.34 - 0.010T)(S - 35) + 2.9 \times 10^{-4}T^3] \quad (2)$$

where T is the temperature expressed in units of degree Celsius; S is the salinity in parts per thousand (g/kg); and z is the depth from the sea surface in meters. While Equation (2) is not accurate by modern standards, its simplicity makes it particularly suitable for investigating the sensitivity to temperature and pressure (parameterized as depth), which are of interest to this historical account.

Another important aspect when it comes to the acoustic communication is the speed of sound beneath the water surface, which is denoted c_{water} is 1490m/s. More generally, the parameters S, T, and P all vary with depth and therefore so too does the sound speed, resulting in significant refraction. Neglected for simplicity the wavelength, λ at a certain frequency f is in Eq. (3):

$$\lambda = \frac{c_{water}}{f} \quad (3)$$

Acoustic technology is mainly used during diving and on ships. However, it is limited to several hundred Kbit/s at ranges with a few kilometres, supports slow data rates and can be harmful to marine mammals such as dolphins and whales[27] The propagation delay underwater is five orders of magnitude higher than in terrestrial radio frequency (RF) channels and is extremely variable. In addition, the available bandwidth is severely limited due to the frequency range, which is only between 10 and 15 kHz. In addition, the underwater channel is severely affected, especially by multipath propagation and fading[28]. Due to the extreme characteristics of the underwater channel, high bit error rates and temporary connection losses (shadow zones) can occur.

2.1.2 WEARABLE COMPUTING

The work presented in this thesis contributes to the research and development of a wearable freedive computer with acoustic communication for freedivers and a Wearable dive computer for Monitoring, Logging and Presentation of large-scale Freediving studies as well as a wearable dive computer suitable for large-scale studies. As this belongs to smart wearables, we will look on general aspects of personal and socio-cultural studies related to wearable computers, and present works that reflect on how wearables shaped our habits and how we strive further away from smartphones to smartphone independent wearables.

2.1.2.1 PERSONAL AND SOCIO-CULTURAL ASPECTS

A key strength of mobile devices is their ability to provide a strong sense of expediency and immediacy that lead users to believe that the devices allow them easy, fast, and timely access to information [29], [30]. Gillick et al. argued that the anywhere-anytime access to content and services offered by mobility and availability is the greatest benefit of mobile information and communications technology [29].

> *While people buy watches to tell time, the number one criterion in choosing a [smart] watch for most people is how it will look. It's a fashion statement, not a technology one*
>
> *(Bajarin, 2014*[29]*)*

The Statement above clearly shows that people buy wearables more for fashion than their actual use. However, the mobile information and communications technology is clearly as well an important factor. If the wearer can't see or tell the time, the smart watch would be obsolete. Cherrylyn Buenaflor and Hee-Cheol Kim outlined, that the most important parts for people to accept wearables are [31]:

(1) Fundamental needs

(2) Cognitive activity

(3) Social aspect

(4) Physical aspect

(5) Demographic characteristics

However, the influence of these factors on the attitude or behaviour towards the acceptance of the wearable devices will depend on who the target users are and the nature of their environment to which the device is intended to be utilized. Unfortunately, there is no research for freedivers and smart wearables currently available.

2.1.2.2 HABITS OF SMART WEARABLE USAGE

The daily habits while using a smart wearable device is manifold. We will focus on the parts, which are relevant for freedivers in general.

Stress is one of the major problems in modern society[32]. Therefore, many people try to find a balance. A few of them choose freediving to relax. At first glance, the concept of smart wearables and freediving seem opposite to one another since freediving is labelled as an extreme sport. However, in freediving, unlike in most other sports, stress and adrenaline are counterproductive. Several studies focused on this topic and find physiological or behavioural markers for stress during the usage of smart wearables. Those markers have to be considered for a further development and either confirmed or refuted especially in the context of freediving.

2.1.2.3 SHIFT FROM SMARTPHONE TO WEARABLE

Recent developments in the commercialization and usage of wearables led to a huge gain of popularity. Today, after a long time of technological improvements, smart wearables seem to be heading in the same direction as mobile phones: multiple functionalities. Especially

> *smartwatches have two strong advantages over other devices: their mount location and (probably more important) the continual connection to the skin*[33].

However, the downside of those smartwatches is clearly their display size. Compared to a smartphone the user just has to raise their hand or lower the head. However, with innovative devices, this could, performance and battery provided, replace the typical smartphone. Since Microsoft failed with SPOT (Smart Personal Object Technology) because of cost and battery limitations, and the delay of Apples Watch release show these two factors[34]. Considering the actual development, we can say that the smartphone will be more and more unnecessary, because all the computing power will be stored in each of those devices[5]. Even the connection between them will be done automatically.

2.1.3 WEARABLE COMPUTER USAGE

Wearable technology is rapidly advancing in terms of technology, functionality, size and applications[35]. The currently available wearables are mainly used for one or more functions such as: Fitness tracker and health issue monitoring, navigation tool, media device, communication gadget or

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[5] Authors assumption. Article: https://www.notebookcheck.net/Samsung-believes-smartphones-will-become-obsolete-in-5-years.426860.0.html last accessed 16.06.2023

just as a fashion statement. As most of those devices support more than one of those functions we will focus on several parts and their statistics.

Many people use fitness tracker in their daily life. More specific, over half of all Americans (51%) using a fitness tracker at least once a day, according to a report conducted by Researchscape International[36]. Furthermore over 53 million are sold and 26.43bn USD revenue have made with wearables for fitness and activity tracker in 2018[37]. Beside the fitness tracker there are not so strong gains in popularity in the other fields. The predicted wearables boom is all about the wrist as a statistic outlined. The prediction for the year 2019 was, in the wrist wear, significantly higher (over 90%) than all other fields such as modular, clothing, eyewear, earwear or others[38].

However, this couldn’t stop the rapidly increasing amount of people who use such a device for one or more of the functions mentioned above. In 2014 already one out of five American adults had a wearable device according to the 2014 PriceWaterhouseCoopers Wearable Future Report[39]. With the appearance of Samsung and Apple smartwatches, the wearable device sector started gaining mass market attention. Another study in 2014 by MSI and McAfee reported that 70% of people think that wearable technologies will soon send health vitals readings to physicians. In professional sports, wearable technology has applications in monitoring and real time feedback for athletes. The constantly decreasing price of those devices is encouraging widespread adoption and availability. According to a study by Forbes back in 2014 71% of 16 to 24-year-old people want wearable tech[40]. While another study in 2015 carried out in the UK among 1000 people reported that 56% said that wearable tech was “just a fad”; indeed, the consumer satisfaction level with wearables commerce usage in 2017 showed that 84% rated the experience as “excellent” or “very good”[41]–[43].

2.1.4 ELECTRONIC-USER-DEVICE INTERACTION

The Interaction with electronic devices is usually performed with a mouse, touchscreen or keyboard. The Result is in general displayed on a screen. In mobile Human Computer Interaction (HCI), however, the requirements are shifted. The user has to adapt his attention to different environments and might not be able to devote too much attention to the device. In the freediving scenario this is an important part to focus on. In the recent years different concepts of HCI had to be applied to reduce the amount of attention the wearer has to pay, including a natural or leastways easy to learn input method. Following we will outline those different attempts for a general mobile and wearable device use as seen in Figure 4.

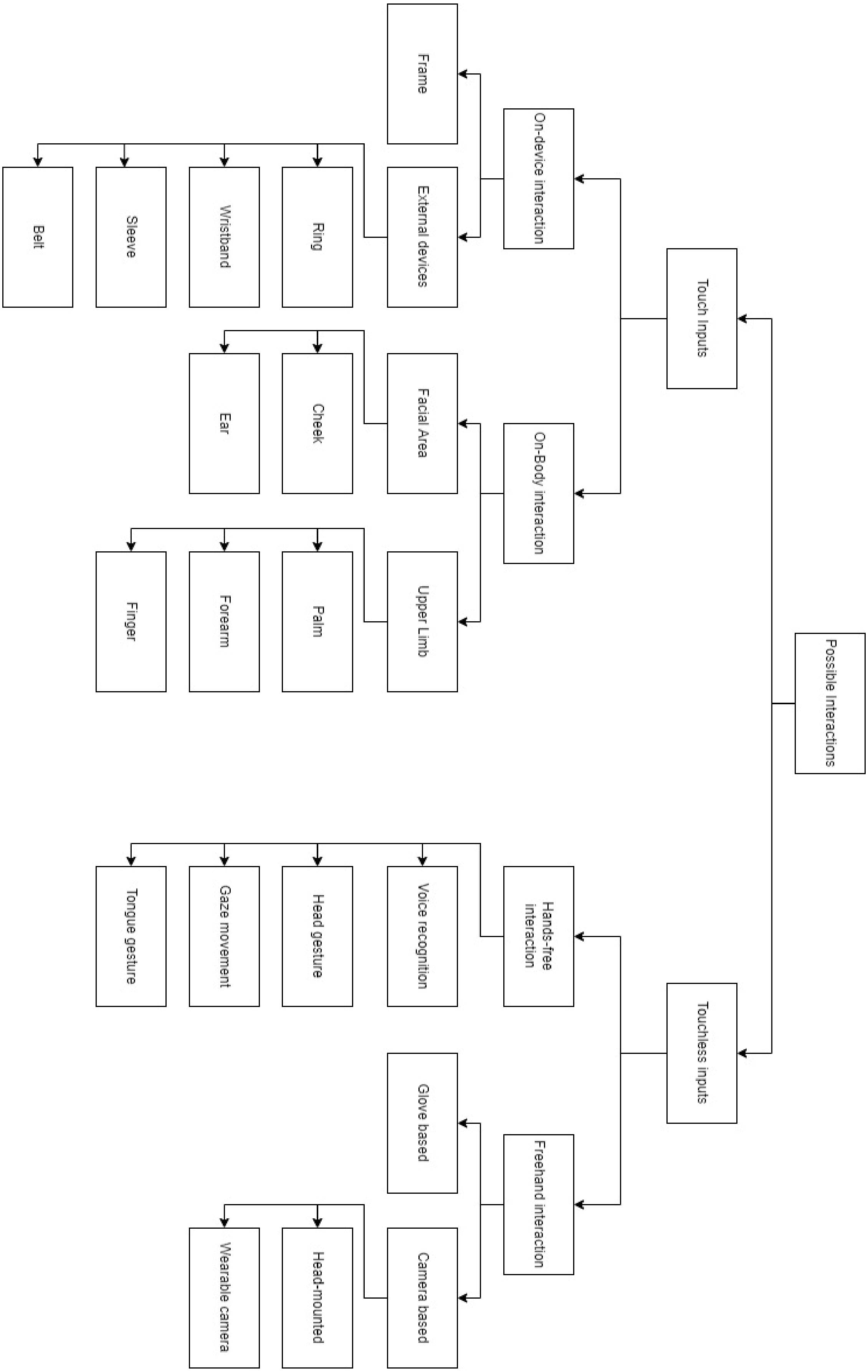

FIGURE 4. POSSIBLE INTERACTIONS BETWEEN HUMAN AND THE DEVICE[6]

In principle, we divide the interaction into touch and touchless inputs. A different division may also make sense in a different context. However, this division was chosen here because entering underwater with a pressure-intensive or conductive material is significantly more difficult in both cases than on land.

2.1.4.1 TOUCH INPUTS - ON-DEVICE INTERACTION

Touch Inputs are currently the most used on mobile devices. This chapter is of utmost importance since we also try to address this problem and adapt it to the underwater world. This interaction has a touchable spectral frame, where gestures like swiping, pointing, dragging, etc. can be acted on the frame. Researchers propose a swipe-based gesture for text entries[44], [45], especially on very small devices which have a reduced form and size to interact with touch interaction. Therefore, the need for complementary interaction methods is evolving. Currently external devices can be made in various physical forms such as rings[46]–[48], wristbands[49], sleeves[50] and belts[51]. The research in this field is manyfold.

Finger-worn devices have gained a lot of attention in the recent years, because those devices are small, discreet and allow single handed controls[52]. As we already outlined the most important factor for people to wear or buy such a device is the look rather than the pure functionality. Therefore, those devices are more like a fashion statement which could bring them the advantage to be better accepted within the potential users. There are several different approaches for those rings to be the controller. MagicFinger use an optical sensor positioned on the fingertips[48]. These types of hardware allow stroke-based gestures on any surface. In contrast LightRing consists of a gyroscope and an infrared emitter positioned on the second phalanx of the index finger[47]. Other rings are iRing and Nenya which both provide a touch surface on the ring[46], [53]. However, iRing can detect both the touch and bending of the finger which allows a huge increase of combinations. In addition, Nenya senses the absolute orientation of the finger with a magnetometer in the bracelet. One example for a commercial version of such a smart ring is the Oura Ring in Figure 5.

FIGURE 5. OURA RING[7]

Arm-worn devices are, compared to the finger-worn devices, relatively large. In addition, this facilitates the interaction possibilities due to the greater size of the touch surface compared to finger-worn devices[50]. However, when the control will be done with muscle tension or arm movements the size isn't important anymore[49], [54]. Those devices are controlled with capacitive sensors and an inertial measurement unit (IMU). Touch-belt device are touch sensitive belts. Dobbelstein et al. proposed such

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[6] All further figures and tables are solely made by the author when there are no additional sources given.

[7] https://www.welt.de/wirtschaft/webwelt/article231626067/Oura-Ring-im-Test-Sensoren-messen-die-Qualitaet-des-Schlafes.html

a device, which increases the input area and therefore a more easy and advanced control About the device[51].

Figure 6. Left: Subtle user input with the thumb. Right: Opening a digital[51]

The developed device shown in Figure 6 allows swipe gestures to manipulate the pixel cards on the optical display. The approach is claimed to be unobtrusive as the user does not need to raise the arm as well as a subtle interaction with the belt.

2.1.4.2 TOUCH INPUTS – ON-BODY INTERACTION

Touch inputs done by the body interaction can offer a huge advantage. Users no longer need to rely on visual clues to accomplish their tasks when the tactile clue can help them to locate their touch[55]. This can lead to an eyes-free input that is useful in actions where the user has lower cognitive or physical efforts or lack-of-attentions scenarios[56]. Especially in freediving, this can offer the diver a huge advantage, because he does not need to focus on the device and the control rather than the dive itself. This can reduce the distraction and danger[57]. Several works investigated in various parts of the human body, such as the palm[58]–[63], the forearm[64]–[66], the hand[64]–[66], the finger, the face[67] and the ear[68].

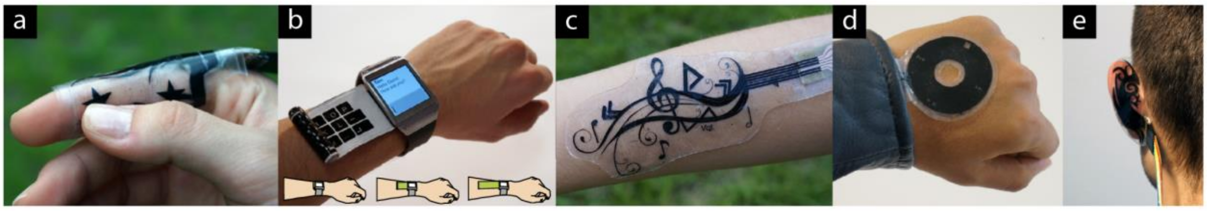

Figure 7. Different approaches based on iSkin[63]

Palm as surface devices are projection-based techniques which project a picture on their body including their palm and interact with multi-touch gestures[59]. OmniTouch developed a proof-of-concept with a shoulder worn device that is equipped with depth-sensor and a projector. The user can receive tactile feedback from the finger when active touch is acted on these surfaces [58]. In addition, Skinput is an arm-worn device equipped with a vibration sensor and a projector[69].

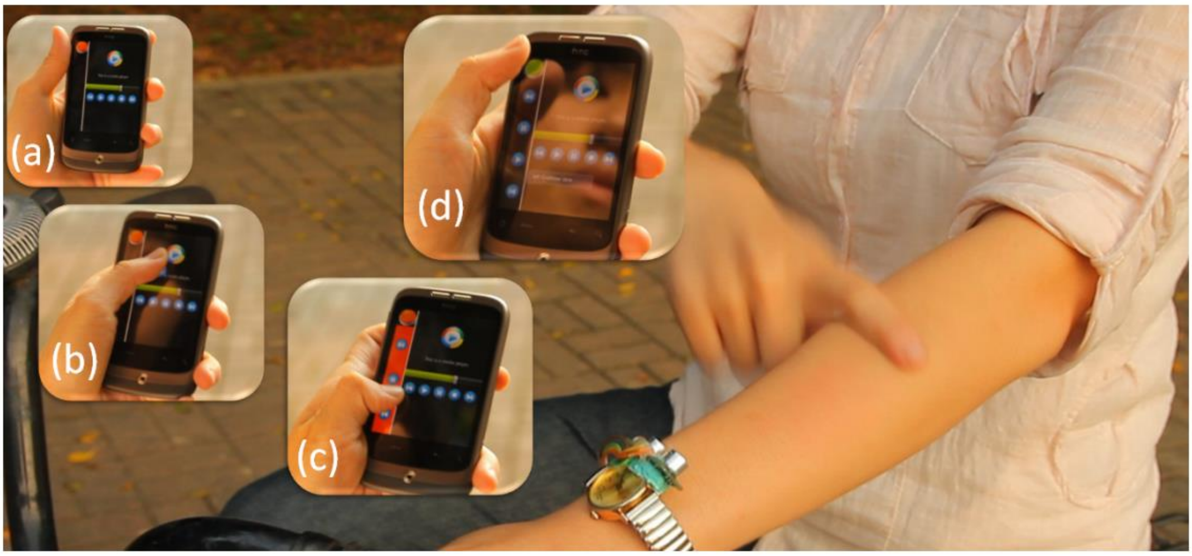

FIGURE 8. INTERACTION BASEN ON AN ULTRASONIC DEVICE MOUNTED ON THE WATCH[65]

Different to the OmniTouch the Skinput use vibration sensor to capture the movement of the skeletal structure when a finger presses on the skin. There exist several more palm-controlled devices such as PalmGesture, SenSkin and PUB as shown in Figure 8 [61], [65], [66].

2.1.4.3 TOUCHLESS INPUTS – HANDS-FREE INTERACTION

Touchless inputs are those inputs where users make general mid-air movements and receive visual clues from the optical display on the device. This touchless input is twofold: Hands-free and Freehand interactions. Hands-free interaction can be made by the movements of the head, gaze, voice and tongue while freehand interactions focus on mid-air hand movements for gestural input. Hands-free interaction is, without a doubt, one of the most popular techniques for interaction with devices. This technique enables the user to control the specific device without any use of the hands. This is specifically for freedivers associated with high interest because they need the hands free for diving. The Category of hands-free interaction includes voice recognition, head gestures and eye tracking.

Voice recognition will not be further discussed, due to the reason that divers can’t talk under water. In general, voice recognition is widely used in interaction with devices such as Alexa, Siri, Cortana or Google Assistant which are nearly in any smartphone, tablet or in smartglasses available.

Head movements are mainly controlled with gestures. Those gestures can be recorded with built-in accelerometers and gyroscopes in such devices. This technique is applicable to text input, user authentication or game controllers [70]–[72]. Those gestures can be achieved in smartglasses with high input accuracy. However, this input method cannot be considered as the main input source, due to the reason that head movements are exhausting. Gaze movement can move and control the cursor movement for several tasks, for instance choosing an object with an eye gaze, text input based on an object with an eye gaze or even the recognition of objects in augmented reality[73]–[78].

Even for head-mounted displays several gaze interactions have been proposed[72], [75], [79], [80]. Eye movements are undeniable natural and fast input channels, in which only a minimum necessary amount of muscle usage is needed to perform a certain task. In addition, the greatest downsides are that these devices are error prone and that they lack of fast usage due to the needed calibration, which is often not available in smart glasses[81]. The common eye-tracker technology will not be popular for the next several years, because of the price for those trackers and their needed processing power, to map the infrared signal to the displayed image in front of the eyes.

However, in some parts a compromise can be applied for improved accuracy. Those drawbacks can be large. As Kozaki et al. outlined, they use a fairly simple design, to analyse if the eye is opened or closed[82], [83]. If this system would be adapted and made more complex, the possible eye movements which can be tracked will increase. Compared to the expensive eye-tracker this system can't be as precise in the current state of art. However, if this precision is not needed the advantages are obvious. Lower costs with basic eye-movement control. As miniaturization progresses, a portable system will gradually become normal in this area too.

2.1.4.4 TOUCHLESS INPUTS - FREEHAND INTERACTION

Although various hands-free techniques are available, there is no evidence that those hands-free input outperform the other types of interaction techniques such as freehand interaction. Zheng et al. made the conclusion that human beings are good at adapting to various conditions whether or not their hands are occupied by instruments, tasks or not used at all. Another study outlined, that the gestural input is preferable to on-body gestures and handheld devices especially in an interactive environment[84]. Since those touchless inputs will not reach, in the current technology state, the versatility of the other interaction techniques, we will neglect them in the rest of this work.

2.2 CONTEXT IN WEARABLE TECHNOLOGIES AND SENSOR SYSTEMS

Once we established and explained the different input methods available, we have to take a closer look at these in the respective context. Wearable technologies refer to electronic devices that are designed to be worn on the body, often incorporating sensors, computing power, and wireless communication capabilities.

Wearable technologies are used in a range of fields, including healthcare, sports and fitness, entertainment, and fashion. They can be used to monitor health and fitness metrics, track and analyse athletic performance, enhance user experiences, and even enable new forms of human-computer interaction[85], [86].

To specify the user activities while using a wearable device, we will use the concept of context to characterize the interaction between the user and the wearable device and the applications. It certifies the importance of the concept of context that there is more than one definition and that the context is in most cases a situational context.

In this thesis, we refer to the definition of situational context provided by Schmidt[87]:

> "*In our work we propose to regard situational context, such as location, surrounding environment or state of the device, as implicit input to the system. We use the term situational context to describe implicit interaction fragments. This extends the concept of context beyond the informational context into real world environments."*

In this thesis we refer to Schmidt's definition of situational context when describing the location, environment or state of the device. Conterminous we use Schilit and Theimers definition of context-aware computing as the

> *"ability of a mobile user's application to discover and react to changes in the environment they are situated in"*[88].

Although their primary focus was on the locations of people and objects for their Active Maps System[8] we know that context is more than this [89]. They stated that there are three categories for context-aware features. First the presentation of information and services to a user, second the automatic

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[8] Active Maps System itself isn't of importance here. Just that context is more than this. For further information go to reference [88]

execution of a service and third the tagging of context to information for later retrieval [90]. The context-aware system in form of a wearable device has to deal with all of those three categories. Mainly because the wearable device has to present information to the user, second it has to adapt by changing the state of the device while running when a special event happens and third to log those special events for later use and evaluation. Based on the aforementioned situational context we use in this thesis the definition of Schmidt, where the situational context is defined as followed [89]:

1. running on a specific device (e.g. input system, screen size, network access, portability, etc.),
2. at a certain time (absolute time e.g. 9:34 p.m., class of time e.g. in the morning)
3. used by one or more users (concurrently or sequentially),
4. in a certain physical environment (absolute location, type of location, conditions such as light, audio, and temperature, infrastructure, etc.),
5. social setting (people co-located and social role),
6. to solve a particular task (single task, group of tasks, or a general goal).

In this thesis we will mainly focus on the items 1., 4. and 6. with different approaches for 2, 3 and an outlook for 5. Retrospective this thesis will research the design and use of computer technology, focused on the interfaces between people (users) and computers.

The discipline of wearable technologies draws on a range of fields, including computer science, electrical engineering, materials science, and human factors engineering.

As the field continues to evolve, wearable technologies are becoming increasingly sophisticated, incorporating advanced sensors, artificial intelligence, and machine learning algorithms. The discipline of wearable technologies is therefore poised to continue to grow and expand, enabling new and exciting applications in a wide range of industries and domains.

After we specified the context in the field of HCI, we can define sensor systems as a part of context-awareness. Beside this, we need to find a definition for sensors and sensor systems. While sensors are devices or pieces that can sense things or states, sensor systems are a bit greater than that. A system is a group of interacting or interrelated entities that form a unified whole. A system is as well delineated by its spatial and temporal boundaries, surrounded and influenced by its environment, described by its structure and purpose and expressed in its functioning. Once we see both aspects together, we can say that

A sensor system is a group of interacting and interrelated sensors, which can sense things or states in their environment described by its structure and purpose delineated by its spatial and temporal boundaries.

When comparing the previous sensor systems and context awareness definitions we can conclude that they contain very clear similarities.

One could argue that both the context and sensor systems describe the same. However, there are still differences between those two. One the one hand, context is a more abstract construct of the current situation based on many factors. On the other hand, there are the different sensors and communication systems between them to serve with information. With that information generated by the sensor system, the context can be, hopefully, identified and in the needed way handled. Therefore, the combination of context aware sensor systems is the interaction and communication between the complete ecosystem of context aware sensor systems.

Once we defined the term context aware sensor system we analyse and question the different sensor systems which were treated in papers and their ability to fulfil the requirements for context aware sensor systems as we defined above in order to complete our description of the state of the art.

Since most of the literature divide the different sensor systems often in consumer, commercial, industrial, and infrastructure spaces, we will adapt this[91]. However, in this thesis we focus only on the consumer market in which connected vehicles, home automation, wearable technology (as part of Internet of Wearable Things (IoWT)) and connected health belong[92]. The correlation between those parts and the thesis are discussed in the following chapters with a listing of the most relevant sensors in their respectively use case.

As already outlined, wearable technology groups under a common name smart devices that can be incorporated into clothing or worn on the body as implants or accessories[93]. Those devices are mostly used for collecting data with sensors and adapt them for either the user or for commercial purposes. Following we will outline and describe smartglasses, smartwatch and e-textiles which are the most common sensor systems currently available.

2.2.1 SMARTGLASSES AND SMARTWATCH

Smartglasses add information alongside or to what the wearer sees[94]. Like other computers, smartglasses may collect information about the environment, the body of the wearer or other information with internal or external sensors. Some of those smartglasses may also have all the features of smartphones[95]. They can as well as smartphones, smartwatches and/or E-textiles support activity tracker functionality features, voice and video communication and other functionalities.

A Smartwatch is a wearable computer in the form of a wristwatch. They currently provide a local touchscreen for daily use and an associated smartphone app for management and adjustment of the smartwatch. Smartwatches offer several typical features depending on the use case. Most smartwatches offer more than one of the features below. While sport watches include the functionality to track the activities which are made for training, diving, and outdoor sports, they can as well include training programs, speed display, GPS tracking unit, Route tracking, dive computer (ascent, decent, time, oxygen, etc.), heart rate monitor compatibility, lap times, Cadence sensor compatibility, and compatibility with sport transitions. They can even cooperate with a smartphone to carry out more functionality if needed. Over the years smartwatches are advancing, especially their design, battery capacity, and health-related applications[33].

2.2.2 E-TEXTILES

Electronic textiles offer a compelling solution for seamlessly integrating digital technology with the human body. By leveraging our clothing needs, electronic textiles can eliminate the intrusiveness and risks associated with implantable or epidermal electronics. To achieve autonomous functionality, these textiles require various technological capabilities, including sensing physiological signals, harvesting energy, and wireless data communication without causing discomfort or interfering with daily activities[96]–[99]. This enables the creation of a network of sensors, actuators, and displays around the body for applications ranging from health monitoring to human-computer interfaces. However, integrating electronics with clothing materials remains challenging due to the stark contrast between the rigid nature of conventional electronics and the flexible, porous structure of textiles.

Several innovative approaches have been explored to overcome the inherent incompatibilities in materials and geometry. For instance, button-sized electronics integrating sensors, batteries, and wireless communication components can be attached directly to existing clothing. Nevertheless, the size constraints of such devices limit their functionalities, performance, and sensing opportunities. Another approach involves fabricating textile functional systems by printing or coating functional materials, such as conductive fillers, into the porous structure of the textile substrate. However, these methods are prone to failures like cracks and delamination due to the mechanical mismatch. Moreover, they often cause discomfort by stiffening the textile materials and obstructing the necessary transport of moisture and air through the porous structure. Hybrid strategies that combine miniature electronic modules with large-area textile sensors can address some of the limitations but require non-intrusive solutions for powering and communication during daily activities.

One promising solution is the use of conductive threads that can be digitally embroidered into clothing, enabling wireless powering and communication[100], [101]. This can be achieved through computer-controlled textile manufacturing, ensuring a seamless translation from digital design to fabrication. Embroidered conductive threads offer advantages over coating and printing processes as they preserve the flexibility and permeability of the textile while leveraging existing manufacturing processes for scalable production. However, existing conductive materials for textiles suffer from a trade-off between mechanical and electrical performance[102]–[104]. Metal-based threads, for instance, have low resistance but are fragile under repeated bending, whereas carbon-based threads with high elasticity have insufficient electrical conductivity for essential components like antennas and radio-frequency elements.

In contrast, liquid metal encapsulated with stretchable polymer, such as silicone rubber, exhibits high electrical conductivity and adaptability to mechanical changes[105]–[107]. This unique combination of properties has enabled the creation of stretchable electromagnetic devices and liquid metal fibres for sensing and energy harvesting[108], [109]. However, previous demonstrations have not fully harnessed these properties to develop textile threads compatible with digital embroidery or incorporate them into clothing to form autonomous systems.

2.2.3 SENSORS

Wearable sensors are advanced devices that combine the characteristics of point-of-care systems with mobile connectivity. They operate autonomously as self-contained units, enabling continuous monitoring of an individual's biometrics in a non-invasive or minimally invasive manner. This allows for the detection of subtle physiological changes from baseline values over time[110].

The concept of wearables has been around for several decades, with examples like the Holter monitor, a medical sensor used for measuring heart electrical activity, dating back to the 1960s[111]. While the specific components may vary depending on the application, wearable devices generally consist of common building blocks. These include the substrate and electrode materials, sensing units responsible for interfacing, sampling, biorecognition, signal transduction, and amplification, decision-making units that handle data collection, processing, and transmission, and power units to sustain their operation.

The line between consumer and medical wearable devices is becoming increasingly blurred as modern wearables can perform high-quality measurements comparable to regulated medical instruments. Initially, first-generation wearables like watches, shoes, and headsets focused on monitoring biophysical parameters such as physical activity, heart rate, and body temperature[112], [113]. However, with the widespread adoption and success of these devices, there has been a gradual shift towards non-invasive or minimally invasive biochemical and multimodal monitoring, aiming to achieve truly personalized healthcare[114]. In freediving, however, this development still poses a problem, since the sealing of such sensors is extremely difficult or, as of now, cannot be solved in many cases.

Second-generation wearables come in various forms such as on-skin patches, tattoos, tooth-mounted films, contact lenses, textiles, as well as more invasive options like microneedles and injectable devices[115]. A notable characteristic of these second-generation wearables is their utilization of biofluids, where biorecognition elements convert the presence of specific analytes into detectable signals. While most of these examples are still in the laboratory prototype stage, there are a few commercial exceptions, such as the FreeStyle Libre glucose monitoring system and the Gx Sweat Patch[110].

Wearable sensors, both biochemical and biophysical, have demonstrated their effectiveness in disease detection, management, and wellness applications[116]. Beyond human-centered health and well-being, wearables have also found applications in animal health monitoring for the pet and animal husbandry markets[117]. The versatility and expanding applications of wearable devices are revolutionizing healthcare and extending their impact beyond human health also in freediving.

2.3 RESEARCH METHODOLOGY

The approach taken in this study was influenced by the concept of implementing real systems and utilizing them for research purposes. This methodology serves a dual purpose: first, it allows for the acquisition of scientific insights, and second, it enables the development of systems that cater to the actual needs of users. For this specific reason we choose to apply design thinking as our iterative approach[118].

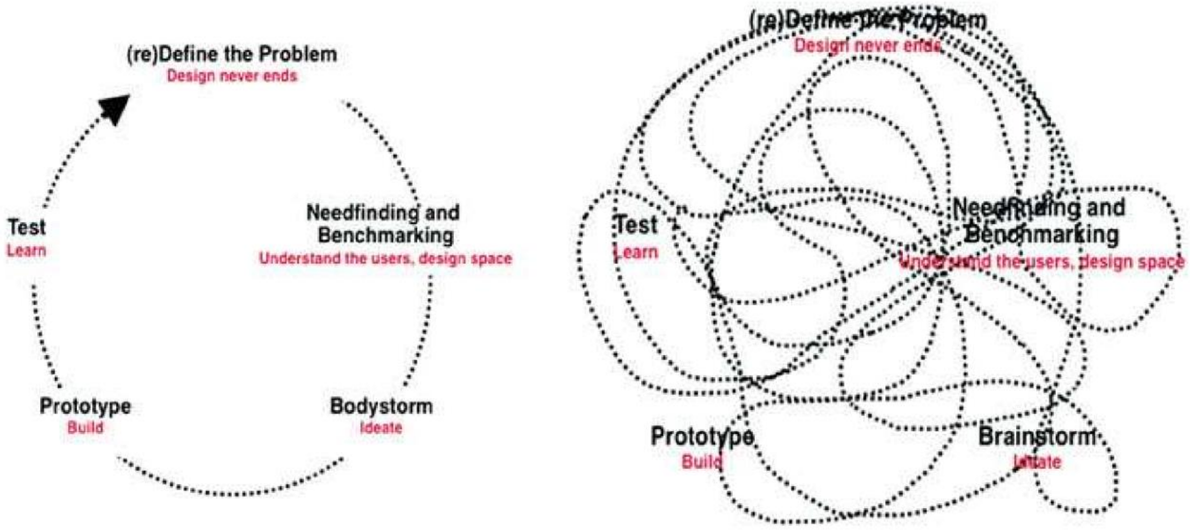

FIGURE 9. DESIGN THINKING PROCESS VS. STANDARD FORM[118]

In deployment-based research, empirical observations are derived from systems that have been deployed, providing valuable insights for enhancing theoretical understanding of human-computer interaction. These insights, in turn, contribute to the iterative improvement of the design of the deployed system. This design thinking approach follows a user-centered design methodology, creating a cyclical progression of iterative refinement.

To achieve this goal, we made a twofold approach which we will discuss in detail in the following two chapters.

2.3.1 RESEARCH THROUGH DATA FROM OTHER STUDIES

The work of this dissertation started, and first papers, reviews and articles were scanned. Our early idea was to develop a device which could communicate below the surface of the water in any direction. This development was mainly driven by the experience of the author during freediving itself. However, as we advanced further into this topic we discovered a lot of research papers, reviews and articles which focused on other parts and not the communication aspect itself. Driven by this observation we thought it would be reasonable to switch to this topic first and to conduct a collection of data regarding wearables development, usage and results from these studies. The paper [119] was a direct result of this idea.

Chapter 3 Wearables in Diving: A Scoping Review examines the applied methodological approach through scoping reviews in detail and, among other things, goes into this methodology and why it was chosen.

2.3.2 COLLECTING DATA IN THE WILD

As stated by Rodgers, the concept of "turning to the wild" aims to investigate phenomena within their natural context rather than in isolation[120]. It involves observing how individuals adapt, respond to, or incorporate new technologies into their daily lives in this case during freediving. This approach, known as studying technologies in the wild, has been employed in various fields of Human-Computer Interaction (HCI) and ubiquitous computing to examine the usage of new or existing systems in real-world settings[121], [122].

Rodgers also acknowledges the challenges of isolating specific effects observed in an in-the-wild study, as participants have control over the study rather than the researcher. Additionally, the observed effects may be influenced by complex dependencies between various factors.

For the developed communication device, we took into consideration user feedback and data logging. We collected data on the usage of the device to at least outline improvements for their user interface; to improve the technical system (e.g., through users` recommendations after the usage) and to inform the design (e.g., through users` feature requests).

2.3.3 FIELD EXPERIMENT

A field experiment is a research method in which an experiment is conducted in a real-world setting, such as a natural environment, rather than in a controlled laboratory environment. It involves manipulating independent variables and observing their effects on dependent variables under natural conditions. Field experiments are valuable for studying human behaviour and social phenomena as they provide insights into real-life contexts and minimize artificiality.

Field experiments have been widely used across various disciplines, including psychology, sociology, economics, and environmental science. They offer advantages such as increased ecological validity, allowing researchers to examine behaviour in natural settings and capture real-time responses. These experiments also enable researchers to explore causal relationships between variables and generate practical implications.

One classic example of a field experiment is the study conducted by Milgram (1963) on obedience to authority, where participants were instructed to administer electric shocks to a person (a confederate) in a different room[123]. This experiment revealed unexpected insights into human behaviour and the influence of situational factors.

Another notable field experiment is the work of Thaler and Sunstein (2008) on behavioural economics, exploring the concept of "nudging" to influence individuals' choices and decision-making[124]. Their study demonstrated how small interventions in real-world settings can have significant impacts on behaviour.

Field experiments continue to be a valuable research tool, allowing researchers to investigate complex phenomena and their practical implications in authentic settings. They offer a bridge between controlled laboratory experiments and the complexities of the real world, providing valuable insights into human behaviour. In this thesis, we are motivated by field experiments (when proposing a device to use in Chapter 4 and Chapter 5).

2.4 APPLIED METHODS

This chapter deals with the applied methods in the different studies which were already tested and proofed in other fields. First, we will look at scoping reviews, which were then used in Chapter "3 Wearables in Diving: A Scoping Review" for data collection and the analysis of the data. Then we will go into more detail on the topics of iterative prototyping and usability testing, which were applied and used in Chapter 4 and Chapter 5.

2.4.1 SCOPING REVIEW

To make a better distinction and classification, we will briefly explain reviews and systematic reviews in contrast.

A review in general is an overview of the research that's already been completed on a topic, while a systematic review differentiates from other types of reviews in that the research methods are designed to reduce bias. The methods are repeatable, and the approach is formal and systematic[125].

Systematic reviews have become increasingly popular in recent years by first emerging in the 1970s[126]. This triggered an exploding number of systematic reviews over a period, both in terms of number and popularity[126].

Like a systematic review, a scoping review is a type of review that attempts to minimize bias with transparent and repeatable methods. However, a scoping review is not a type of systematic review. The main difference is the goal: instead of answering a specific question, a scoping review explores a topic. The researcher attempts to identify the key concepts, theories, and evidence, as well as gaps in current research[127]. Sometimes scoping reviews are an exploratory step in preparation for a systematic review, and sometimes they are a standalone project. The first question is why we used a scoping review and not a systematic review or some other type of review. In contrast to other review types that deal with relatively precise questions, such as systematic reviews of the effectiveness of interventions based on well-defined outcomes, scoping reviews serve to map the key concepts of a research area, to create working definitions or the substantive boundaries to stake out a topic [128]. Scoping reviews can be deployed and used for various purposes. The general direction of a scoping review is to use evidence-based examination of a broader area to identify gaps in knowledge, clarify key concepts and report on the types of evidence relevant to practice[129]–[131].

A first demarcation and delimitation compared to systematic review took place in 2005 by Arksey and O'Malley[128]. Various scoping studies were identified and classified by the authors through publishing a first methodological framework for conducting scoping studies.

Further Levac and colleagues build upon their experience conducting scoping reviews using the aforementioned methodology and proposed recommendations that clarify and enhance each stage of the framework[132].

Based on this work the JBI (Joanna Briggs Institute) published a guidance document for the conduct of scoping reviews with an update in 2017[133], [134]. Up to this point in time, however, there was no reporting guideline for scoping reviews. Reporting guidelines establish a minimum set of elements that must be included in research reports and have been shown to increase methodological transparency and the acceptability of research results[135], [136].

In 2018, the Preferred Reporting Items for 97 Systematic Reviews extension for Scoping Reviews (PRISMA-ScR) was developed by an international team of experts in scoping reviews and evidence synthesis, including members of the JBI/JBC working group, to be consistent with the JBI's scoping review methodology and to provide reviewers with a reporting checklist for their reviews[134].

In its current state, the checklist contains 20 essential reporting items and 2 optional items which should be considered when conducting a scoping review. Scoping reviews are used to synthesize evidence and assess the body of literature on a topic. Among other things, scoping reviews help to determine whether a systematic review of the literature is warranted[137].

Since freediving is a relatively young area in terms of technical solutions, especially wearables, we decided to carry out a scoping review for the first step according to the status of the framework. The knowledge gained in this way is examined in more detail in Chapter 3 Wearables in Diving: A Scoping Review upon which we further build our prototypes in Chapter 4 and 5 Low-Cost Wearable Dive Computer which is the consistent further development of the findings in this review.

2.4.2 ITERATIVE PROTOTYPING

A prototype is an artifact that approximates a feature (or multiple features) of a product, service, model or system to test a concept or process[138], [139]. The design and the prototype are linked throughout history. Palladio already used wooden prototypes to better plan the architectural elements more cost-effectively regarding stones[140].

We can distinguish different types of prototypes defined by Ullman and later refined by C.S. Lai and G. Locatelli[141], [142]:

- Proof-of-Concept develops the system function for customers' requirements or engineering specifications comparison. This prototype acts as a learning tool, and details (e.g., materials and manufacturing process) are unimportant (e.g., a prototype could be built from any material or part available).
- Proof-of-Product is constructed to aid refining the assemblies and components. This prototyping examines the details and the performance of the system. The prototyping time and cost can be optimised with rapid/desktop prototyping, using stereolithography, 3D printing, or computer-aided design.
- Proof-of-Process verifies the design details. The precise manufacturing processes and materials are employed to manufacture system samples for functional testing.
- Proof-of-Production verifies the whole production process. This prototype is the outcome of a preproduction run.

In principle, prototypes that are to be used for an underwater mission are much more difficult to produce, since the above-mentioned requirements and the engineering cannot be implemented 1 to 1 as in a land-based scenario. This includes, for example, the use of 3D printing for the first prototype. As a rule, they do not withstand the pressure under water. We will focus on this part in more detail in the sub-chapter 3.7 Housing and Sealing. After we could see that a desired communication solution also had to be developed from scratch for a new field of research, we were able to develop an initial proof of concept based on this data. The exact steps and content are described in detail in Chapter 5.

The development of an advanced prototype and disclosure of the same has already been used many times in a scientific context to collect data. A good first reference point for such prototypes is the journal Hardware-X.

We were able to test the complete development of the two prototypes at any time with relatively little effort in the reservoir Aggertalsperre, which is not far from the TH Köln University of Applied Sciences and the authors home, so that, while complying with the safety regulations, the development could be managed quickly and clearly from the start. The fairly good conditions for such dives are clearly visible in Figure 10.

FIGURE 10. FREEDIVER WITH A PROTOTYPE, MAP OF THE AGGERTALSPERRE

Since both developments are a relatively young field of research and have so far only been associated with considerable costs, we were able to use this approach to implement and develop it quickly and at significantly lower costs using iterative prototyping. In this way, various tests could also be carried out in this water reservoir, as can be seen in 4.5 Dive Experiment. The relatively constant conditions on site enabled us to focus on the essential aspects of the tests. The studies carried out later, however, ran under scientifically more precisely determined parameters. These tests were all carried out on the same day to ensure objective comparability.

2.4.3 USABILITY TESTING

Usability testing is a crucial method used to evaluate the effectiveness and efficiency of a product or system in meeting the needs of its users. It involves observing users as they interact with the product, gathering feedback, and analysing their experiences to identify areas of improvement.

The primary goal of usability testing is to ensure that a product is intuitive, easy to use, and provides a satisfactory user experience. By conducting usability tests, designers and developers can gain valuable insights into how real users navigate through the system, uncover any usability issues, and make informed design decisions.

The process of conducting usability testing typically involves the following steps:

- Planning: Define the objectives of the test, identify the target audience, and determine the scope of the testing. Develop tasks and scenarios that reflect typical user interactions.
- Recruitment: Recruit participants who represent the intended user base. The number of participants may vary based on the resources available, but a general guideline is to test with 5-10 users per testing round.
- Test Setup: Set up the testing environment, which may include preparing the test location, recording equipment, and any necessary software or prototypes.
- Test Execution: Conduct the usability test sessions, where participants are asked to perform specific tasks while their actions, comments, and feedback are observed and recorded. It is important to encourage participants to think aloud, expressing their thoughts, impressions, and difficulties encountered.

- Data Analysis: Review and analyse the collected data, including observations, notes, audio/video recordings, and participants' feedback. Look for common patterns, trends, and usability issues that emerged during the testing.
- Issue Prioritization: Prioritize identified usability issues based on their severity and impact on the user experience. This helps in determining which issues should be addressed first during the design or development process.
- Reporting: Document the findings and recommendations in a usability test report. This report provides stakeholders, designers, and developers with actionable insights to improve the product's usability and user experience.
- Iterative Testing: Incorporate the feedback and recommendations from usability testing into the design or development process. Conduct additional rounds of usability testing to validate the effectiveness of the improvements made. Goes hand in hand with the previous chapter.

Usability testing should be an iterative process, integrated throughout the product development lifecycle. By involving users early and continuously seeking their feedback, designers and developers can create products that better meet user needs, enhance user satisfaction, and ultimately increase the likelihood of product success in the market.

FIGURE 11. WORKSHOP AT THE EXPERIENCE DAYS IN HEEMOOR 2020

Depending on the respective development and test stage we were in, we had several sides where we gathered necessary information. This included workshops during freediving events such as the biggest event in freediving the Experience days in Hemmoor 2020[9] as seen in chapter 4, A novel wearable freedive computer with acoustic communication and in Figure 11. In addition, the usability laboratory of TH Köln was used to analyse the software and identify potential for further improvements. Tests in the nearby Aggertalsperre were also used as seen in 4.5 Dive Experiment with subsequent expert interviews. In addition, surveys and ideas could be carried out at the Boot trade fair and during various freediving events located in Germany where valuable feedback on ideas could be obtained at an early stage of the development. Some of the ideas were not pursued further afterwards and are not dealt with in this thesis either, since they were rejected by the same feedback in its early stage.

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[9] Video of the Experience days https://www.youtube.com/watch?v=W060xJnssXE

During those events we captured ideas, problems, solution approaches and challenges mainly through expert interviews, Usability tests with the usage of eye-tracking, heatmaps and guided interviews as well as the UEQ (User Experience Questionnaire). As the name shows, the UEQ can be used to measure the user experience very well. The classic usability aspects (efficiency, perspicuity, dependability) as well as the user experience aspects (originality, stimulation) can be measured[143], [144]. This questionnaire was used to measure those aspects for the prototype in chapter 4.5.2 User Experience Questionnaire - Dive Result. The Raw Material of those questionnaires are in the appendix.

2.5 SUMMARY

In this chapter we have introduced the foundations of this thesis, presented the research approach we have taken for the work conducted, and discussed works relating to the two fields of this thesis as they are described in chapter 1.4 Thesis Outline which are – understanding and supporting – as well as wearable computing in general. First, we introduced the term context and its relation and meaning for this work and described the context as a situational context, where the situation for the context is the most important factor. In 1.3 Research Questions the research approach is explained which were carried out in this thesis. Further an explanation of the applied approach, how and why it is needed to strive further into this direction as well as highlighted for this the several approaches done by different people, companies or startups and outlined the need for a greater approach.

Next, we presented work relating to wearable computing in general, to get a better understanding of the topic. Based on this knowledge we could introduce and outline related work for the two other fields of our thesis. The link between those related work and these specific fields is as follows:

- In Chapter 3 Wearables in Diving: A Scoping Review we were one of the first to examine the general orientation and the development status of the wearable devices used for divers and freedivers in the form of a scoping review since we could see that this field isn't covered very well.
- In Chapter 4 A Novel Wearable freedive computer with acoustic communication: From related work and the scoping review on wearable devices, we have most importantly learned that users accept different devices only under special circumstances. While this acceptance is important, we answered this in Chapter 4.5.2 User Experience Questionnaire - Dive Result. In addition, we've seen wearables gain more and more popularity and acceptance among the people and especially freediver even when they are completely different.
- In Chapter 5 Low-Cost Wearable Dive Computer: We will go into more detail approaching the low-cost devices to further enhance research through large scale data collection during freediving and to provide a prototype which is feasible for this task.

In the following chapters we present the work based on the foundation we presented in the chapter 1 Introduction and then grounded in this chapter Foundations, Background and Related Work. We will first start to go into detail regarding the capabilities, features and current development direction of wearable technology for freediver. We will describe the methodology, investigate the different use cases, and finally take a deeper look in the applied housing and sealing of those devices to get deeper into the part understanding. Once this is done, we will go into more detail in chapter 4 and 5 the two developed prototypes as well as the respective results to close the gap for the second part supporting.

3 WEARABLES IN DIVING: A SCOPING REVIEW

This chapter deals with the capabilities, features and current development direction of wearable technology for freediver. We will first describe our methodology, then investigate the different use cases, and finally take a deeper look in the applied housing and sealing of those devices. Some of the results in this chapter have been presented in the publication [119].

3.1 INTRODUCTION

Over the past few years, wearables have been widely adopted and became a tool for many people in their daily lives [145]–[147]. As a result, interest in using these for data collection and evaluation for scientific purpose also increased in many areas in the last decade, especially for monitoring fitness and health related metrics [148], [149].

Divers can be divided into different categories just like mainstream users. These include SCUBA divers, who tend to be recreational divers, as well as freedivers who want to stay under water for as long as possible with one breath. A transition from SCUBA diving to technical diving is fluent. Authors consider technical diving activities beyond the depth and conditions of SCUBA diving. Technical divers have a clear focus on professional activities under water with mostly increased demands on the equipment and conditions under water.

Although divers are generally at higher risk than non-divers, far fewer studies have been conducted in this area[13] . The underwater environment is for humans unnatural and dangerous, which makes it particularly necessary to survey physiological factors. Those factors relating to the pulmonary, cardiovascular, neurological, and renal systems have so far been described in detail[150]–[152].

Due to the significantly smaller number of people who are divers, but also to the higher demands on the wearable device in terms of water resistance and water pressure makes development challenging. With the increasing pressure under water, many sensors and actuators must further be treated differently than on land. In particular, the medical values such as oxygen saturation, heartbeat or Holter monitoring must be adapted to the different conditions underwater to function smoothly. Furthermore, the water represents an almost impenetrable barrier for various radio networks such as WLAN or Bluetooth and reduce the propagation of radio waves underwater as the frequency increases. This results in enormous hurdles, especially when networking different wearables under water, since radio wave-based connection methods cannot be used. In addition to wired connections, primarily the acoustic and optical data transmission has been investigated and recognized as useful so far [153]–[155].

Ongoing development and research made it possible to propose initial prototypes, concepts and ideas in the field of diving physiology while wearable sensors were also extensively investigated recently[156], [157]. Therefore, using devices to collect and process these data, could be helpful in minimizing future resulting dangers, such as drowning, floating away or fear. Previous studies have already been able to collect and describe in detail the individual sensors that have been used underwater [[156]–[158].

However, none of the studies went into more detail as to whether and how these sensors can be combined in a portable, compact and, if possible, networked end device. In addition, only sensors directly related to the health of the diver have been covered in the literature so far.

To close this gap and to show a first tendency of different portable wearables for any kind of diver and therefore, for a general underwater use; we especially try to answer the following questions:

- What use cases do wearables acknowledge, besides a depth logger dive computer, and in which directions are they developing?
- Which communication technologies and seals are the most forward-looking for wearables and up to what depth were they used and tested?
- To what extent were the wearable devices tested and what were the results attained?
- Are there important topics that have only been covered to a very small extent by scientific literature?

For the sake of completeness, individual wearables from other reviews are included, provided they are intelligent electronic devices that can be worn on the body or on the surface of the skin and can detect, analyse and/or transmit information. Dive computers that depict the classic approach of a pure depth sensor are not included in the review, as we consider them too simple to be compared with devices we defined as wearables. Similarly, commercial dive computers were not considered in this review for the following reasons. The details of the specifications of the individual dive computers can only be compared with great effort and not in a review since they were often tested according to manufacturer-specific conditions. In addition, the built-in sensors and actuators are often not disclosed, which would have to result in a direct comparison in the laboratory. Purely commercial studies on dive computers have been published so far, to which the reader can refer[159]–[161].

3.2 METHODOLOGY

The methodology used in the study is based on the approach of a scoping review. The scoping review approach aims to present certain key concepts that have not, or only partially been reviewed so far.

The review targeted wearable devices which are used underwater to make a comprehensive map of their capabilities and features, and to discuss the general direction of the development and orientation of research and prototype design of this kind of devices.

For this study, a scoping review was used to identify and discuss the extent, scope and nature of this line of research, to propose a summary of existing research, and to identify gaps in the existing literature [132], [162], [163]. During the process, we followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines and its extension for scoping reviews (PRISMA-ScR)[137].

The search syntax was developed on PubMed and the Scopus database using different word variations and combinations for the search in the search field for PubMed in “Title-Abstract” and in the Scopus database in the “Article title, Abstract, Keywords” field. Each iteration the search results were searched for 10 publications previously known to the authors to randomly examine the results of the search. If not all 10 papers were found, the search was repeated with a different search string. The final search formula "wearable OR device AND (diver OR diving)" yielded the most complete and strongest results with containing all 10 papers. Other terms did not yield any useful results in the respective databases and were further discarded. By using a final search string that was as generic as possible, most of the results with a possible match could be found.

The final search was conducted on September 2021, including the PubMed, Scopus, ACM databases and further checked Google Scholar for additional literature which may has not been covered by any of the beforementioned databases.

To get only relevant results, the search was restricted to the period after 2005. The reference lists of included articles were screened for any potentially missed papers.

A total of 2320 articles were identified by the search; of which PubMed returned 664, Scopus 992; while additional sources were included, like 15 papers from the respective references section of the mentioned papers that didn't appear in the initial results lists. After excluding duplicates, a total of 1420 papers passed the initial filter and were subsequently checked for title and abstract in terms of the objectives of the review. If the paper could not be clearly rejected or accepted based on the title or the abstract because it did not match the conditions, a full-text analysis was also carried out. To be considered as an appropriate paper, the following criteria had to be met:

- prototype or device that was described and tested in water.
- could be worn and interacted with (e.g., display, buttons, etc.)
- fully functional without external equipment
- English written, peer-reviewed academic source

Wearables that could not function independently as a research object were excluded. This included individual sensors which did not function as an independent device, actuators or non-portable sensors or systems which are not a wearable device[164]–[166].

After discussion with all Authors, we decided to include 171 studies for a full text screening. 41 articles were retained for synthesis an analysis from which, in a later stage, 5 were further discarded, since they did not fully meet the inclusion criteria. The individual steps carried out can be seen in 2.4.1 Scoping review and in Figure 12.

The subsequent steps of the review are presented in more detail in the next sections.

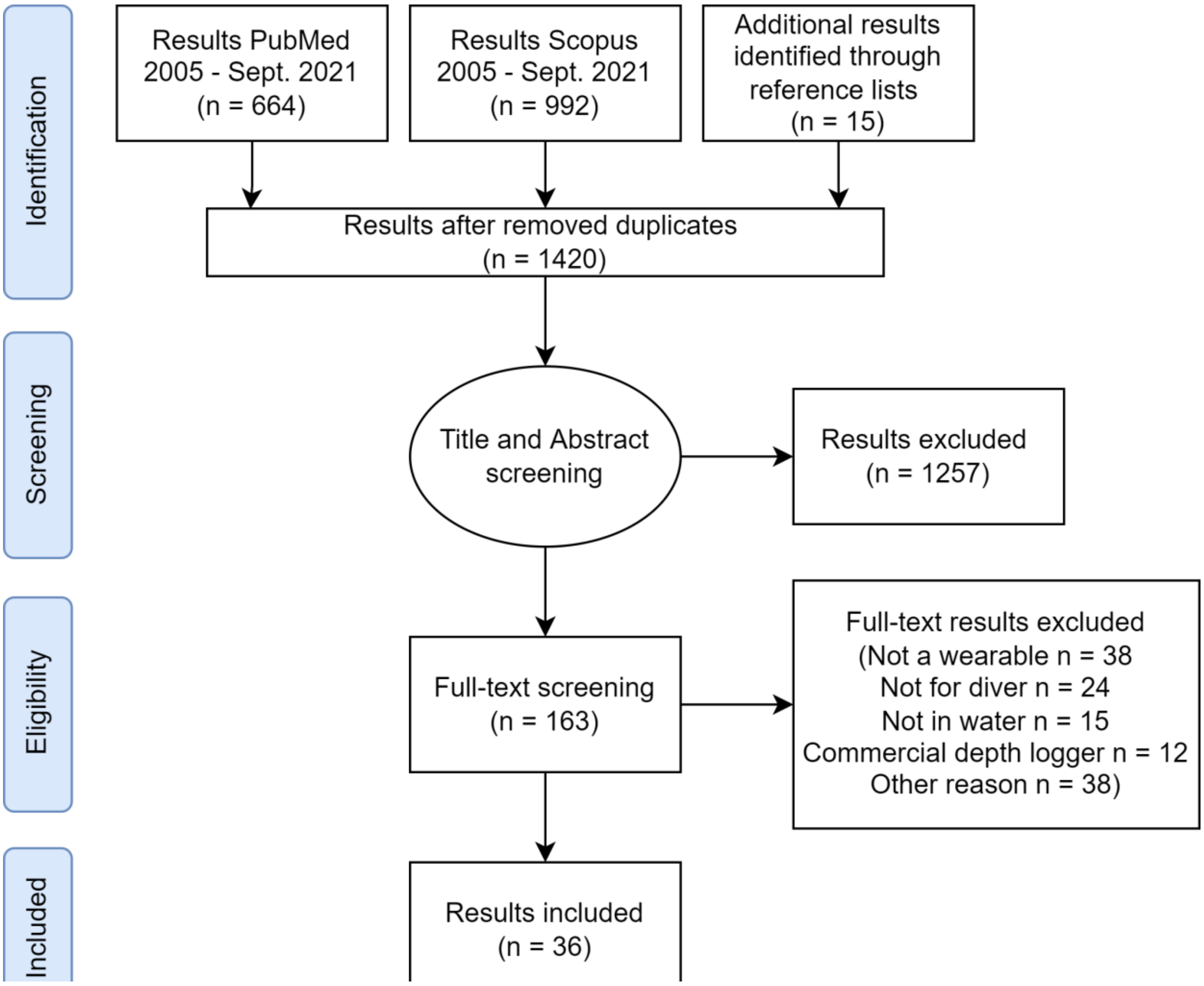

FIGURE 12. FLOW DIAGRAM OF STUDY SELECTION FOR WEARABLE DIVE COMPUTERS

A Spreadsheet table was created to present the data from the individual papers. Data extraction was performed by the first author. In cases where individual parameters of the wearable devices were not clear, these were examined more closely with all authors and a joint decision was made. There was no document instance in which a final consensus was not achieved among the four authors. The data extracted from the articles included in the review: Type of the article, source, title, study topic, study sample, housing and sealing, depth rating, location on body, implemented sensors/actuators, results and other studies who used this device. In particular, the housing type and the tested depth were listed on a separate Spreadsheet and displayed in a graphic. The application of the respective wearables was compared with the respective preferred way of wearing, which, however, did not show any further added value and was therefore discarded.

From these 36 studies retained in the review, 9 studies focused on communication as a wearable underwater between different devices, while 7 articles dealt primarily with the development of a head-up display, 2 studies with human-computer interaction possibilities underwater and the remaining 18 as different kind of safety devices. Theoretical measures are extracted from the wearable components' specifications, where this information was available. In the following, the "max. depth" is the depth at which the respective wearable was successfully used and tested underwater. The "construction depth" is the theoretically possible depth based on the design and commercial specification of the components reported in the publication.

3.3 SAFETY DEVICES

Most of the studies deal with divers' safety. This is nothing unusual considering that when something happens it usually ends fatally [13]. The applied maximum test depth varied between 2.7m and theoretical 300m. In this and the rest of the tables, both tested and theoretical depth measures were analyzed.

The section on safety device can be divided and specified in further sub-sections. The primary areas of application were vital signs (7 studies), Underwater determination of a diver (6 studies), breathing detection and cognitive functions (each. 2 studies). Although breathing detection is a part of the vital signs, this part has its own section due to its relevance and importance.

3.3.1 VITAL SIGNS

Four out of the seven studies had the collection of electrocardiogram (ECG) values as the subject of the study (Table 1). In doing so, depths of 2.7m up to 30m were reached. All systems could be worn regardless of the surface or external devices. Measuring oxygen saturation, blood pressure and heart rate is particularly relevant for freedivers.

Ref.	Study topic	max. Depth (Construction depth)	Sensors/Actuators	Results
[167]	heart rate (HR), stroke volume (SV), and cardiac output (CO) during dynamic apnea (DA)	3m (90m)	miniaturized impedance cardiograph	no changes in HR, SV and CO compared with surface breathing, immersed at the surface and at 4m depth.
[168]	heart rate (HR), stroke volume (SV) and cardiac output (CO)	3m (90m)	Impedance and ECG-recorder	bradycardia, decrement in SV an CO
[169]	measuring body temperature (core and skin) and electrocardiogram (ECG)	30m	ECG, Temperature, Bluetooth,	housing weak, cables problematic
[170]	underwater monitoring of a diver's ECG signal, including an alert system that warns the diver of predefined medical emergency situations	2.7m	ECG sensor	show the good accuracy of the analysis system as well as the alert system
[171]	wrist mounted apnea dive computer for continuous plethysmography monitoring of oxygen saturation and heart rate	11m (200m)	transcutaneous oxygen saturation, heart rate, plethysmography pulse waveform, depth, time and temperature	continuous measurement of O2, heart rate and plethysmography pulse wave for, water temperature and depth were successful
[172]	measurement of blood pressure underwater	10.5m (200m)	Pressure sensor, sphygmomanometer	accurate non-invasive measurement of blood pressure underwater
[173]	detect peripheral oxygen saturation for rebreather ECCR diver	14m	pulse oximeter	Detecting pulse oximetry during an immersion makes diving with a rebreather safer

TABLE 1. STUDIES COVERING VITAL SIGNS

3.3.2 BREATHING DETECTION

The detection of breathing has received too little attention in the literature so far but is of elementary importance for maintaining or increasing safety underwater. To know whether a SCUBA diver is drowning or not, it is helpful to know if the diver is still breathing or not. Two different approaches were successfully tested (Table 2). A precision of over 97% could be achieved with one device by reading the intermediate pressure (IP) signal on the SCUBA regulator and evaluating it with the help of an algorithm. In the second study, a textile sensor was attached to a diver's chest, which expands accordingly when breathing and thus provides different values. With this system, a breathing signal can be read independently of the SCUBA equipment. Both studies achieved depths of 25 m and 30 m, which are acceptable for recreational use.

Ref.	Study topic	max. Depth (Construction depth)	Sensors/Actuators	Results
[174]	breathing detection device	25m (100m)	two pressure sensors	sensitivity as high as 97.5% in 16 dives of 13.9hours recording
[175]	enhance safety, collect biometric information	30m	MS5803-14BA, respiratory sensing	steps entering detailed menu should be shortened and setting functions that deem to be unnecessary and dangerous (for example, rising speed warning alarm function) should be removed. Diving computer usability got overall average valuation of 84.7%.

TABLE 2. STUDIES COVERING BREATHING DETECTION

3.3.3 UNDERWATER POSTURE DETERMINATION OF A DIVER

A determination of the position under water has been pursued by many studies with other approaches (Table 3). A clear tendency towards a specific solution to record the position for diver in general is not discernible since the technologies shown cover very different approaches. However, an automated buoyancy vest is particularly suitable for SCUBA and technical divers, as commercial products have already shown [176], [177]. A posture determination suitable for freedivers could be carried out by means of the depth sensor and an inertial measurement unit (IMU) [38]. Other approaches pursued a possibility of recording unconscious behaviour of the diver with a camera that was pulled behind the diver or determined the position of a diver with GPS or by holding a sonar device.

Ref.	Study topic	max. Depth (Construction depth)	Sensors/Actuators	Results
[176]	automatic buoyancy control	30m (80m)	pressure sensors (water, and first stage), 3D accelerometer, pneumatic valves	initial correlations between the real dives and the simulated dive results were satisfactory.
[177]	increase the safety of divers. aimed at detecting the occurrence of too fast, possibly uncontrolled, ascents of the diver	300m	servo, (Pressure sensors, but not mentioned)	the proposed application seems feasible
[178]	automatically collect and average pressure data	4.4m (30m)	Pressure Sensor, Display, Magnetic Induction Switch	sunlight/temperature affects the pressure sensor, therefore misleading results for the depth
[179]	underwater pose determination	N.A.	three-axes accelerometer, three-axes gyroscope, camera	could analyze poses and fin kicks in real-time
[180]	enhance the diving experiences by recording user's unconscious behavior	N.A.	Camera, wire transmission to the diver	The camera can capture the diver fully and even other diving members
[181]	accurate and affordable geo-referencing for diver	N.A. (300m)	GPS, Pressure Sensor, Display	accuracy less then 5m
[182]	whether a handheld sonar device reduces the mean time to locate a missing diver	9m	Mark Track sonar dive equipment (RJE International, Irvine, CA).	Handheld sonar significantly reduces the mean duration to locate a missing diver

TABLE 3. STUDIES COVERING UNDERWATER POSTURE DETERMINATION

3.3.4 COGNITIVE FUNCTIONS

To move in a strange and hostile environment like water, intact cognitive functions are required. Although the topic is extremely relevant, only two systems could be identified that could function independently. The effect of cold water and cognitive impairment could be recorded by a significant increase of 111.7% with CFFF values. The other study could only determine a reduced performance at a depth of 20m when processing the Stroop test (Table 4). At a depth of 5m or on land, no changes were found.

Ref.	Study topic	max. Depth	Sensors/Actuators	Results
[183]	critical flicker fusion frequency (CFFF) test	45m	Display, flickering LED light	increase of 111.7% in CFFF compared to pre-dives, skin temp. dropped 0.48°C
[184]	Stroop test, Number/Letter test, 2-back test and a simple reaction time test	20m	heart rate and tank air pressure stored with Galileo Sol	several findings and results

TABLE 4. STUDIES COVERING COGNITIVE FUNCTIONS

The collection and storage of vital values received the most attention, since little is known about the medical background of diving, especially among divers and freedivers. However, due to the advancing development in this area in recent years, the use of these devices has made it possible to achieve initial results. By linking the previously developed and functioning safety devices with underwater communication, almost real-time monitoring of the diver can take place in various disciplines in the future. Possible scenarios include the use of these for technical divers, freediving competitions and other areas and as well as increasing the safety conditions of these activities. By specifically measuring the vital parameters of freedivers in all competitions, a significantly larger and more meaningful database can be accessed in the future. In subsequent developments, predictive algorithms can be developed on this database that will warn the diver before a critical condition occurs. This approach as a concept has already been presented but not yet tested in real use [185]. For this, however, it is necessary that the prototypes are significantly further developed to be able to be used meaningfully outside of a scientific study. Preferably as a finished consumer product.

As a result of the fact that divers can move freely in all 3 dimensions, contrary to a land-based deployment, the location and position determination receive a significantly higher level of attention. In addition, since GPS does not work when used in water, various localization options were investigated, but show weaknesses in various situations such as caves, strong currents or great depths of the diver[181]. The location and position determination with an integrated IMU shows promising results and should be further investigated. An almost real-time transmission of the position of a diver underwater also has many applications such as monitoring the individual students at a diving school, early detection of dangers such as currents and drifts or, for freedivers, the analysis of the movement sequences by a trainer.

The use of breathing detection devices in combination with underwater communication also opens new possibilities. In addition, by using the developed respiratory sensor system, a further focus on the collection and evaluation of contractions in freedivers on the diaphragm can be achieved[175].

3.4 UNDERWATER COMMUNICATION

Underwater communication is the most important aspect of a wearable for the Internet of underwater things (IoUT) [155]. Without a wireless connection between each other and the Internet, this would not be able to establish itself. That is why wireless connectivity is of particular importance in the future development and establishment of the IoUT. Due to the complexity and size of the modems for wireless underwater transmission, there are so far only a handful that have been successfully implemented and tested in a wearable.

Ref.	Communication technology	Data rate	Maximum range (m)	power consumption	depth	Sensors Actuators
[186]	light	N.A.	few meters	N.A.	1m	N.A.
[187]	acoustic	N.A.	18m (direct positioning)	>5W and <10W	N.A.	hydrophones, speaker, keyboard/display
[188]	acoustic	N.A.	N.A.	N.A.	N.A.	N.A.
[189]	acoustic	N.A.	>50m	N.A.	6.6m	beacon (GPS), acoustic communication, MS5837-BA30, pressure transducer
[190]	optical	500Kbps	20m	<10W	30m	camera, photoelectric sensor, audio acquisition, Display
[191]	acoustic	20bps	15m	N.A.	18m	acoustic transducer, depth, IMU
[192]	GPS/GSM Cable	N.A.	N.A.	N.A.	16m	pressure sensor, tank pressure sensor, GPS/GSM, Display
[193]	acoustic	64bps	200m	2.6W	250m	pressure sensor, RTC, acoustic modem, temperature, heartbeat sensor, display
[194]	light	4Kbps	7m	N.A.	1.5m	Light sensors, Earphones, Phototransistors

TABLE 5. STUDIES COVERING UNDERWATER COMMUNICATION DEVICES

As seen in Table 5. Studies covering underwater communication devices, two of them fall back on a two-part solution, in that the transmitter / receiver is attached to the back and the diver simply connects a wearable to the device on the back [188], [189]. Furthermore, apart from [193], none of the wearables can reach a range of more than 20m, which is not sufficient for a meaningful use until now. Conversely, however, the data rate also decreases significantly with the range.

Underwater communication between multiple devices or to the surface is a fundamental pillar for the extensive networking of wearables.

This is currently limited in its spread by three essential factors. These factors are the size, cost and bandwidth of the module that currently do not allow any economic dissemination. Due to a constantly advancing development in the IoUT and the underlying sensor networks, these will be useful in the future due to scalability in wearables for underwater use. The use of underwater communication in wearables are diverse and expand the possibilities enormously.

By implementing the AHOI acoustic modem in a wearable, a significantly more compact and cheaper option for use under water could be created in the future[195]. If the development proceeds in the same way as with mainstream wearables, an area of development could focus on miniaturization and arrangement, which would benefit the current bulky modems underwater[196]. By networking the divers devices with each other and with the Internet, the potentials were often examined and shown in regard to IoUT[150], [152].

Through a further connection of the wearables to other sensors on reefs, boats or sights, safety-relevant aspects can also be transmitted to the divers independently of vital parameters through underwater positioning, navigation or currents, for example, and appropriate recommendations (appearing, changing direction, etc.) to avoid accidents. An overview of the variety of options is provided by Jahanbakht et al [155].

As soon as this can be solved inexpensively and compactly, the other sub-aspects such as the collection of vital parameters will automatically arise. The first promising step in the direction of a more cost-effective and compact device with an acceptable range has already been presented[193]. A wearable device with data transmission can be manufactured commercially through consistent further development based on previous approaches. Whether freedivers are willing to spend more money for unique products, has yet to be investigated.

Since GPS also does not work under water, a different approach is required here as well. With an entry and exit point recorded by GPS, the location of the diver under water can be determined with an IMU.

Algorithms that can recognize whether the diver is in danger based on the movement data can also make enormous progress here and significantly increase safety, which has already been described in great detail in land-based use cases[197], [198]. Vinetti et al. concludes that monitoring, feedback and transmission of oxygen levels and the most effective economical swimming technique will have the greatest impact in the future [157]. By considering both aspects, monitoring and data transmission under water for the first time, we also assume that this trend will continue in the future and will have the greatest impact on the underwater world.

3.5 HUMAN-COMPUTER INTERACTION

The interaction with a conventional dive computer usually takes place via various buttons that are sealed against the ambient pressure under water. Although there is great potential for improvement in this area, only two of the papers dealt with the topic of interaction as seen in Table 6. Studies covering human-computer interaction devices. For this purpose, both the implementation of a touchscreen that is insensitive to water pressure and the interaction by tilting the device for input were tested. For both variants, the advantage over button-based interaction stands out. Furthermore, there is no need for a physical connection to the outside of the housing, which always represents a potential weak point.

In both studies, good results were achieved under all conditions, which makes further tests in this direction appear sensible. A comparison of the two options for interaction with those of a classic dive computer with buttons makes sense.

Ref.	Interaction type	Mounting	max. depth	Sensors Actuators
[199]	touchscreen	wrist	50m	Temperature, Water pressure, Direction
[200]	tilting for underwater typing	handheld	5m	Samsung S8 Sensors

TABLE 6. STUDIES COVERING HUMAN-COMPUTER INTERACTION DEVICES

Because the focus in the development of dive computers has so far been almost exclusively on scientific studies, it is not surprising that this aspect has only been considered very rudimentary so far. As a result, the number of studies that have been carried out on the subject has been very limited until this moment. However, both identified approaches showed a clear trend and the associated need for further investigations. A trend towards a design without weak points and connections to the outside can be seen in the literature. While once the classic touchscreen was chosen as the interaction method, the others opted for an interaction by tilting the device. As soon as a wider commercialization becomes established, as in mainstream wearables, this aspect could gain in importance and attention in the next years [201]. However, it is possible that insufficient attention is paid to the subject, as has been the case in the mainstream wearables market in recent years [196].

Whether this type of interaction turns out to be better or more useful compared to a wearable device controlled by a button should be further pursued and investigated.

It may well be that the general paradigms of usability and user experience cannot be applied underwater to the same extent. So far, however, no studies have been carried out in this direction to the knowledge of the authors. Nevertheless, as soon as underwater data communication is offered as a commercial function in a dive computer, this aspect could also receive increased attention, since it opens both completely new ways of interaction and interaction needs for the user, since the computers will allow much more extended functionality.

3.6 HEAD-UP DISPLAYS

Head-up displays are difficult to manufacture for the mainstream and to design in an appealing way, as the aesthetics are primarily decisive. As a result, only the large manufacturers of electronic devices could claim this market for themselves and developed HUDs for everyday use like Microsoft HoloLens, Google Glass or Intel Vaunt. And even these have partially stopped production for the time being, due to a lack of acceptance as a mainstream device [202], [203], even if they are currently offered to help carrying out working activities. However, since functionality is clearly in the foreground in diving, and a diving mask or a full-face mask is used anyway, the acceptance among divers is significantly higher. As can be seen in Table 7. Studies covering Head Mounted Display Devices, there are relatively many studies devoted to a HUD for divers. Due to the extensive integration of the technology into the mask itself, and the associated balanced pressure, most of the HUDs can experience a significantly greater depth or pressure without any problems. This is of particular benefit to technical divers; in whose environment they are most likely to be used. Of the 7 studies, only 2 enabled a see-through mounted HUD. Only one of the two can be attached to a conventional mask, which would be a potential use in freediving. Since the HUD is often integrated into a full-face mask, these are not subject to the classic challenges of a wearable device and can instead be placed in the mask without a waterproof housing and without direct seals. As a result, they reach a significantly greater depth than HUDs mounted outside the mask.

Ref.	Type of HUD	Mounting	Dive Mode	Depth (Construction depth)	Sensors Actuators
[204]	Not see-through	Mounted outside a mask	rebreather diving	300m	HUD, 3 pO2 sensors, depth, time, and decompression obligations
[205]	Not see-through	Mounted inside a full-face mask	SCUBA, surface supplied gas, rebreathers	45m (100m)	full color display, depth sensor, tilt compensated compass and a tank pressure sensor
[206]	Not see-through	Mounted outside a mask	Military combat diving	N.A.	micro display, optical lens, electronic compass, depth sensor, microprocessor, associated electronics, and battery
[207]	See-through	Mounted inside a mask	SCUBA, surface supplied gas, rebreathers	9m	Depth sensor, compass, LEDs, HUD
[208]	See-through	Diving helmet	Military combat diving	12m	HUD
[209]	Not see-through	Mounted outside a mask	all (copies the dive computer screen)	95m (300m)	Bluetooth, Pressure Sensor, Display, Buttons, pO2
[210]	Not see-through	Mounted outside a mask	rebreather diving	130m	IR receiver, 3 axis IMU, pressure sensor, tank pressure sensors, galvanic pO2 sensors, Display, Buttons

TABLE 7. STUDIES COVERING HEAD MOUNTED DISPLAY DEVICES

3.7 HOUSING AND SEALING

Particular attention should be paid to the implementation of the housing for the large number of different studies, as this is currently one of the greatest hurdles for the development of new and innovative ideas for the IoUT. As can be seen in Table 8. Housing and sealing comparison, almost every housing type was used for different study designs. Nevertheless, a clear tendency in the choice of the primarily used housing type polymer / PMMA can be seen with 13 out of 36 (36%) of the studies analysed. The second most common option was either an aluminum case or a commercial smartphone / tablet case / case with 7 out of 36 (19%) each. With 3 out of 36 (8%) each, the device was either sealed in a diving helmet or with a potting compound within the corresponding studies. Only 1 out of 36 (2%) was a tempered glass used for the housing. In 2 out of 36 studies (5%), no information on the housing was given.

Housing and sealing	Study topic	Ref.	tested depth (construction depth)
aluminum case	communication	[187], [192]	N.A., 16m
	HUD	[205][a]	45m
	Safety device	[176], [174], [181], [173]	30m (80m), 25m (100m), N.A. (300m), 14m
commercial smartphone/tablet housing/bag	communication	[186], [188], [189]	1m, N.A., 6,6m
	Interaction	[200]	5m
	Safety device	[169], [170], [178], [179], [184]	4.4m (30m), 20m, N.A., 30m, 2.7m
Diving helmet/mask	communication	[190]	30m
	HUD	[208]	12m (N.A.)
	Safety device	[173]	14m
Polymer/PMMA (Lexan, Acryl, Plexiglas, etc.)	communication	[191], [193], [194]	1.5m, 18m, 250m
	HUD	[204], [205][10],[206], [209]	300m, 45m (100m), N.A. ,95m (300m)
	Safety device	[176], [167], [168], [171], [172], [177], [180], [183]	30m (80m), 11m (200m), 3m (90m), 10.5m (200m), 45m, 3m (90m), 300m, N.A.,
potting compound	HUD	[207][11],[209],[210]	9m, 95m (300m), 130m
tempered glass	Interaction	[199]	50m
not specified	Safety device	[175], [182]	30m, 9m

TABLE 8. HOUSING AND SEALING COMPARISON

As expected, across all examined studies, the depth tested is well below the theoretical respectively the construction depth (Figure 13. Housing type and waterproofness in meter, white: tested and confirmed depth, grey: calculated or specified depth). Only the use of tempered glass was tested to the maximum specified depth. A direct comparison of a housing made of polymer / PMMA and potting compound shows that both depths achieved are approximately equivalent. By weighing the costs and benefits of each specific study to be carried out, a decision can be made between the two housing types. The most common primary cause cited against the use of a potting compound housing was the difficult access to the device for charging, programming and interacting after pouring [178]. If the challenges are overcome, the use of cast housings could prevail in the long term, also regarding the use of sensors in water.

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[10] Device consists of 2 parts and is therefore listed in 2 housing and sealing categories.

[11] It is only 9m because the potting compound has not been applied to all components. Instead, those had own compartments which are a problem with sealing. The buttons where sealed with O-Rings.

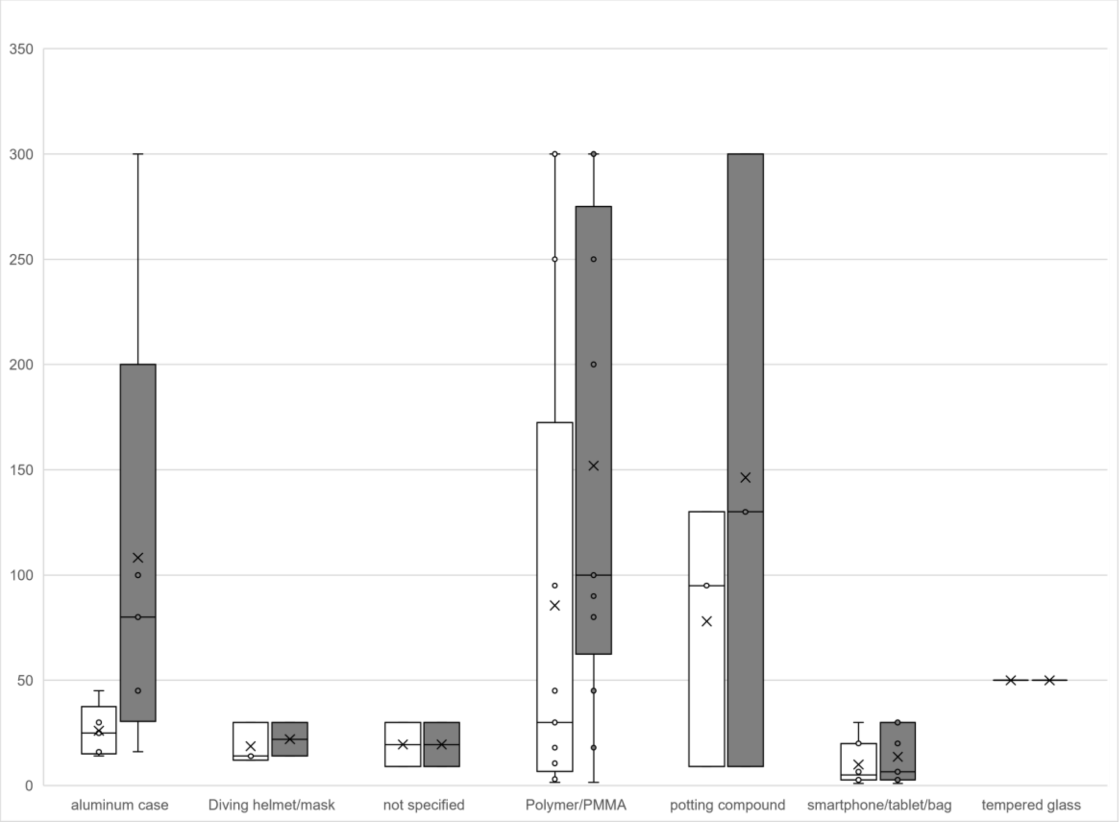

FIGURE 13. HOUSING TYPE AND WATERPROOFNESS IN METER, WHITE: TESTED AND CONFIRMED DEPTH, GREY: CALCULATED OR SPECIFIED DEPTH

Several lines of evidence suggest that especially the sealing against environmental influences under water will continue to distinguish the development of wearables for underwater use from those for land-based use in the future. As far as the authors research shows, no source is known that has dealt with the subject before. With the data on housing and sealing and their respective achieved or projected depths, we assume that polymer / PMMA and cast housings will continue to be the primary use in the future[204]. The cast housing can assert itself in eliminating various problems such as heat generation, programmability, chargeability and user-friendliness. Furthermore, the next step should be a careful study of the relationship between cost, aesthetics, design and achievable depth, which has direct implications for the various seals. Here it is particularly important regarding a completely cast housing whether this will be accepted in a commercial product. Even if the individual reasons were not mentioned, a completely encapsulated housing only occurred in three HUDs[207], [209], [210]. Therefore, no clear trend can be identified in this area. Reasons can be poor aesthetics, maintainability and heat generation. The introduction of different coloured epoxy adhesives in connection with LEDs and a special form of the dive computer could certainly appeal to the market.

3.8 SUMMARY

Most of the reviews previously carried out had the collection and evaluation of physiological and psychological parameters during diving as the primary research objective. The focus was either on generally available sensors that can be adapted for underwater use[156] or dealt exclusively with the sensors and not the entire wearable[157] or only dealt with physiological measuring devices [158].

Apart from the fact that some of the papers mentioned above were published a few years ago, they only dealt with safety related aspects in the field of diving. This trend was repeatedly confirmed in this review, since most of the wearable devices examined were also safety related. Furthermore, the wearable devices identified in this review in terms of safety, largely corresponded to those from previous studies. The only differences here were, if they could not be used as a wearable device as in the Methods section or if they were published after the respective review.

By considering other devices under water for the first time, a first approach could be shown in which areas potentials and challenges can be seen. So far, the development areas of underwater communication and human-computer interaction for divers have not received any real attention. Furthermore, this is the first review summarizing the available full-fledged diving devices that can be considered as a scientifically tested wearable prototype for diving. Commercial dive computers themselves have already been studied in terms of various parameters such as precision in measuring depth and their ergonomic performance[161], [211]. A review of modern dive computers and a comparison of 47 dive computer models as well as a comparison of the specifications was carried out before [159], [160]. By gathering the respective housing in combination with the maximum tested and the theoretically calculated depth in which a wearable device is functional, we were also able to show a first tendency in this area, which has not been shown before, as far as the authors know.

The present scoping review shows a first comprehensive insight into the various sub-aspects of developed prototypes of wearable devices for an underwater usage.

The possibilities and challenges of the respective technologies were considered and evaluated separately. In addition to the well-covered field of safety devices relating to the collection of vital signs from divers, other areas such as underwater communication between divers as well as topics such as human-computer interaction and specialized wearables for divers were also covered for the first time. Recent research has shown that the underwater communication has the most significant influence on future developments.

In contrast, human-computer interaction has so far received far too little consideration. This is particularly surprising because the conditions under water are different from those on the surface. A scientific summary and overview of the housings and seals used in devices for scientific purposes should be considered in a future and larger scale.

Currently, none of the individual wearable devices can lead the general development. The greatest future potential will result from a combination of all the aspects mentioned above with a special focus on safety and communication. A trend like mainstream wearables can thus be identified here as well, which focuses primarily on sensor design, communication protocols and data processing and analysis [196]. In this way, the underwater safety devices could communicate with other divers and stations in the IoUT and, if necessary, immediately carry out an action. This could e.g., significantly shorten and optimize a rescue chain in an emergency. By focusing research on wearable devices in underwater use and further developing them into a consumer product, such underwater networking could also be used for other sub-areas, besides safety measures or human physiology data collection[156]. Possible application scenarios would be the maintenance and repair of underwater structures such as bridges or drilling platforms, data collection and evaluation of animals using sensor material or a broad-based data collection on submarine environments using wearable devices underwater. In order to take a first step in this direction of development, the key point for a smart wearable device was built and tested as a prototype in the following chapter: probably the first wearable diving computer with wireless data transmission. We also underline the relevance and necessity of this prototype through an extensive test with the help of test subjects in the water.

4 A NOVEL WEARABLE COMMUNICATION DEVICE FOR FREEDIVER

As already discussed briefly in the previous chapter, the focus of Capabilities, Features and Current development direction of wearable technology strive in four different categories. In this chapter we developed, implemented and tested this prototype relying on the communication aspect between different devices under water. The studies outline the importance of such a communication system which is why such a system for supporting this task will be proposed. The results of this chapter have been presented in the publication[193] and were extended with, until now, unpublished material from the prototype and the results.

4.1 INTRODUCTION

Freediving is the most natural form of diving, limited only by the ability to hold your breath. A study by the Divers Alert Network from 2018 included 855 reported accidents that occurred while freediving. Of these, 78% were fatal[13]. The data collected are only a fraction of the accidents that occurred during this period, but clearly show the dangers and challenges during freediving. The term freediving can also vary greatly so that both top athletes and snorkelers appear in these statistics. A likely not insignificant part of the accidents probably occurred among non-certified freedivers. However, recreational freediving is the most popular and, in some aspects, the most dangerous kind of freediving[212]. While every recreational freediver holds the risk of an accident in their hands because of their own willingness to take risks, inexperienced partners or those diving at a different level of performance can represent an incalculable risk. Those who go diving alone are excluded, as they expose themselves to a completely different type of danger. However, the choice of a diving partner can be a problem if the diving partner is not aware of the significantly poorer performance. This can be dangerous, for both the diver and safety diver especially in lakes with poor visibility. If something unusual should happen to the diver that poses the risk of not getting to the surface in time, it is of little use to the diver to know that he is already in danger. On the contrary, triggered by this certainty, especially inexperienced freedivers can get hectic and panic, which has a negative effect on the oxygen demand and what amplifies the process of danger even further. In such a situation, this information can help the safety diver considerably more, as he can prepare, before he dives, for the challenge of rescuing the diver. Krack et al. made in 2006 the statement: "We want to know where a person is and how they are doing at any time during their dive"[213]. Even if this statement was not aimed at a technological solution, it can still be described exactly with these words. It is always particularly important to know where the freediving partner is underwater. In this paper, we propose a prototype that is capable of calculating, logging, displaying and communicating between several devices through acoustic data transfer. The contribution of this paper is threefold: An easy expandable and powerful processing dive computer with a near real-time communication underwater between several dive computers as well as the first scientific investigation in this direction. Results evaluated through the User Experience Questionnaire (UEQ) of 14 healthy freedivers who tested the Wearable Apnea Dive Computer with Acoustic Communication (WADAC) in water showed, that this should be the next logical step in the further development of dive computers.

4.2 SAFETY AND EXPERIENCE NEEDS

Technological progress has had a major impact on sports from the very beginning. Up to now this has been limited to a few areas. In diving, there is so far little to be seen of this multitude of possibilities. There is a simple cause. While most wearables, smart watches, smartphones, etc. are almost mainly faced with recurring challenges during development, equipment for underwater use must also be sealed watertight. And water tightness is a challenge for some sensors and actuators. In addition, conventional transmission technologies such as Bluetooth, WLAN, ZigBee, etc. do not work under water[19]. This makes it more difficult to exchange data in the local body area network as well as between several divers. These data can make a significant contribution to improve safety and the perceived experience during the dive. It is precisely the safety of freediving that makes it necessary due to the enormous increase in freediving performance in recent years. The safety of every diver is always of the utmost importance. Attempts are currently being made to achieve this goal in various ways. Buoys are used with the use of a lanyard on the diver to be able to rescue them if necessary. In addition, there are various procedures and rules that are all discussed in advance of the dive. Further, due to the increasing importance of the Internet of Underwater Things (IouT), the development in the maritime sector is being strongly promoted in recent years[214], [215]. In this article we describe a prototype that takes a first step towards networked freedivers underwater, to enable them for better and more pleasant decisions and to increase the perception of the safety diver. While the prototype is in the early stages of development, the results which have been achieved make further research in the area promising and necessary.

4.3 RELEVANT TECHNOLOGY IN FREEDIVING

The physiological factors relating to the pulmonary, cardiovascular, neurological, and renal systems have so far been described in detail[150]–[152]. In contrast, very few efforts in the technological area for freedivers have been developed so far. Kuch et al. (2010) developed a wearable apnea dive computer that records and displays oxygen saturation and other parameters [171]. Kuch et al. (2012) also designed a wired GPS system for divers[181]. In 2013 Terry Maas developed a Freediver Recovery Vest (FRV) that activates at a pre-set depth or duration and that carries the diver to the surface using a vest that is filled with air [216]. In this way, if the diver experiences a blackout, the diver can be safely carried to the surface. The same principle of the life jacket is used by the SENS07VEST, which is supplemented by an app with which the vest can be configured in advance with a smartphone[217]. Wiehr et al. proposed an early prototype of a personal freediving safety wearable that can detect high risk of a blackout before resurfacing[185]. However, all these devices have the disadvantage that the diver itself must react or that the safety diver is uncertain about the condition of the diver. A correct reaction cannot be guaranteed, especially in problematic situations. To increase safety, it is advisable to transfer these relevant data to the diving partner or partners. In this way, namely while the diver is on the bottom or is on the way to the surface, the safety diver is given the opportunity to be prepared even before something happens. This enables the safety diver to submerge at an early stage, knowing that he must intervene to help.

4.4 WEARABLE APNEA DIVE COMPUTER WITH ACOUSTIC COMMUNICATION

While self-contained underwater breathing apparatus (SCUBA) dive computers were often used in the early days of freediving, freediving computer have become increasingly independent over the last few years. Nevertheless, most of the SCUBA dive computers are equipped with an freedive mode, as this ultimately offers more functionality and can thus save costs for both the manufacturer and the user. This is one reason why manufacturers develop independent freediving computers only to a limited extent.

4.4.1 PROTOTYPE

In order not to make the prototype unnecessarily large, we designed a circuit board on which the individual components could be soldered. As can be seen in Figure 14. PCB Layout and Schematic, we developed the PCB elongated based on the schematic next to it. To produce the boards for testing we used the company JLCBCP. To minimize the effort involved in developing an individual housing for the various tests, we opted for an existing, round housing from Blue Robotics. In combination with the respective seals, cables and connectors, a clean solution for small tests could be developed, depending on the resources available, quickly, which as well offered a depth rating of 200 meters.

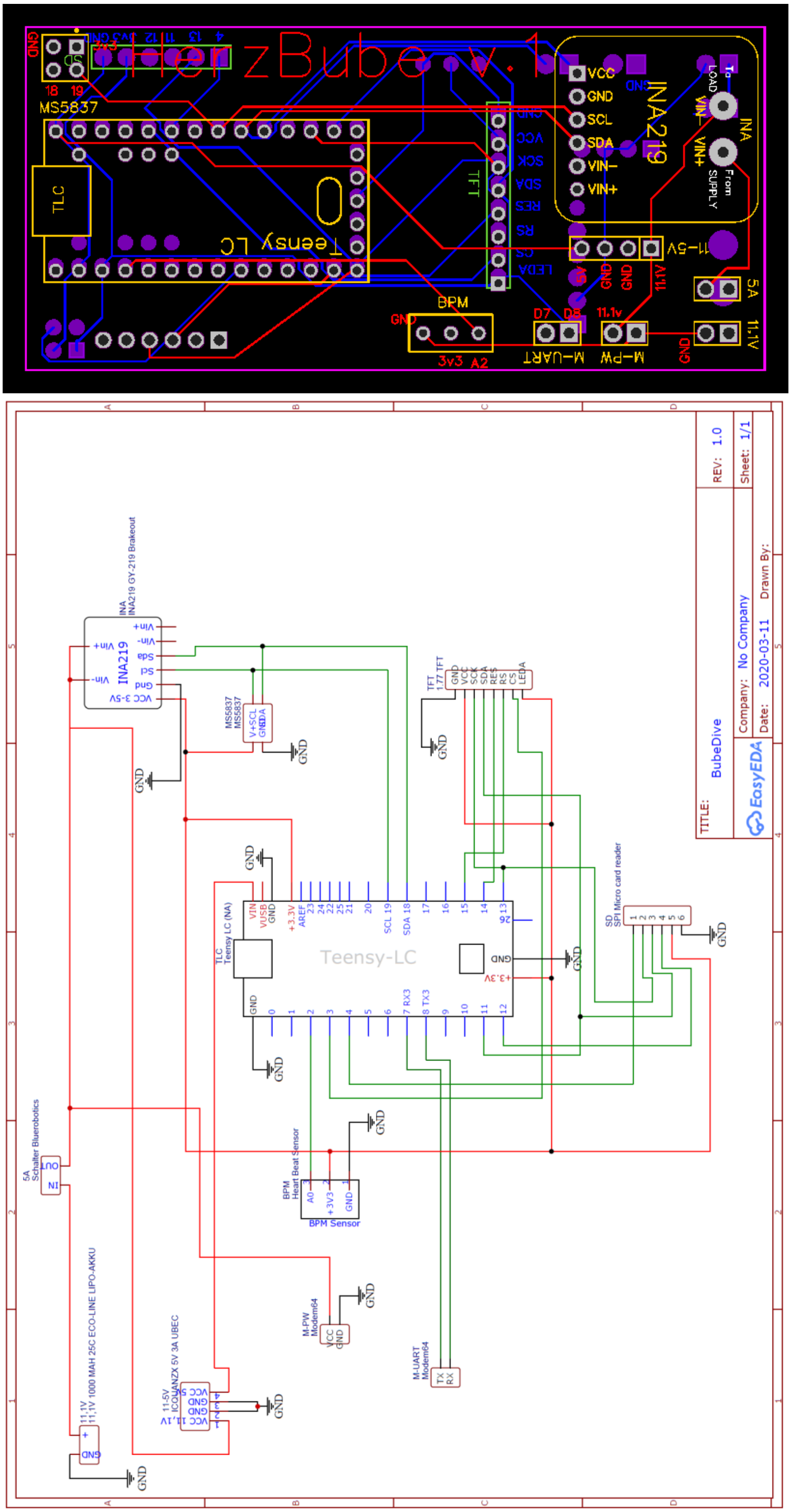

FIGURE 14. PCB LAYOUT AND SCHEMATIC

Furthermore, we developed the prototype, based on feedback from both world-class athletes and beginners. An iterative incremental approach was followed for the entire development process. During development, there was deliberately no focus on the external design so as not to influence the results of the test, and to test the usefulness of such a novel device. The cylindrical pressure-resistant body contains all relevant components of a conventional dive computer.

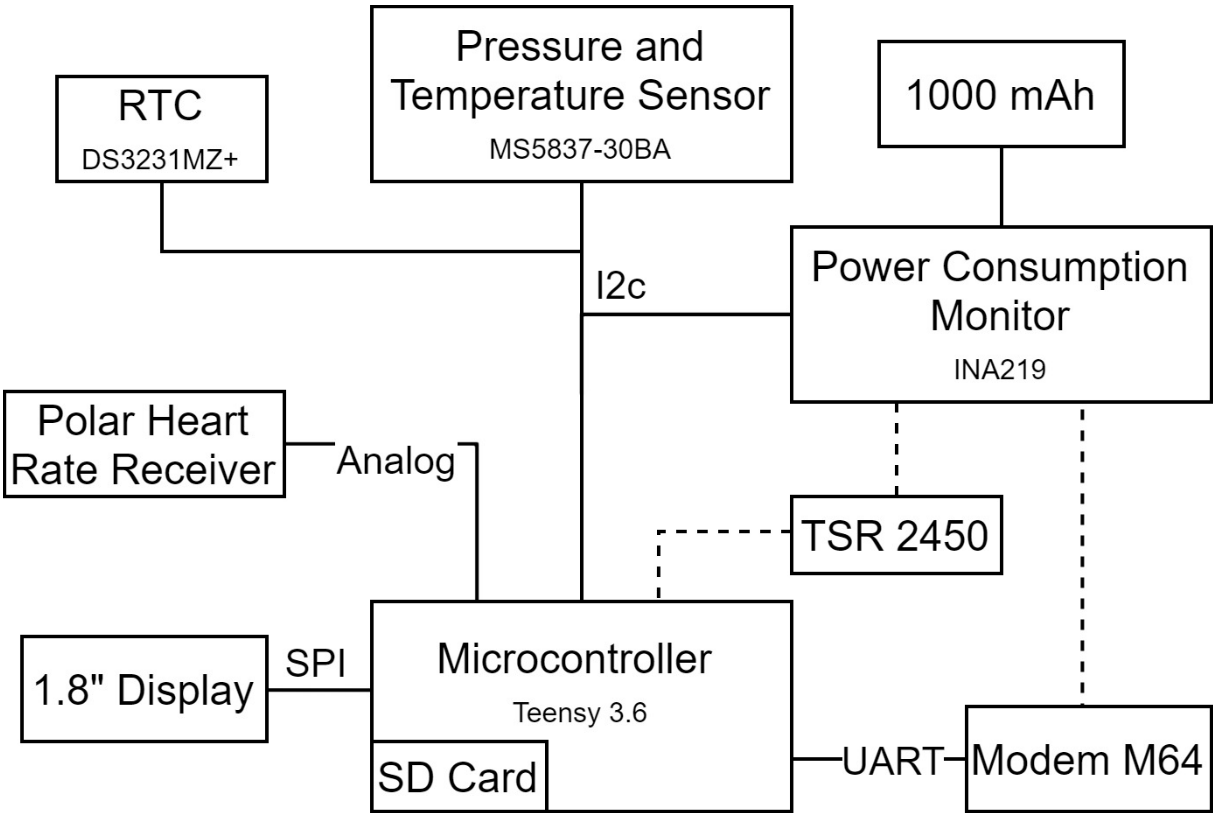

FIGURE 15. COMPONENTES OF THE WEARABLE FREEDIVE COMPUTER WITH ACOUSTIC COMMUNICATION

The constellation of the individual components can be seen in Figure 15. This includes the powerful Teensy 3.6 microcontroller with a clock frequency of 180Mhz and an integrated micro-SD card slot. The code for all components were written in C / C ++ and partly in Arduino C with Platform.io. The rudimentary data about a dive is provided by the precise pressure and temperature sensor MS5837-30BA from Texas Instruments. The sensor enables an application range from 0 bar to 30 bar with an accuracy of 0.2 cm in water. The energy consumption is given as only 0.6 µA. Further, the WADAC is supplemented with a real-time clock (RTC) of type DS3231MZ + with its own power supply via the button cell CR1220. The RTC was used both to display the time for the diver and to log the data on the SD. The M64 modem from Waterlinked AS was implemented to obtain a cost-effective, compact module that meets the requirements for data transmission[218]. This enables us to transmit data at 64 bits / s, which currently transmits the depth, temperature and heartbeat in two digits. The last 8 bits are currently not used.

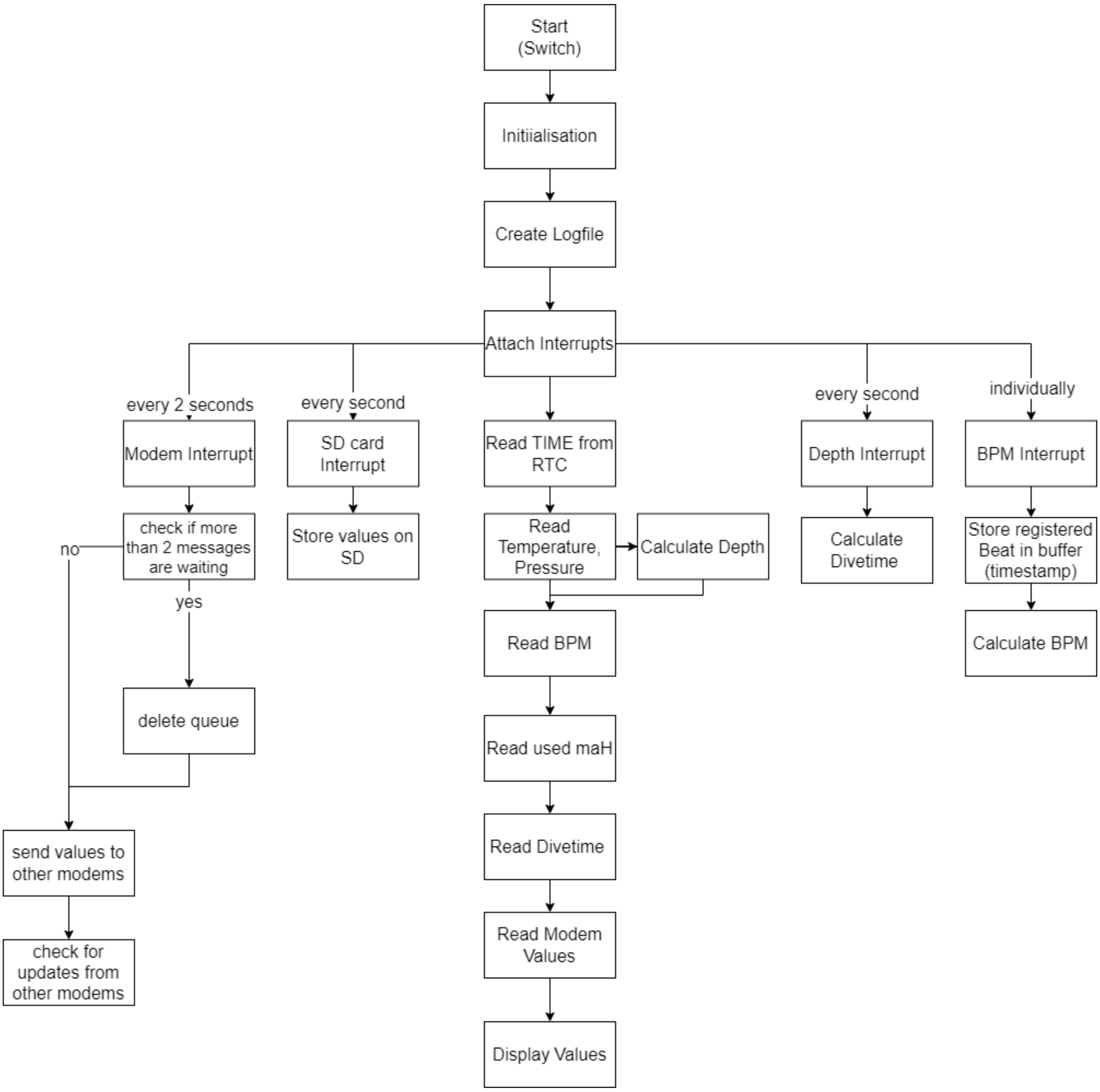

FIGURE 16. PROGRAM FLOW CHART

The duration of the dive is calculated on the other WADAC from the depth received. The modem M64 consumes an average of around 2.6Watt and was attached outside the watertight enclosure and connected to the inside by cable penetrators. The watertight enclosure is made of cast acrylic plastic with an inner diameter of 50mm and a length of 150mm with a depth rating of 250 m. Each side of the enclosure is sealed with a flange cap made of aluminium and two holes which house the connections to the outside. Communication with the microcontroller was implemented using the 3.3V UART. Since the voltage for the modem must be somewhere between 10V and 18V, a 3S lithium polymer accumulator (LiPo) with 1000 mAh was chosen as the energy source. This ensures continuous operation for about 3-4 hours. Since the microcontroller allows a maximum of 6v at the input, a Stepdown Tracopower tsr 1-2450 was switched between the LiPo and the Teensy. A digital current sense amplifier from TE the INA219 transmits permanently the power consumption from the modem and the other components via I2C to the microcontroller. This information is then shown to the user next to the date on the 1.8 " full 18-bit colour display with a resolution of 128x160. The whole program flow chart is shown in Figure 16. To demonstrate the capabilities of the WADAC, a heart rate receiver released by Polar was added, which records any signal at a frequency of 5.2Khz[219]. This is a commercially available and widely used uncoded chest strap sensor that is primarily used in the fitness sector. The calculation of the current heart rate is added and averaged from the last 10 registered signals based on the time. The Polar T34 chest strap used for this allows a maximum water depth of 100m. An expansion or replacement of the system with the SPo2 measuring device developed by ONIN OEM III is also possible and has already provided acceptable results in another study[171].

4.4.2 AIM AND APPROACH

The aim was to develop a dive computer that offers all the basic functions, is easily expandable and enables communication between several of the same type. The focus was on lakes with poor visibility of only a few meters as well as great diving depths in the sea as seen in Figure 17. In both situations, it can take a few seconds to several minutes before the safety diver knows about the condition of the freediver. In a threatening situation for the freediver, these periods of time can significantly reduce the reaction time of the safety diver, whereby accidents and their consequences can be minimized. A not insignificant question that arises is how a freediver reacts to such a technical development. Is the freediver more likely looking for inner peace combined with relaxation and does not want to be distracted by such a dive computer or would the freediver like to know where their diving partner is at any time. However, at any time it would be a very helpful benefit for the safety diver to know where the buddy is.

FIGURE 17. LEFT: THE WADAC CONNECTED TO THE RIGHT ARM. RIGHT: A FREEDIVER WITH THE WADAC IN THE RIGHT HAND JUST BEFORE DIVING.

4.5 DIVE EXPERIMENT

The following chapter contains two different dive experiments which were observed during the same dives. One focuses on the user and the experience while the other focuses on the dive performance and connectivity of the dive computer itself.

4.5.1 SETUP

To find out the general product acceptance, the developed WADAC was made available for a full day during a freediving event in Ibbenbüren and another day in the Aggertalsperre then evaluated using the UEQ [17]. 14 people were enrolled for this study which were all healthy freedivers (12 men, 2 women) with an average age of around 50 (M = 53.5, standard deviation [SD] = 11.38), between 29 and 65 years old. Dive Experiment with Packets send and lost. To assess the experience of the freedivers as best as possible, the number of dives deeper than 20m were used as an indicator, in which the average was 350 dives (M = 200, SD = 333) ranging between less than 100 and more than 1000 dives. The Personal Best (PB) in deep diving with an average of around 34m (M = 33, SD = 9.2). Informed written consent was obtained from each participant as well as subject information about possible risks and challenges. The tests took place in the Aggertalsperre (Fig. 3) and during a freediving event in Ibbenbüren where all necessary safety regulations were met as well as a medical statement about the fitness to dive and a brevet from any of the recognized diving organizations. During the event, each individual participant could choose whether he wanted to participate in the survey. During the dives, the WADAC was either attached to the arm like a wearable or held in the hand. Each of the participants could choose the duration and number of dives. Dives into caves, wrecks and other underwater facilities were carried out at will, where there was most of the time no visual contact between the participants. Thanks to the use of an independent safety diver, it was still possible to secure protection for those who were diving at any time. Once a freediver finished testing, he gave the WADAC to the next participant, went ashore, and filled out the questionnaire which can be seen in the appendix. A briefly interview about improvements, wishes and suggestions in relation to the WADAC was carried out.

The data obtained during the dives were stored on a built-in SD card in the WADAC and later analysed.

4.5.2 USER EXPERIENCE QUESTIONNAIRE - DIVE RESULT

The data set with which we compared the WADAC consists of 20.190 data sets collected through 452 studies. The values of the UEQ are divided into the six categories attractiveness, perspicuity, efficiency, dependability, stimulation and novelty. The attractiveness determines the overall impression of the product, whether users like this product or not. The measured value of attractiveness showed in the benchmark that only 10% of the results are better, which means that the achieved values were above average (see Figure 18). Perspicuity tries to answer the question of how easy or difficult it is to operate and empathize with the product. The values identified for perspicuity are the worst of all six in this category. Nevertheless, the WADAC achieves better results than 50% or is worse than 25% of the entire data set compared with. Especially in freediving, a technical device should solve the assigned tasks quickly and easily for the user without great effort. Here, the efficiency is particularly important to what extent the user can complete the task quickly and without unnecessary effort.

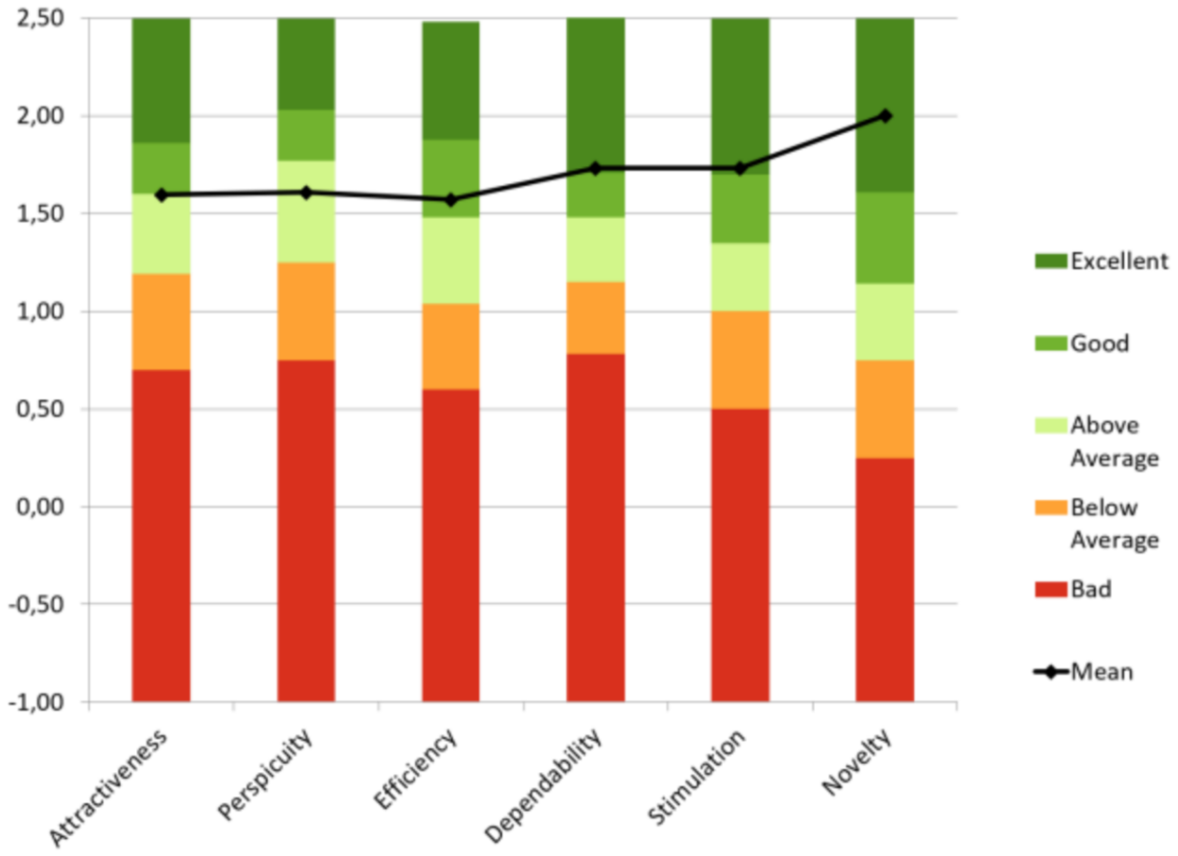

FIGURE 18. THE MEASUREMENT RESULTS COMPARED TO THE BENCHMARK

In comparison, this value showed that only 10% of the data sets performed better. However, the Cronbach's α value for the efficiency only shows 0.34, which is why the informative value gained in the questionnaire is questionable (see Table 9). The three other scales, dependability, stimulation and novelty, achieved all excellent values and are all in the top 10%. The dependability tries to make a statement about whether the user controls the product and whether it is secure and predictable. The stimulation, on the other hand, determines the fun and pleasure in interacting with and using the product. Particular attention should be paid to this point, especially regarding recreational freedivers. The last point determines the novelty of a product with what is known so far. As there is currently no freediving computer with a function like this, the novelty is, as expected, very high. The amazing thing is that it is just a first prototype, with no emphasis on design, functionality or usability. And yet high to very high values were achieved in comparison. Our assumption is that the functionality of wireless communication underwater and its possibilities in freediving overshadows all other points.

Scale	Mean	Std. Dev.	Cronbach`s α
Attractiveness	1.595	1.029	0.94
Perspicuity	1.607	0.836	0.71
Efficiency	1.571	0.682	0.34
Dependability	1.732	0.857	0.72
Stimulation	1.732	0.840	0.83
Novelty	2.000	0.797	0.83

TABLE 9. UNITS UEQ RESULTS MEAN, STANDARD DEVIATION AND CRONBACH`S A.

This assumption is reinforced by the fact that the participants repeatedly mentioned the advantages of a no longer existing line of sight and that these are enormous. In addition, the WADAC is particularly suitable for the safety diver, who receives good support in securing the diver. From the diving point of view, the WADAC was received with mixed feelings.

4.5.3 TECHNICAL ANALYSIS – DIVE RESULT

In addition to displaying the various parameters, the data was also logged on an SD card in the dive computer. Internally, the current values were saved every second by means of an interrupt. Below we will take a closer look at a package excerpt and go into the individual values. The data was saved line by line in a file every second. The file names used were searched after each start of the WADAC according to the principle BD_01.TXT, BD_02.TXT... BD_N.TXT and saved as BD_N+1.TXT. As a result, after each session, the divers could be clearly assigned according to the respective data set. The size of a data record of 1 second is approximately 80 bytes on average. With a continuous operation of 1 hour (60 minutes * 60 seconds) that is 288 Kbytes of data. As seen in Figure 19, the data has been delimited for easier processing.

```
2020.9.26;10:31:19,138521|-.14,17.90,119.25,  999.00|0|wrd,y,42,4,8.0*7b ,4,17,84
2020.9.26;10:31:20,139658|-.14,17.89,119.25,  999.00|0|wrd,y,43,4,3.6*5a ,4,17,83
2020.9.26;10:31:21,140764|-0.12,17.90,102.43,1001.00|0|wrd,y,43,4,5.4*29 ,4,17,83
2020.9.26;10:31:22,141767|-0.09,17.90,77.25, 1004.00|0|wrd,y,43,5,5.4*4b ,4,17,83
2020.9.26;10:31:23,142771|-0.05,17.90,43.78, 1008.00|0|wrd,y,44,5,11.8*4f,4,17,86
2020.9.26;10:31:24,143888|-0.09,17.91,77.25, 1004.00|0|wrd,y,45,5,20.8*0d,4,17,68
2020.9.26;10:31:25,144901|-0.13,17.90,110.84,1000.00|0|wrd,y,46,5,18.6*79,4,17,60
2020.9.26;10:31:26,145904|-0.11,17.89,94.03, 1002.00|0|wrd,y,46,5,14.8*a9,4,17,60
2020.9.26;10:31:27,147024|-0.14,17.91,119.25, 999.00|0|wrd,y,47,5,19.4*0f,4,17,0
```

FIGURE 19. WADAC LOGGED EXAMPLE (FORMATTED)

The first characters represent the date and time generated by the built-in clock. The data set shown here were produced on September 26, 2020, at the time 10:31 from second 19 to second 27. The number behind it is extrapolated internally in the WADAC. This always starts at the beginning with 0 milliseconds and permanently adds the time that has already elapsed. In the example, between 138 seconds and 147 seconds have elapsed. The next value is the depth of the current WADACS in meters. Due to the use on the water surface, these values are often negative at less than 1 meter. The next value in the respective line beginning with 17 reflects the current water temperature. The following value shows the altitude above normal 0 in meters. However, this is not calibrated and therefore fluctuates. The values in the next column represent the ambient pressure in Mbar. Since this WADAC is not currently diving, approx. 1 bar is constantly displayed here. The value |0| only serves as a checksum for internal operations. The values that follow represent the data received via the modem. The abbreviation “wrd” in combination with the y indicates that this is a valid connection and that the other WADAC has been found and connected. The following values are for internal purposes and are processed further until the final checksum in the 9*3b format. Finally, the data from the other WADAC is given, separated by a comma, in the form of water depth in meters, water temperature in degrees Celsius and heartbeat in beats per minute.

During the tests carried out in the water, the data was continuously saved in parallel. The data obtained in this way was then formatted with a spreadsheet program and filtered according to the parameters mentioned above. Values less than 1 meter were shown as 0 meters and straightened out. Values greater than 1 were not further modified because the sensor works very precisely in this range[12].

Figure 21 shows the depth in relation to the accumulated number of lost packets during several dives. The dives are shown in grey with a maximum depth of around 30 meters. After several dives we reset the dive computer to start a new logging interval which led to the abrupt change to zero in the orange accumulated line. It is interesting to observe that during the regular descent to the maximum depth, almost no packet losses occurred. Only at the so-called "turn" of the free diver did the number of lost

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[12] https://www.te.com/deu-de/product-CAT-BLPS0017.datasheet.pdf

packages increase rapidly within this short time. This can be seen particularly well in the dive on the first dive or the dive at second 1429. There are 2 possible explanations for this. One possibility can be characterized by a more active phase of diving and thus significantly more movement. The free diver only has to move to a limited extent when descending, while he has to work actively when surfacing and is therefore in motion. On the other hand, most have held the WADAC either on their wrist or in their hand. Due to the natural, relaxed posture when diving, the fins are used to descend and emerge, while the arms are close to the body. By diving headfirst, the dive computer is in a direct "line of sight" to the other dive computer on the water surface. This is how most of the signals arrive. As soon as the diver makes the turn below, the dive computer is on the "shadow side" of the body and no longer allows direct visual contact with the counterpart on the water surface. On closer inspection, it also becomes clear that the deep dives in particular have an above-average number of errors. This can either be due to the increasing depth and thus generally poorer reception, or it can be due to the fact that the greater depth means that freedivers have to work against a significantly stronger downforce, which causes greater movement and more noise. We compared the same time window of the dives with the data of the safety diver. It is easy to see over time that the runtime between the individual WADACs does not deviate significantly. Otherwise, the free diver's data would be different in blue from the backup diver's data in orange. The depth at which the safety diver picks up the diver and accompanies him to the surface is clearly visible. However, it is worth mentioning that due to the rounding of the safety diver's dive data to full digits, the depth can either be below or above it.

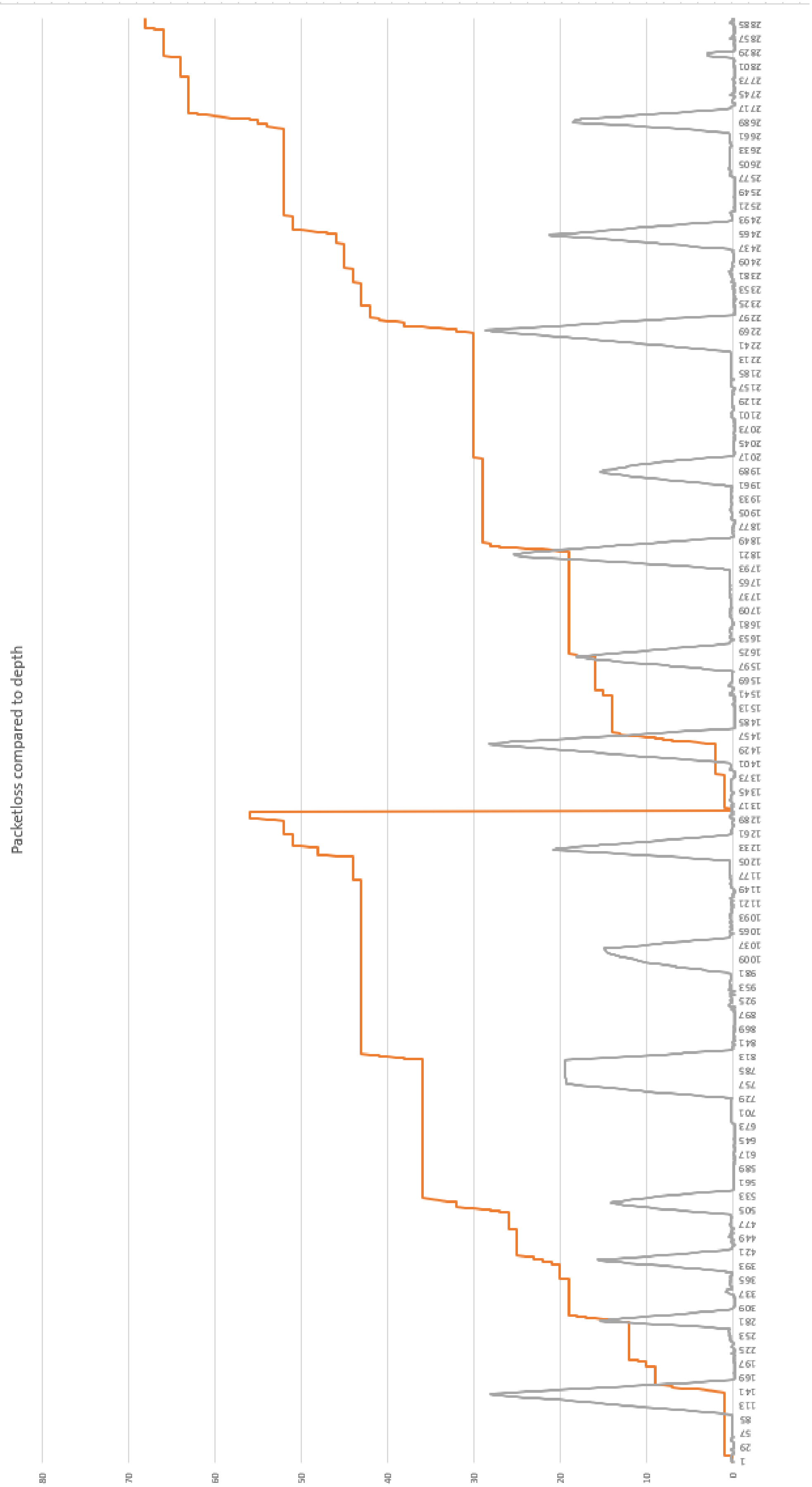


FIGURE 20. WADAC PACKETLOSS COMPARED TO DEPTH

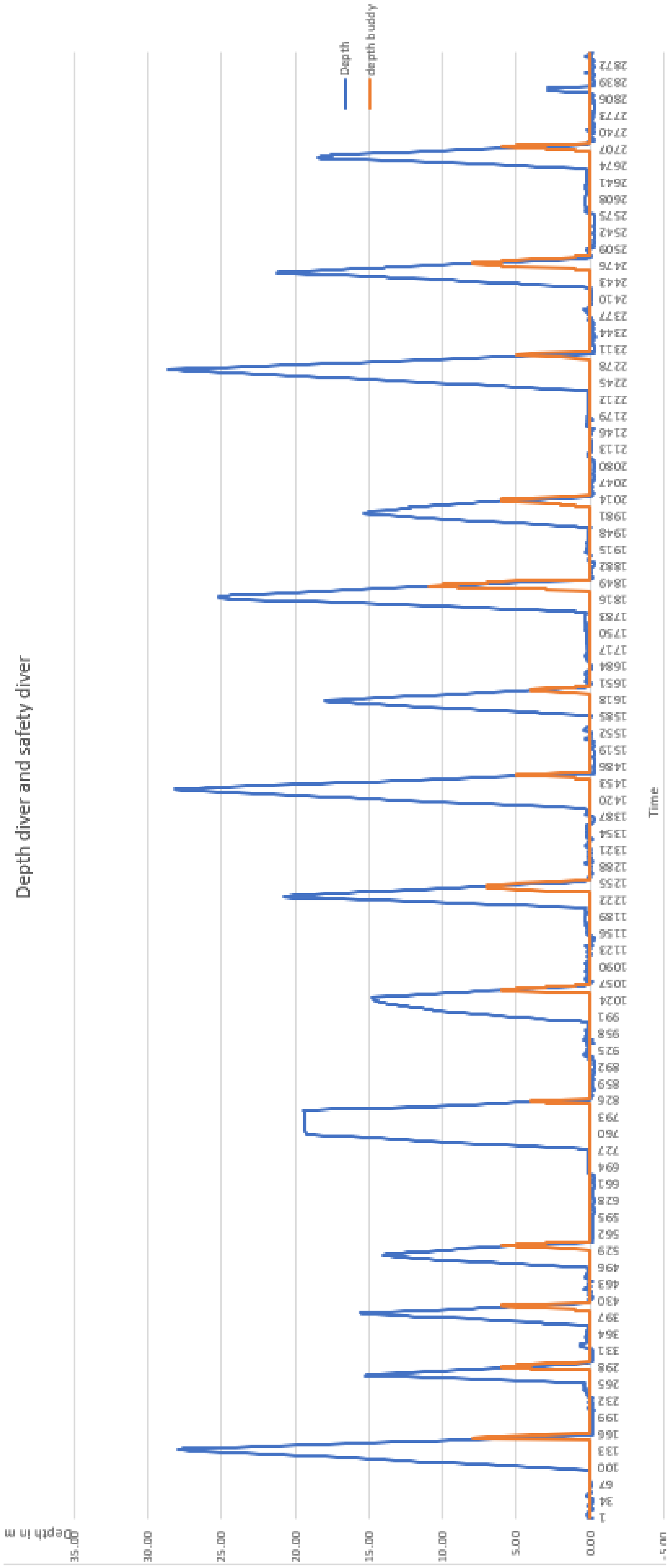


FIGURE 21. WADAC DEPTH OF THE DIVER AND SAFETY DIVER

4.6 SUMMARY

This chapter presented the work done on a prototype of diving computer (WADAC), which was built mainly in order to test underwater wireless communications.

The primary goal of the WADAC is to support the safety diver in safeguarding the actual diver by providing permanent monitoring without visual contact. Under certain conditions, the WADAC creates enormous advantages. However, the safety diver must still be able to assess the situation based on the transmitted values. In addition, when there are many obstacles between diver and safety, the WADAC has a limited connection quality. The connection was interrupted more often in winding caves. In the shipwreck, on the other hand, permanent data transmission could be guaranteed. A major disadvantage of the WADAC is its clearly too small and low-contrast display, which almost every subject noted. Most of the subjects, however, wear glasses and go diving without glasses, yet the brightness was not set to the maximum brightness at the beginning, as this in turn is dazzling. By installing an ambient light sensor, the brightness could be adjusted automatically. The heart rate sensor posed a further challenge. It only delivers a high level when a heartbeat is detected. This revealed that this system was not reliable enough, as signals from the chest strap could get lost or other chest straps caught them incorrectly. The size of the WADAC was also found sometimes bulky on the wrist, but this is due to the early prototype.

The WADAC has room for improvement in many areas. In the event of further development, the form factor can be reduced, the design developed, and power consumption optimized. In addition, the cost of manufacturing a WADAC is around 2000€. By changing to another, more compact and cheaper modem, the WADAC can also be implemented at significantly lower costs[220]. In relation to developments in recent years, there will be many possibilities in this regard. Another challenge is IouT for freedivers. Through integration, relatives, coast guards and other authorized persons could intervene at any time in the event of danger. That could enormously shorten the time span of a rescue chain. By linking a life jacket for divers to the WADAC, the safety diver can deploy the jacket externally and without exposing himself to any danger. This is especially important when the weight difference between safety and diver is huge, but also when unforeseen safety events such as cramps, pressure equalization problems, etc. occur. Thanks to the modular system of the WADAC, any components can be added or removed at any time, which is an ideal basis for further scientific investigations. In addition, the collected data can be used to identify different situations with the help of machine learning. Consistent further development towards a user interface is also useful.

We will go into some of these challenges in more detail in the following chapter and present a prototype that has a modular structure. Special emphasis was placed on optimizing the size of the device, but also on making it accessible for others to recreate and expand this prototype.

5 LOW-COST WEARABLE DIVE COMPUTER

Due to the enormous spread and acceptance of wearables, it has become easier in recent years to collect physical data and use it to improve the living conditions of the wearer. On the other hand, there is the underwater world, in which technological development could not progress so quickly; mainly because the sealing of the device and the interaction with it pose different and novel problems compared to more widespread wearables. To close this gap, a low-cost dive computer with a customizable set of sensors which is suitable for large-scale data collection for divers is presented in this contribution. This prototype makes use of existing electronic components such as sensors or modules aimed to develop a fully functional and low-cost portable system. In addition, the portable system is also able to store the data of all users bundled on a server for further research. These results cover two primary goals: (1) to provide an easily reproducible portable system at low cost, and (2) to collect data in an easily adaptable platform and its subsequent easy accessibility. Finally, the prototype was built based on the instructions and tested under real conditions.

5.1 HARDWARE IN CONTEXT

Over the past few years, wearables have been widely adopted and become a worthwhile tool for many people in their daily lives, especially those aimed to the collection of health-related data from the user. Consequently, wearables have already been scientifically examined in detail in many areas in recent times. This resulted in many solutions that can be used for scientific tests and data collection[119], [193], [221]–[224]. Beside this, wearables have been actively used in a wide variety of areas for personal or scientific data collection in the wild for several years[225]–[227]. As a result, interest in using wearables for scientific surveys and evaluation toward a scientific purpose has also increased in many areas within the last decade, especially for the monitoring of fitness and health-related metrics, where this data can be viewed by the users and analysed either with or without supporting applications[119], [224]. In cases where there was no commercially viable solution, an in-house development has been used. With the consent of the test subjects, the data obtained in this way were able to drive scientific developments in several cases [174], [228] . However, so far, only one suitable study for wearables has been offered for a general large-scale study in freediving underwater[119]. Only studies that had already been carried out with special hardware were used in some cases in order to be able to carry out further investigations by improving the previously developed devices [172], [229]. At the same time, the commercially available dive computers are only very limited for collecting scientific data, due to the lack of open interfaces, proprietary sensors, data formats, or they are simply too expensive for large studies. The iX3M from Ratio Computers as well as the Garmin Descent Mk2 dive computers cost around €1000 while the Aqualung i770R, Suunto EON Core and Mares Genius are all over €600 per unit [230]–[233].

This is largely because the dive computers available are tailored to the consumer and less to scientific studies. Furthermore, the data collection and evaluation among the models are not automatically comparable, because often the integrated sensors or approaches to collect data work differently in each dive computer.

Although divers are generally at higher risk than non-divers, far fewer studies have been conducted in this area, compared to those considering the general population[13]. The underwater environment is, for humans, unnatural and dangerous, which makes it particularly necessary to survey physiological factors. Due to the significantly smaller number of people who are divers, as well as the higher demands on wearable devices in terms of water resistance and water pressure, the development of underwater wearables has been challenging, mainly due to the lower commercial potential of this effort. As a result of the increased pressure under water, many sensors and actuators must be treated differently than they are on land. To allow further investigations in this area a customizable wearable that can withstand the special conditions under water is needed. Furthermore, the wearable should be easily adaptable and expandable to be able to correspondently adapt to the rapidly growing technological development, while a further advantage of this dive computer would be that the use of the same sensor models allows for a more consistent data collection.

Therefore, the aim of this project is to offer a waterproof dive computer that is easy to build, easy to expand, inexpensive and suitable for collecting large amounts of data. To ensure the best possible support and reproducibility also in future projects, it was decided to use the popular open-source solution Arduino [234]. The Arduino Platform combines the advantages of hardware and software that is useful for both beginners and professional prototyping. The reusability and further development are supported precisely by the use of widespread components and publicly available code. Ongoing development and research have made it possible to propose initial prototypes, concepts, and ideas in the field of diving physiology, while wearable sensors have also been extensively investigated recently [156], [157]. Unfortunately, only a few of those projects with Arduino compatible components are suitable for underwater use and therefore do not allow them to be easily adapted and extended[193], [194].

These results in two primary demands on the device presented in this contribution. Through the integration and detailed description of many components in the system, we enable a wide range of scientists to collect data in the context of diving or, in this case, freediving, without major hurdles. The other aspect results from the inexpensive construction, so that even in a large-scale data collection, the cost of the dive computer is contained. The consistent use of off-the-shelf products further enhances reproducibility and adaptability, whereby the dive computer can be easily and uncomplicatedly adapted to conditions of a given study.

5.2 HARDWARE DESCRIPTION

The dive computer consists of the primary component microcontroller, display, SD card, temperature and pressure sensor, Real Time Clock (RTC) and battery. These are sufficient for use as a classic dive computer and allow normal operation. To demonstrate the capabilities and customizability of the dive computer, an Inertial Measurement Unit (IMU) with 9 Degrees of Freedom (DoF) was also installed. This sensor can be replaced by any sensor that is better suited to the respective study and used instead. To seal the dive computer against environmental influences, especially water, the entire device was cast in epoxy[207], [209], [210]. To still allow communication with the prototype, two touch pins of the ESP32 with the contact surface were led outwards. A QI wireless charger is installed to charge the system without physical connection. New updates for improvements or bug fixes can be applied over the air in the settings via the Arduino OTA Library. A magnetic USB plug was also tested as an alternative to wireless charging. This method is recommended for easier handling, especially during software development. The dive computer can be loaded via the connection and updated with new software if the OTA update does not work. The blocking diode protects the USB port against short circuits and thus conductive water. As a result, researchers without a deeper technical understanding should achieve results with manageable effort in the future. The already justified desired characteristics result in various requirements for the dive computer:

- Built from cheap and widely used components (breakout boards)
- Development of an adaptable prototype to the respective needs
- Freely usable and customizable software
- Beginner-friendly operation of the dive computer
- Robust, waterproof, reusable dive computer

To drastically simplify data collection, an app for android smartphones was also developed. It provides the user with a straightforward digital tool to processes the data collected by the dive computer, enrich it with study-specific information and forward it to a server for central analysis.

The microcontroller forms the core of the dive computer. There are several requirements that the microcontroller must meet: It must be able to exchange information via WLAN, it must have high performance, a small form factor, the hardware must be freely available and already be equipped with various configuration options for batteries. It is responsible for saving the individual data from the sensors on the SD card, presenting them appropriately to the user on the display and establishing connections to other devices via WLAN. In addition, the module must have a small form factor and at the same time be easy to use to be optimally integrated into a diving computer. Most of the above parameters can be reached by different microcontrollers. To facilitate reproducibility for other studies, the cheapest module was deliberately not sought, but instead a compromise between price and documentation of the components was taken into consideration. Especially in commercial solutions, Adafruit stands out as the best provider of the requirements. Among the products offered, the HUZZAH32 with an ESP32 were considered as the most suitable given the initial requirements[235]. This offers high performance with a small form factor, a battery connection with charging option and the possibility of mounting a display directly on it. Further advantages such as a USB connection for debugging and the simple possibility of testing other components have become a matter of course in this environment.

FIGURE 22. LEFT: THE DIVE COMPUTER CHARGING WIRELESS WITHOUT HOUSING. RIGHT: DIVE COMPUTERS SETTINGS SCREEN

The availability of so-called touch pins also enables direct input by simply touching them, making additional components superfluous. With a built-in voltage divider, the remaining voltage of the battery can easily be read out by doubling the voltage on a permanently assigned pin, which allows an approximate state of charge to be calculated. To be usable for different types of studies, it was decided to use a large display for the data presentation and hardware interaction. At the same time, as with the microcontroller, the compatibility and documentation should be in good condition. Since the TFT FeatherWing - 2.4; 320x240 with micro-SD and touch were developed directly for the above microcontroller, there is optimal compatibility with minimal effort. With the integrated micro-SD card slot, another source of error is minimized by design. The pressure sensor MS5837-30BA from TE Connectivity is at the same time the most difficult and most important sensor on the whole dive computer. Without this, the pressure, depth or temperature of the surrounding environment cannot be determined. The most difficult part is mounting the sensor on the dive computer, as it is an SMD (surface mounted device). For the tested prototypes, this sensor was soldered to 4 header pins with a soldering iron and then attached with a hot glue gun under the display in such a way that it sticks out with the head after the epoxy has been poured. The header pins can be connected directly to the header pins of the HUZZAH32 using short cables, as this sensor requires the 3.3V, which the Huzzah offers. The two communication cables SDA (Serial Data) and SCL (Serial Clock) can also be connected to the corresponding connectors without PULL-UP resistors, as the IMU have these already installed on the board.

To record the movement of the user in the best possible way, a 9-axis IMU (Inertial Measurement Unit), the TDK InvenSense ICM-20948, was also installed[236]. This IMU can record 3-axis accelerometer and 3-axis magnetometer, supplemented by a 3-axis gyroscope. However, in this Design the IMU is optional and can be omitted if desired. However, the pressure sensor must then be connected to 3V with 2 4.7KOhm resistors. The complete connection and wiring are shown in Figure 23.

To ensure a long enough operation of the dive computer, a significantly oversized Lithium Polymer 3.7V battery with 2500 mAh has been installed (Figure 22). However, since this battery has the same dimensions as the display, the size is not so important at a first glance.

We used a special USB adapter with magnetic contacts to increase the availability and reliability of the dive computer during underwater activities. The inbuild protection diode allows a short-circuit prevention and gives an easy access to all the data needed on the SD card.

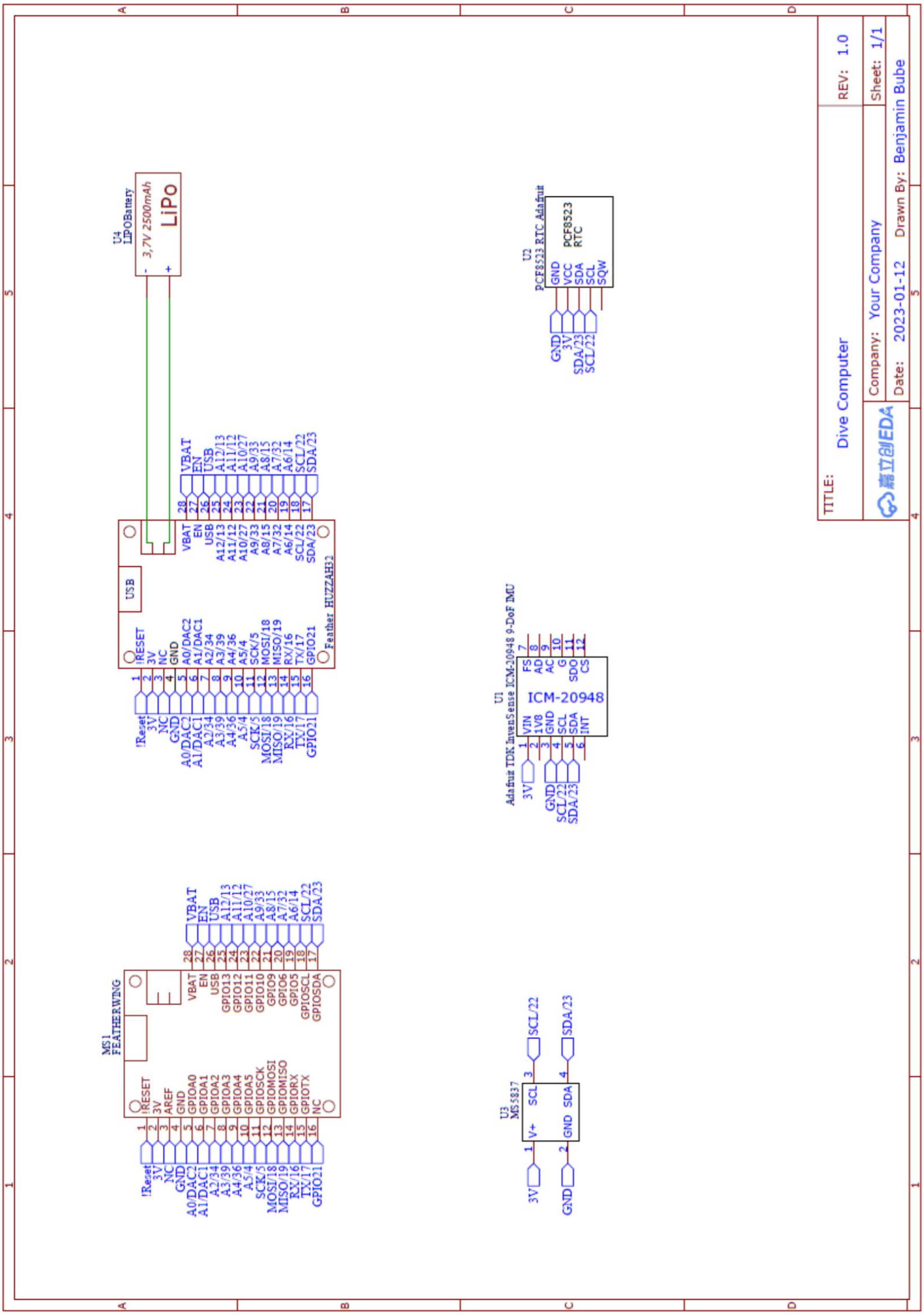


FIGURE 23. COMPONENTS OF THE DIVE COMPUTER

Since the development of a waterproof housing with various connections (e.g., interaction, charging the battery or the pressure sensor) requires considerable cost and development effort, it was decided to cast the complete dive computer in epoxy resin. This eliminates the greatest challenge to an enclosure, namely water pressure. This triggered, however, other problems that had to be resolved.

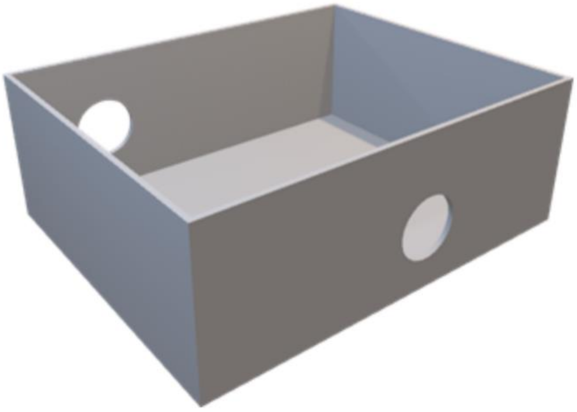


FIGURE 24. EPOXY HOUSING

Therefore, a solution had to be found for the buttons and their operation by the user. In the end, the existing touch pins of the ESP32 were used for this, which deliver a changed signal when touched by a person. However, since these touch sensors also trigger when they encounter water, a submersion in water could lead to incorrect user entries. To prevent incorrect entries on the touch sensors under water, they are blocked when they encounter water by using appropriate threshold values. Interaction under water is possible, but not yet fully developed at the current stage of development.

The touch pins are brought out with short cables or metal rods in such a way that they lie directly on the mold when the epoxy is poured. After the epoxy has cured, the entire dive computer can be polished to fuse both the aesthetics and the buttons in one plane with the epoxy. For this purpose, the pressure and temperature sensor are also pressed against the casting mold so that they lie outside the hardened epoxy. The 3D printed housing (Figure 24) is needed as an extension to cast the device in its final form.

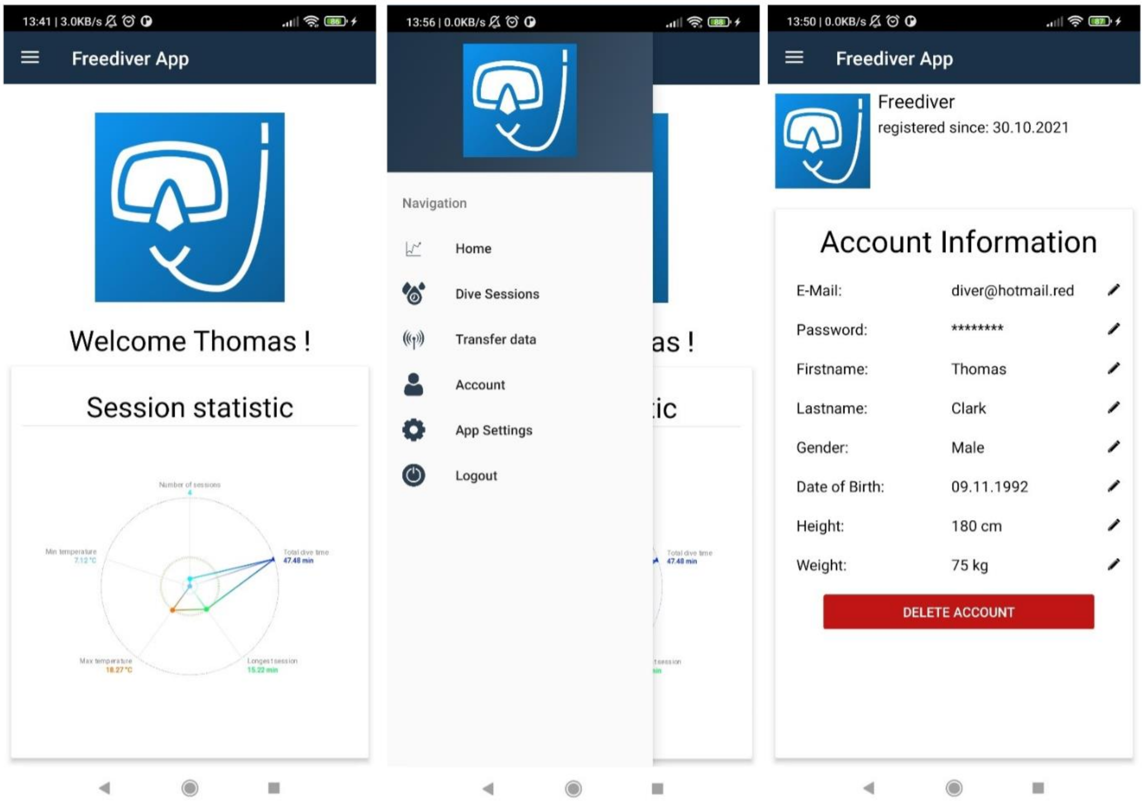
5.3 DESIGN FILES SUMMARY

In order to be able to build the prototype as described in this chapter, other materials and components are required in addition to the hardware components. Beside the exact connection of the individual hardware components shown in the schematic, the housing or the corresponding file for the 3D printer is also required. To upload the software to the dive computer, the Arduino IDE or Visual Studio Code with the platform.io plugin is required. The app can be installed directly as AKP on an Android smartphone (Table 10).

Design file name	File type	Open-source license	Location of the file
Schematic	figure	GNU General Public License (GPL) 3.0	https://doi.org/10.17605/OSF.IO/PGU6T
Android mobile application – Source Code	.apk file		
Dive computer source code	Folder		
3D printed housing	.stl file		

TABLE 10. DESIGN FILE SUMMARY

Schematic: The electronic schematic of the device with all the necessary components and their connections. Android mobile application: The ready-to-install Android application file containing the application partially shown in Figure 25. The data of the dive computer can also be exchanged and displayed via this app. Over the air updates for the dive computer are also possible, but only recommended for advanced users.



E-Mail:	diver@hotmail.red
Password:	********
Firstname:	Thomas
Lastname:	Clark
Gender:	Male
Date of Birth:	09.11.1992
Height:	180 cm
Weight:	75 kg

FIGURE 25. SCREENSHOTS OF THE FREEDIVER APP: (A): HOME SCREEN; (B): SIDEBAR SCREEN; (C): ACCOUNT INFORMATION SCREEN.

5.4 BILL OF MATERIALS SUMMARY

In order to be able to build the prototype in the form described, various components are required, which are listed in detail in the Table 11.

Designator	Component	Number	Cost per unit - currency	Total cost - currency	Source of materials
Adafruit HUZZAH32 – ESP32	Microcontroller	1	21€[237]	21€[237]	EXP GmbH
TFT FeatherWing - 2.4" 320x240	Display	1	28,30€[238]	28,30€[238]	EXP GmbH
Micro SD card 8GB	Storage	1	3,99€	3,99€	Amazon
MS5837-30BA	Depth, Pressure and Temperature Sensor	1	7€[239]	7€[239]	Mouser electronics
Adafruit TDK InvenSense ICM-20948	9-DoF Inertial Measurement Unit (IMU)	1	17,39€[240]	17,39€[240]	Eckstein Komponenten
Lithium-Ion polymer battery 3.7V 2000mAh	Battery	1	8,05€[241]	8,05€[241]	Eckstein Komponenten
Reed Contact N/O N/C SPDT (2,5 mm × 14mm)	On / Off Switch	1	1€	1€	Amazon
Epoxy Resin	Pouring Material	1kg	15,99€	1,19€	Epodex.com
3D printed House	Polyethylene	9,65gr	39,96 € / kg	0,38€	3D Jake

TABLE 11. BILL OF MATERIALS

The corresponding sources for procurement are listed in the table. No intensive optimization of procurement was undertaken here, as the specific components may vary depending on the project.

5.5 BUILD INSTRUCTIONS

Former, as a first step, the 3D housing should be printed. The following steps need to be performed during printing.

To later switch the dive computer on and off, first the reed contact is soldered to the pins under the micro-SD card slot (on/off switch). This should be placed in such a way that the switch is as close as possible to the edge of the housing.

Regarding the assembling operation, it is possible to take two forms: by plugging or soldering the connections where necessary as shown below. When assembling, it is important to note that each of the pins on the Huzzah32 is accommodated in the mounts on the display and that no pin on the Huzzah32 is without connection to the display. Insert the Micro SD card and glue the Adafruit 9 DoF sensor onto the yellow display cable as shown in Figure 5. The pressure and temperature sensor will then be soldered to the 9-DoF Sensor and plugged into the board. The connection to the display doesn’t need to be soldered as there are spring contacts installed.

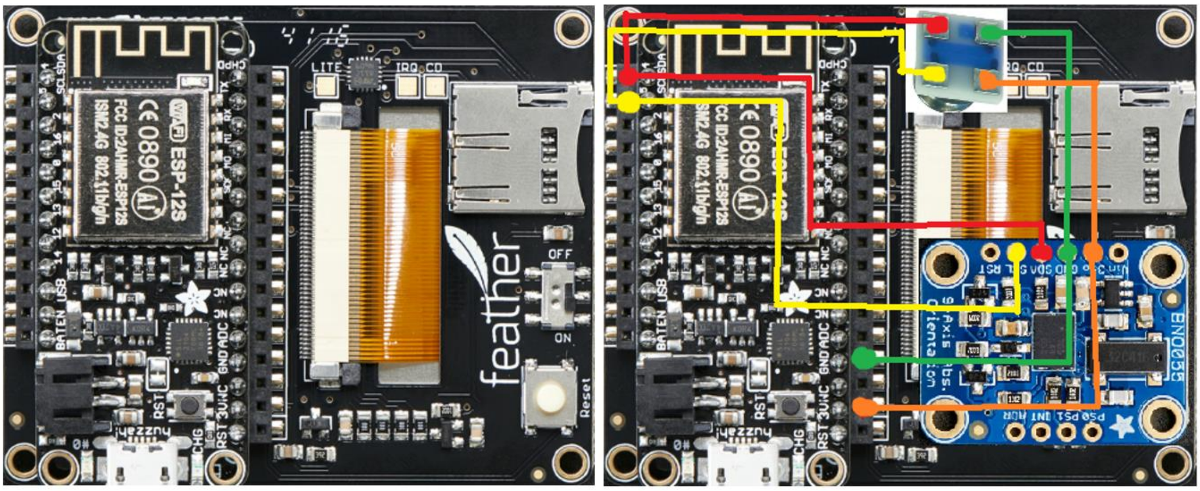


FIGURE 26. HUZZAH32 MOUNTED ON FEATHERWING AND SUPPLEMENTED WITH THE 9 DOF AND MS5837 SENSOR

The connection shown on the right in Figure 26 is the simplest of the possible wiring options. The pins were chosen correctly here, but the schematic should always be carefully observed when replicating the dive computer.

At this point, it makes sense to upload the code in advance and test all sensors to minimize later effort. Once done, the pressure and temperature Sensor MS5837 should be glued to the exact position to later align with the housing for casting.

As soon as this is done, the battery can be plugged in and glued to the board.

After the 3D printing is complete, the dive computer is embedded in the housing and the magnetic USB connection is attached from the outside. To prevent the casting resin from leaking out, the openings in the housing should be sealed watertight. Alternatively, a viscous resin can also be used. Finally, it needs to be poured. Later in the stage the 3D printed housing can either be removed and the epoxy be beautified by falling and grinding or the housing could stay in place.

5.6 VALIDATION AND CHARACTERIZATION

After completion of the assembly of the described prototype, the dive computer was tested by one person in 15 dives to a maximum depth of 7 meters in freediving. There were no problems with recording or water resistance of the complete prototype. The depth and pressure sensor worked very precisely as stated in the data sheet. This data was then visually processed in Excel and presented graphically as seen in the example Figure 27 as collected by the prototype and uploaded to the storage server. For better readability, individual time segments of the surface intervals were cut out of the data set. Since the sensor shows negative values at rest on the water surface, these have all been replaced by 0 meters for better readability.

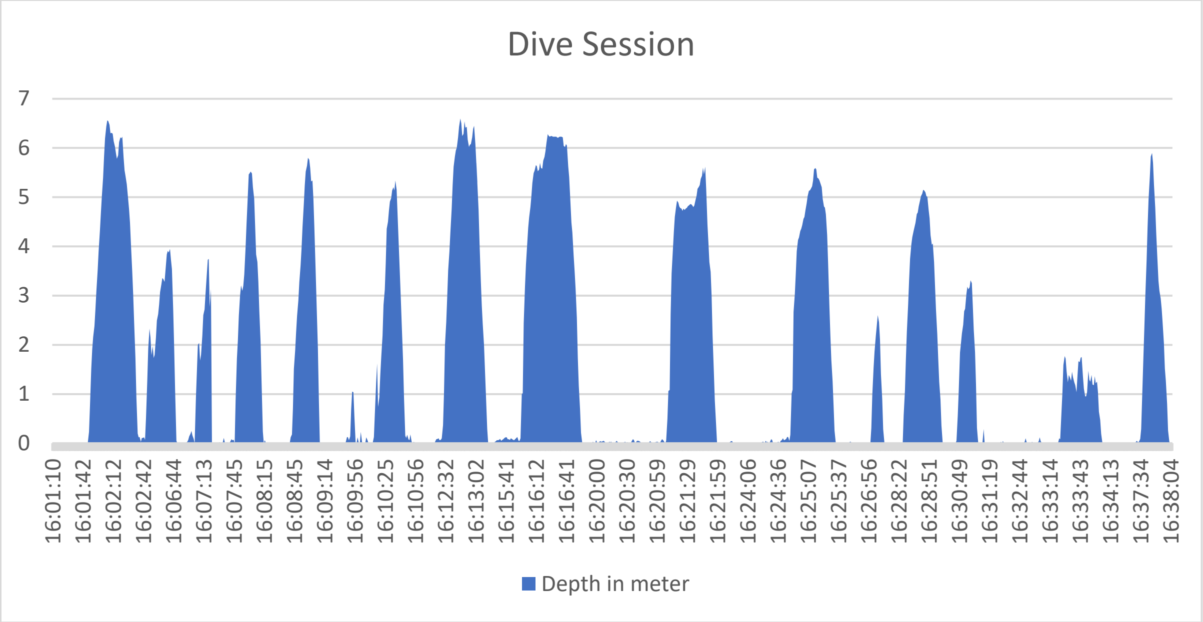


FIGURE 27. DATA COLLECTION DIVE COMPUTER

To determine the usability for future large-scale studies, the transmission rate was tested with the default configuration of the WIFI chip from the ESP microcontroller. For the test scenario representative data files ranging from 100 kB to 100000 kB in size were created. To measure the time needed to transmit the distinct data files, the app was temporarily modified by using the Stopwatch class from the .NET framework[34]. 100 iterations for each data package were made to ensure the validity of the test results. From that the average time was calculated and then used to determine the transmission rate.

Data size	Transmission time	Transmission rate
100 kB	1476 ms	~67.75 kB/s
1000 kB	5873 ms	~170.27 kB/s
10000 kB	53034 ms	~188.56 kB/s
100000 kB	499141 ms	~200.34 kB/s

TABLE 12. COMPARISON BETWEEN DATA SIZE EACH PACKAGE AND TRANSMISSION VALUES

As can be seen in Table 12, good to very good transfer rates were achieved between the dive computer and the smartphone in the tests. Even if several dive computers transmit data at the same time, e.g., after tests with several testers in the water, the speed can be considered good and should also be manageable with several 100 subjects.

5.7 SUMMARY

We were able to achieve the goal of an easy-to-build, waterproof and inexpensive dive computer. The expandability has also been demonstrated by installing the 9 DoF sensor. Through the development and implementation of an inexpensive and significantly more comprehensive dive computer than already available commercial models, we enable to carry out significantly larger and target group-oriented studies in the future with over 1000 volunteers participating. By implementing various concepts, we were able to pave the way to collect significantly more parameters and values than other already available dive computers can achieve and that at relatively low cost. Due to the possibility of mixing and selecting different sensors and modules as needed for the specific research, the values and parameters can be collected the exact needed way. The first real-world results showed the feasibility of the proposed diving computer for developing a low-cost, durable and easy-to-replicate dive computer. By providing all components and the code, the project can also develop into a community project among the divers with increasing acceptance and willingness, thus paving the way for further projects overall. An open-source development can also help in medical matters related to diving or in the much larger field of application of IoUT (Internet of underwater Things), which has grown significantly in recent years[35]. By implementing a cheap modem, the dive computer can function as an independent underwater station reporting data to a near shore or other station[193], [195]. To strive further in this direction we reduced the price, reproducibility and adaptability which are the most important aspects to allow further big data research in this area[155].

Various goals for the further development of the prototype can be derived from this:

- Fixed implementation of the position sensor (9-DoF) in the dive computer and its display
- Modularization of the dive computer by offering modules that can be easily switched on and off.
- Study-specific kits that adapt to the desired study design through questionnaires or assessments of individual aspects.
- independently running station that can remain autonomously in one place in the water for a long period of time to gather data.
- Offering a ready-to-use acoustic module for this dive computer.
- Building a platform for scientists who can use the dive computer for studies without additional effort.

In general, the presented and implemented interaction is perfect for data collection such as vital signs, simple communication between divers underwater or to adapt the prototype to the individual specific needs, since a broad basis of data can be collected. Furthermore, we were able to show the feasibility and usefulness of a cheap and versatile dive computer. The next steps require that this prototype also works without prior instruction and error-free even for non-experienced people.

6 GENERAL CONCLUSION

In this last chapter will summarize the key contributions presented in this work. We will also discuss new opportunities and challenges for future work that result from this work but which go beyond the scope of this thesis. Finally, we will close this thesis with final remarks.

6.1 MAJOR CONTRIBUTIONS

The work presented in this thesis has focused on understanding the principles of wearable devices in freediving and extend the current state-of-the art by proposing a novel communication wearable for freedivers. Successfully understanding the usage of wearable technology for freediver is challenging as this is a relatively new and underexplored area of research, especially on the technological side.

In the first part (Chapter 3 Wearables in Diving: A Scoping Review) we investigated how and in which direction wearables for freedivers were used and in which direction they are currently further developing. In the second part (Chapter 4 A Novel Wearable Communication Device for Freediver), we presented, based on the previous result, a novel wearable freedive computer with acoustic communication which helps diver to improve their dive and safety.

Chapter 5 also addresses the second part, but with a different focus and a different prototype e.g. approach. Trough the very manageable amount of scientific research in this area outlined in Chapter 3, we were able to quickly conclude, that another wearable dive computer is needed that can be easily adapted and with manageable costs build for further data collection which then allows an easier access to this area.

The contributions of this work were made by applying the methods of research through different databases and other methods e.g. collecting data in the wild which are sufficient to the field of freediving. Further, we developed and studied different prototypes contribute to address some of the detected shortcomings of current state-of-the-art technology as well as literature. The work presented in this thesis has made contributions to the two fields of understanding (U) and supporting (S) wearable technology for freedivers:

(U1) **A large-scale study on wearable technologies in diving.**
A total of 2320 scientific articles were identified by the search following the PRISMA-ScR which were than filtered, subsequently checked and which than underwent a further full-text analysis if necessary. Furthermore, each included article or original paper were screened for any potentially missed papers. Of this large-scale study only 36 studies retained in the review. To be considered as a wearable device, the following criteria had to be met: It needed to be a prototype or device that was described and tested in water, could be worn and interacted with (e.g., display, buttons, etc.) and were fully functional without external equipment. Wearables that could not function independently as a research object were excluded, since they are not wearable devices.

(U2) **A first insight into the possibilities and challenges of wearable technologies for underwater usage.**
Through the review conducted in Chapter 3, we were able to provide a first insight into the opportunities and challenges of the technologies used in and for wearable devices intended for use in the underwater environment. Among these, underwater communication technologies have had the most significant influence on future developments. Moreover, further topic that has not received enough attention but should be further addressed were the human-computer interaction. By this first review we could establish a good and powerful basis for the further development and orientation of current underwater wearables within the field, especially the possibilities and challenges for underwater

communication which were identified as the core part of wearable technologies for underwater usage.

(U3) A comprehensive map of wearable devices and their capabilities and features.
The possibilities and challenges of the respective technologies were considered and evaluated separately. In addition to the well-covered field of safety devices relating to the collection of vital signs from divers, other areas such as underwater communication between divers as well as topics such as human-computer interaction and specialized wearables for divers were also covered for the first time. Recent research has shown that the underwater communication has the most significant influence on future developments. In contrast, human-computer interaction has so far received far too little consideration. This is particularly surprising because the conditions under water are different from those on the surface. A scientific summary and overview of the housings and seals used in devices for scientific purposes offered first insights into this until now completely uncovered topic.

(S1) A System to support freediver and their safety during diving.
By implementing and testing a novel wearable device with communication capability, we were able to carry out various tests. This showed that during a normal dive, observation of the diver could take place at almost any time. Krack et al. made in 2006 the statement: "We want to know where a person is and how they are doing at any time during their dive"[213]. Even if this statement was not aimed at a technological solution, it can still be described exactly with these words. It is always particularly important to know where the freediving partner is underwater. We proposed a prototype that is capable of calculating, logging, displaying and communicating between several devices through acoustic data transfer which increase the safety tremendously during diving, as the timespan from an accident to an appropriate reaction is much shorter.

(S2) A study on the impact of a communication device for freediver.
Through the standardized UEQ survey several facets including impact, novelty and other aspects could be identified. The last point in the survey determines the novelty of a product compared to what is known so far. As there is currently no freediving computer with a function like this, the novelty is, as expected, very high. The amazing thing is that it is just a first prototype, with no emphasis on design, functionality or usability it still achieved high to very high values in comparison. Our assumption is that the functionality of wireless communication underwater and its possibilities in freediving overshadows all other points. This assumption is reinforced by the fact that the participants repeatedly mentioned the advantages of a no longer existing line of sight and that these are enormous. In addition, the WADAC is particularly suitable for the safety diver, who receives good support in securing the diver.

(S3) An easily adaptable System to allow large-scale and low-cost data collection in real world scenarios.
Through the prototype presented in Chapter 5 we were able to achieve the goal of an easy-to-build, waterproof and inexpensive dive computer. The expandability has also been demonstrated by installing the 9 DoF sensor. Through the development and implementation of an inexpensive and significantly more comprehensive dive computer than already available commercial models, we enable to carry out significantly larger and target group-oriented studies in the future. By providing all components and the code, the project can also develop into a community project among the divers with increasing acceptance and willingness, thus paving the way for further projects overall. In general, the presented and implemented wearable dive computer interaction is perfect for data collection such as vital signs, simple communication between divers underwater or to adapt the prototype to the

individual specific needs, since a broad basis of data can be collected. Furthermore, we were able to show the feasibility and usefulness of a cheap and versatile dive computer.

In addition to these contributions, which can be used individually to inform the understanding of wearable devices for freediver and to improve future designs of such systems, we also contribute the essential technical systems implemented during the course of the thesis as open source[13] as well as the materials used to build them[14]. This contribution will allow other researchers on the one hand to produce their own results, draw their own conclusions and gain new understanding based on our data, and on the other hand to build their own systems based on the approaches that we have developed and provided in this work.

The contributions achieved in this thesis have been published and presented in two scientific journals included among the highest ranked journals (Q1) indexed in the Journal Citation Reports (JCI) to underline the impact[119], [193]. The third paper is currently under review in an (Q2) ranked journal.

6.2 FUTURE WORK

The findings we provided in this thesis leaves different opportunities and challenges unanswered, due to the time constraints of this kind of research work. To summarize these in one sentence: One could use the information on wearable devices, refine and extend our studies, improve presented information and systems, and build a single device solution integrating all results, as we discuss below:

6.2.1 EXTENSION AND REFINEMENT OF STUDIES

The results and conclusions presented in this work are based on indexed databases and studies of real-life systems. The method of research through databases, which this work mainly relies on, bears some limitations, which we partly addressed through the usability evaluation for the specific part – understanding and supporting – of communication devices in chapters 4 and 5. However, we cannot know the ground truth of the underlying reason why the researchers published the analysed papers when looking into the databases and whether there is any additional material that has not yet been published that would suggest a different direction (see Chapter 3). For future refinement of our work, we propose to validate each of the different proposed categories in our scoping review and compare them to gain additional insights into users' contexts when using wearable devices. By developing a Technology acceptance model (TAM), one could further identify and outline categories and different directions in which one should align the further research.

To dig deeper into wearable devices for freediver, future work might look into the impact of disturbance trough wearables during freediving, since freediving mainly relies on one breath and therefore a limited attention span. This could be done by focusing more on research done in health with a relation on freediving as well as collecting data through new studies where freedivers are part of and where health related data is gathered while doing certain tasks on already available freediving watches.

6.2.2 IMPROVEMENT OF THE PRESENTED SYSTEM

In the event of further development, the form factor can be reduced, the design developed, and power consumption optimized. In addition, the cost of manufacturing a WADAC is around 2000€. By changing to another, more compact and cheaper modem, the WADAC can also be implemented at significantly lower costs[220]. Through integration with different sensors and actuators, relatives, coast guards and

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[13] https://github.com/bbube/FreediverAppAndroid

[14] https://doi.org/10.17605/OSF.IO/PGU6T

other authorized persons could intervene at any time in the event of danger. That could enormously shorten the time span of a rescue chain. By linking a life jacket for divers to the WADAC, the safety diver can deploy the jacket externally and without exposing himself to any danger. Thanks to the modular system of the WADAC, any components can be added or removed at any time, which is an ideal basis for further scientific investigations. In addition, the collected data can be used to identify different situations with the help of machine learning[242]. Consistent further development towards a user interface is also useful.

6.2.3 ONE INTEGRATED SINGLE SOLUTION

One natural next step to the work presented in this thesis would be an integration of all findings and proposed systems and information into one single solution, and the study of such a wearable device under aspects of general usability and user experience. This would be a wearable device that tracks the device usage and supports the diver, analyses changes in the diver's behaviour and acts based on these, by recommending new options. This would further allow the surrounding divers to interact and observe the diver in a much better way to improve safety.

However, while it would be possible to build such a single integrated solution that exploits all findings of this thesis and all supportive functionality into one single solution, this system would demand a high degree of low-level access to fundamental operating system functionality. Such a prototype would result in a proprietary branch of a whole operating system that we would not be able to evaluate with the method of research through databases, which we rely on in this work. We would instead have to distribute a new wearable device with a customized software stack, which would require substantial resources if it were to be done on a large scale. This piece of future work is instead left for industry to inform the design of a new wearable device for diving in general.

6.3 CLOSING REMARKS

This thesis has investigated the current generation of wearables for freedivers resulting from the recent development of hardware and software, which transformed from simple gauge meter into wearables (see Chapter 2). We can only foresee in a tautological way and discuss both options: wearables for freediver will either continue to improve or disappear – i.e., we will proceed either with integration or dis-integration of wearables into our dives as described by Harmon and Mazmanian regarding the Smartphone era[243].

However, since such research as done in this thesis were not provided before, the current state of wearables in combination with freediving is fairly new. Under consideration that freediving is maybe in a few years not anymore, the main focus of wearables, we can say anyway, that other applications of these technologies such as space missions, technical divers, medical monitoring or any other field of direct information insight will or already gained huge importance.

There is ongoing and groundbreaking research in the area of tangible interaction and wearable computing in which everyday objects become smart through enrichment with sensing, computing and networking capabilities; compare for instance Chapter 2.

With the work presented in this dissertation, we lay the foundation to address these central questions by investigating them for the first time in such a scale and by proposing the first device into this direction which strive to be the first connected device and therefore the possibility to became not only smart but also ubiquitous: The first wearable freediving smartwatch with underwater communication capabilities. Furthermore, we have paved the way for large-scale studies and data collection to be carried out with the second prototype. This prototype is one of the first to offer an openly accessible app and all the associated components so that it can be recreated and used. By addressing the low costs and open hardware, a device can be easily manufactured and used in sufficient numbers.

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Eidesstattliche Versicherung

Hiermit versichere ich an Eides statt, dass ich die vorliegende Arbeit selbständig und ohne Benutzung anderer als der angegebenen Hilfsmittel angefertigt habe. Die aus anderen Quellen oder indirekt übernommenen Daten und Konzepte sind unter Angabe der Quelle gekennzeichnet. Die Arbeit wurde bisher weder im In- noch im Ausland in gleicher oder ähnlicher Form in einem Verfahren zur Erlangung eines akademischen Grades vorgelegt.

Declaration of an oath

I hereby declare on oath that I have completed this thesis independently and without using any other than the specified aids. The data and concepts taken from other sources or indirectly are marked with the indication of the source. The work has not been submitted in the same or a similar form in a procedure for obtaining an academic degree, either in Germany or abroad.

Appendix

Freedivecomputer with acoustic communication

Diese Umfrage wird im Rahmen des Tauchevents in Ibbenbüren an allen Probanden durchgeführt, die zuvor den Prototypen im Wasser mehrmals benutzt und sich somit einen detaillierten Eindruck verschaffen konnten. Die Umfrage besteht aus zwei Teilen. Im ersten Teil werden ausschließlich demographische Aspekte des Probanden abgefragt. Der zweite Teil der Umfrage beinhaltet die Bewertung des Prototypen.

* Gibt eine erforderliche Frage an

1. Geschlecht *

Markieren Sie nur ein Oval.

○ Männlich
○ Weiblich
○ Divers

2. Alter *

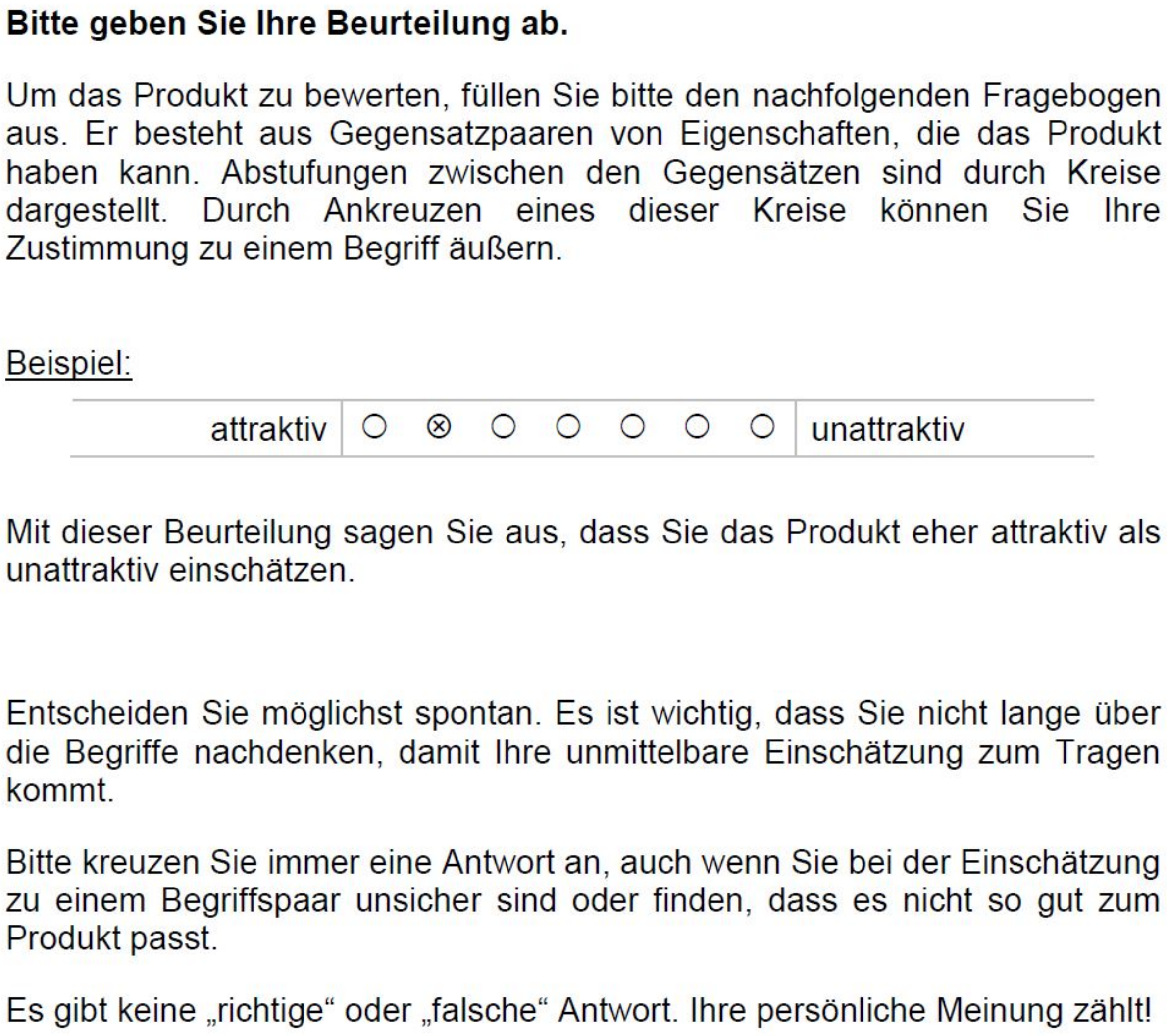
3. Anzahl der Tauchgänge tiefer als 20m *

Markieren Sie nur ein Oval.

	1	2	3	4	5	6	7	8	9	10	
wen	○	○	○	○	○	○	○	○	○	○	mehr als 1000

4. Personal best (PB) im Tieftauchen in Metern *

Fragebogen



Bitte geben Sie Ihre Beurteilung ab.

Um das Produkt zu bewerten, füllen Sie bitte den nachfolgenden Fragebogen aus. Er besteht aus Gegensatzpaaren von Eigenschaften, die das Produkt haben kann. Abstufungen zwischen den Gegensätzen sind durch Kreise dargestellt. Durch Ankreuzen eines dieser Kreise können Sie Ihre Zustimmung zu einem Begriff äußern.

Beispiel:

attraktiv	○	⊗	○	○	○	○	○	unattraktiv

Mit dieser Beurteilung sagen Sie aus, dass Sie das Produkt eher attraktiv als unattraktiv einschätzen.

Entscheiden Sie möglichst spontan. Es ist wichtig, dass Sie nicht lange über die Begriffe nachdenken, damit Ihre unmittelbare Einschätzung zum Tragen kommt.

Bitte kreuzen Sie immer eine Antwort an, auch wenn Sie bei der Einschätzung zu einem Begriffspaar unsicher sind oder finden, dass es nicht so gut zum Produkt passt.

Es gibt keine „richtige“ oder „falsche“ Antwort. Ihre persönliche Meinung zählt!

5. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	6	7	
uner	○	○	○	○	○	○	○	erfreulich

6. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	6	7	
unve	○	○	○	○	○	○	○	verständlich

7. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	6	7	
krea	○	○	○	○	○	○	○	phantasielos

8. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	6	7	
leich	○	○	○	○	○	○	○	schwer zu lernen

9. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	6	7	
wert	○	○	○	○	○	○	○	minderwertig

10. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	6	7	
lang	○	○	○	○	○	○	○	spannend

11. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	6	7	
unin	○	○	○	○	○	○	○	interessant

12. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	6	7	
unb	○	○	○	○	○	○	○	voraussagbar

13. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	6	7	
schr	○	○	○	○	○	○	○	langsam

14. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	6	7	
origi	○	○	○	○	○	○	○	konventionell

15. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	6	7	
behi	○	○	○	○	○	○	○	unterstützend

16. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	6	7	
gut	○	○	○	○	○	○	○	schlecht

17. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	6	7	
kom	○	○	○	○	○	○	○	einfach

18. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	6	7	
abst	○	○	○	○	○	○	○	anziehend

19. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	6	7	
herk	○	○	○	○	○	○	○	neuartig

20. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	6	7	
una	○	○	○	○	○	○	○	angenehm

21. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	6	7	
sich	○	○	○	○	○	○	○	unsicher

22. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	6	7	
akti	○	○	○	○	○	○	○	einschläfernd

23. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	6	7	
erw	○	○	○	○	○	○	○	nicht erwartungskonform

24. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	6	7	
ineff	○	○	○	○	○	○	○	effizient

25. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	6	7	
übe	○	○	○	○	○	○	○	verwirrend

26. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	6	7	
unpr	○	○	○	○	○	○	○	pragmatisch

27. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	6	7	
aufg	○	○	○	○	○	○	○	überladen

28. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	6	7	
attra	○	○	○	○	○	○	○	unattraktiv

29. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	6	7	
sym	○	○	○	○	○	○	○	unsympathisch

30. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	6	7	
kons	○	○	○	○	○	○	○	innovativ

Sonstiges

31. Anregungen, Verbesserungen oder Kritik über den Prototype?

32. Wenn du über weitere Workshops, Studien oder Informationen auf dem laufenden bleiben möchtest, kannst du hier gerne deine Email Adresse oder sonstige Kontaktdaten hinterlegen