A Sense of Direction:

How the Use of Haptic Feedback in a Wrist-Worn Wearables Can Be Utilized for Spatial Directional Stimuli

A bachelor thesis by Gabriel Brodersen

IT UNIVERSITY OF COPENHAGEN

Author: Gabriel Frederik Brodersen (gbro@itu.dk)

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Supervisor: Tomas Sokoler (sokoler@itu.dk)

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Abstract

This explorative project examines the unique capabilities of haptics for personal mobility purposes by examining current issues with pedestrian navigation. A research through design methodology was adopted, using sketching and prototyping practices in the design of a haptic wrist-worn display, able to express spatial directional guidance through vibrotactile stimuli. The final prototype is user-tested, and the process findings are discussed. It is argued that the designed interaction presents an alternative approach to turn-by-turn navigation, although more research is needed in this area.

Keywords

Haptic IxD, RtD, Hardware Sketching, Personal Navigation, Vibrotactile Feedback, Spatial Guidance, Wearables, Wrist Device, Digital Artifact

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Chapter 1

Introduction

The need for eyes-free navigation is becoming increasingly relevant, as our digital devices continue to compete for our limited attention. This happens even when we are on the move, while traveling, and when we need our attention elsewhere. Screen-based navigation solutions rely on many of the same wayfinding principles inherited from car navigation systems, which are not always appropriated for personal mobility and pedestrian navigation purposes. These systems rely on our visual or auditory senses, by requiring us to look at a screen-based map or listen to turn-by-turn directions as we travel the diverse and sometimes unfamiliar surroundings not always occupied by roads. Screen and audio based navigation make it difficult to pay attention to these surroundings, posing a potential safety risk (McCormack, 2015; Renaudin et al., 2017). Wearing headphones to privately listen to voice-based navigation compromises the safety by not being able to hear oncoming traffic or paying attention to people near you. Although visual navigation on screen is less prone to confusion and misinterpretations, it usually requires active grasping of the device in one hand, which can be problematic when already carrying or holding onto other things. The act of walking puts high demands on both our visual and auditory senses (Pielot et al., 2012), but the sense of touch is rarely occupied during this task. Haptic technology provides opportunities for new kinds of pedestrian navigation, that does not interfere with the visual and auditory senses (Panëels et al., 2013a). Using the haptic modality with digital technology to transmit information often use the technique of applying vibrations to the skin, and in various intensities and frequencies, and at different areas of the skin, depending on what type of communication is needed. Using haptic interfaces in the design of technology can allow for truly hands-, ears- and eyes-free interactions with technology (Panëels et al., 2013b). To explore possible approaches to improving personal mobility, using the unique affordances of haptic technology, this project takes on an exploratory role of defining and exploring the research question through a literary study and the act of conducting research through design (see *3 Methodological Approach*). The theoretical framework used is described in *2 Theoretical Framework*, with a focus on the haptic modality, haptics in HCI and haptic interaction design.

The project process described in *5 Process* is structured based on a traditional 'double diamond' model. The problem space is first explored using desk research and self-observation on the topic of personal mobility and pedestrian navigation in *5.1 Discover*. Then the problem space is defined in *5.2 Define* though a research question and using learnings from *4 Related Work* on the topic of haptic interface design and non-visual location-based navigation. Through this process, the project's research question is defined as:

"By utilizing the unique capabilities of haptics for spatial directional guidance, how can a sense of direction towards a point of interest be appropriated in a wrist-worn wearable for personal mobility purposes?"

To attempt to answer this, the project takes advantage of the Research Through Design methodology (see *3.2 Research Through Design*) using sketching and prototyping practices in the design and iteration of various research artifacts utilizing haptics and to explore the solution space, as described in *5.3 Develop*. Finally, to converge on the presented haptic interface design built, and to evaluate the presented findings, a user test was designed and described in *5.4 Deliver* and analyzed afterwards in *5.4.3 Analysis of the User Test*.

The findings from the analysis of the user test and the design process as a whole is examined in *6 Findings*, followed by a final discussion and critique of the overall project process and resulting interaction design presented *7 Discussion*. The project is concluded in *8 Conclusion*, pointing out that although the possibility of locating directional guidance using a wrist-worn haptic display has been presented, it has not yet been sufficiently researched for wayfinding and navigational purposes.

Chapter 2

Theoretical Framework

The theoretical framework for this project is discussed in this chapter, with a focus on our understanding of *haptics* and how it relates to the latest trends within the field of human-computer interaction (HCI).

2.1 – The Sense of Touch

The word *haptic*[1] as an adjective refer to the sense of touch and our perception and manipulation of objects in the world around us. In this thesis, the word is primarily used as a noun, focusing on the domains of haptic technologies and haptic research.

The sense of touch is the earliest sense we developed, evolved in tight partnership with vision and hearing, and in complex ways we are only now beginning to understand (Montagu, 1986). Touch is both a *proximal* sense—that is, it can be used to sense objects that are in contact with the skin—and it is *bi-directional*—that is, it supports both perceptions of, and acting on, the environment (Jones & Lederman, 2006). Although vision and hearing have traditionally been the focus of design for most user interfaces, our sense of touch offers a promising and unique communication channel. A unique trait of touch is that it allows for the design of private as well as very intimate displays when used in a social setting. Dealing with privacy issues is an important affordance that we will explore later (see *4.5 Privacy Concerns*). Another trait is how it can be utilized to convey abstract or hard-to-express information and meaning in a way that can be perceived or *felt*, providing opportunities for new types of communication and information types between the user and the digital.

Haptic technology in consumer electronics today is used mostly in the form of haptic feedback, though simple cell phone alerts and notifications, or as gaming equipment (MacLean, 2008). The two primary types of haptic devices used are *force feedback devices*, designed to act on our proprioception—our sense of self-movement and body position—by providing forces to our movements as we interact with it; and *tactile displays* that target the skin with localized tactile stimulations (MacLean, 2008). These applications have been in feel-focused improvements, replacing mechanical clicks in scroll wheels and touchpads with haptic engines to more finely control the tactile experience and reduce the risk of mechanical wear and tear. Some of these integrations are so replicative of the traditional mechanical experience that several technological advancements in this field remain hidden in the applications they replace. The ambition of this project is to inspire new and novel ways of utilizing this technology in wearable electronics.

[1] Oxford English Dictionary | Definition of 'haptic': https://en.oxforddictionaries.com/definition/haptic

2.1.1 – Haptic Modalitites

A useful distinction when exploring various types of haptic interaction modalities is the distinction between *active* and *passive* feedback (Rodríguez et al., 2019). When we talk about *active* feedback, we imply that the user is in control of her actions to explore the haptic interaction. This happens when we explore the surface or shape of an object by touch. In contrast, when we talk about *passive* feedback, the device is in charge, delivering the feedback back to our senses. A phone vibrating when receiving a notification or call, thereby transferring haptic vibrations to our skin, is an example of this.

Another important classification is related to the type of senses that makes up the haptic experience. These can be categorized as *cutaneous* and *kinesthetic* senses (Rodríguez et al., 2019). *Cutaneous* sensations refer to the sense of pressure, pain, temperature, texture, and vibrations applied to the skin. *Kinesthetics* involve forces, motion, and body position sensed by the muscles, tendons, and joints.

These two types of classifications, *active/passive* and *cutaneous/kinesthetic*, can be combined to distinguish the four types of feedback interactions, as seen in the table below (see *figure 1*). This forms a useful tool to understand a broad range of haptic display devices.

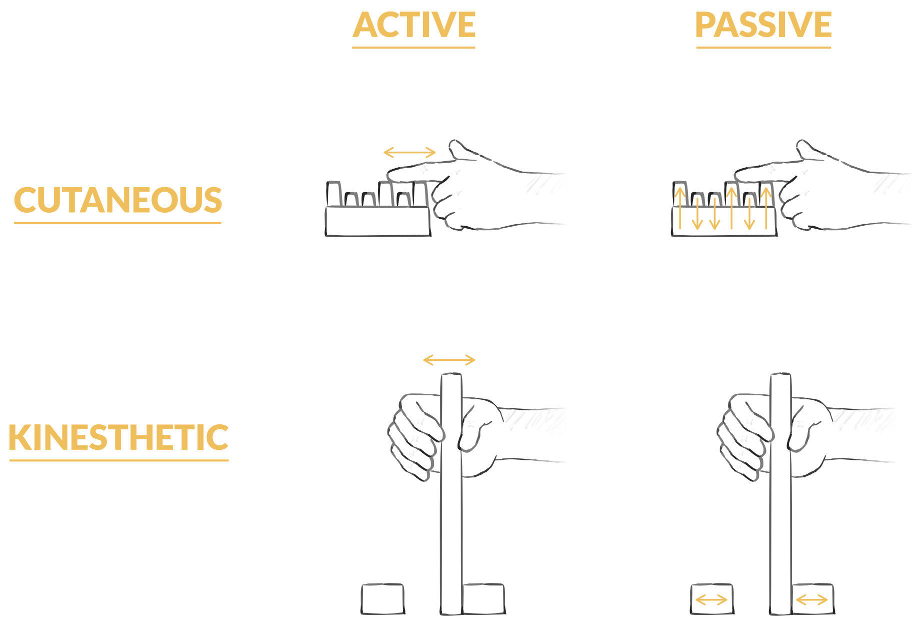

Figure 1: Classification of haptic interactions according to explorative modality: cutaneous active, cutaneous passive, kinesthetic active, and kinesthetic passive (illustration inspired by Rodríguez et al., 2019, p. 2).

An important aspect to consider, when exploring any type of feedback interaction, that happens as a reaction to human input, is that of *coupling*, which can be evaluated as being either *tight* or *not*. Sears & Jacko (2009) suggests how this concept can be used to distinguish between how frequent, timely, and informative a feedback response is, after receiving user input, as well as a means to describe how the feedback stimuli is situated in relation to how and where it is expected. These properties of haptic interaction provide useful concepts to consider when evaluating haptic modalities.

2.1.2 – Direct Manipulation

The direct manipulation paradigm, introduced by Ben Shneiderman (1992) still dominates user interface design today, proposing an explicit style of interaction with computers. Interactions following this paradigm is guided by four main principles: Continuous representation of the object of interest; Physical actions instead of complex syntax; Rapid, incremental, and reversible operations whose impact on the object of interest is immediately visible; and Layered or spiral approach to learning that permits usage with minimal knowledge (Shneiderman, 1993). In relation to haptic interface design, these are just as relevant today, where some of its physical metaphors can be taken almost literally in order to create interactions that are more predictable, intuitive and natural to the user (Kwon et al., 2011) To analyze the application of interactions following these principles, Beaudouin-Lafon (2000) expanded on the idea of direct manipulation proposing the *instrumental interaction model* using the concept of instruments as the mediator of action between the user input device and the data to be manipulated with, referred to as the domain object. Beaudouin-Lafon introduced three properties useful for the evaluation of Shneiderman's principles of direct manipulation. These properties are based on; *degree of indirection*, a measure of the spatial and temporal distance introduced by the instruments; *degree of integration*, being the ratio between the degrees of freedom of the instrument and the input device; and *degree of compatibility*, a measure of similarity between actions on the instrument and the feedback on the object (Beaudouin-Lafon, 2000). Given these properties, he argues that an interaction with low indirectness, high integration, and high compatibility will improve the instrumental interaction. Although Beaudouin-Lafon's focus was mostly on traditional- and post-WIMP interfaces, as well as more recent interaction styles like two-handed input and augmented reality, he argues that it is not limited by it. Rather, the notion of *instruments* as a tool for appropriating data manipulation and interaction provides useful concepts that carry over to the physical as well. As we will explore in this project, the input device and the instrument of interaction can be fused in the same understanding, providing a physical and continuous representation of data through haptic feedback alone, thereby taking advantage of the direct manipulation paradigm.

2.2 – The Expansion of Haptics in HCI

Current progress within HCI has not only focused on the quality of interaction but also extended its focus to different branches of interaction paradigms. According to Karray et al. (2008), this branching has introduced new concepts like multimodality, intelligent adaptive interfaces rather than command/action-based ones, and active rather than passive interfaces, many of which challenge our understanding of haptic technology and its applications. However, a universal lack of haptics in everyday interactive artifacts still exist. Audiovisual human-computer-interfaces still make up the majority of how we experience the digital. However, advances in haptic interface technology and new interactive designs offer a unique advantage over the dominant information infrastructure (Heng Gu, 2018). Most displays are limited to the visual and auditory channels (Culbertson et al., 2018), but at the same time, haptics is making inroads as their unique capabilities and advantages are now being explored more than ever (Moussette, 2012). Our tactile senses provide an opportunity to integrate new, unobstructed channels for digital information sensing, providing opportunities for novel solutions to current problems within HCI (Heng Gu, 2018).

Haptic research has had its roots in natural sciences and engineering, with little impact on the traditional design disciplines (Moussette, 2012). The relatively new field of *Haptic Interaction Design* (Haptic IxD) is where this project finds its place. Haptic IxD is the study of all aspects of haptics that influence the *design*, *expression*, and *qualities* of haptic interactions (Moussette, 2012), much the same way the field of graphics design relates to vision or sound design relates to hearing. The focus of Haptic IxD is on the design of new haptic interactions and experiences, exploring material qualities and touch-based forms of communication and design challenges and opportunities related to new haptic technologies.

2.2.1 – Opportunities for Haptics

The continuous progress of computation and networking technology has introduced new opportunities and possibilities enabled by haptic technology, some of which has been explored throughout this project. MacLean (2008) outlines six such trends with relevance for this technology, which is briefly presented below:

Networking. Everyone is connected. High-speed networks have opened the door for real-time virtual touching and feeling across distances, e.g., during telesurgery where haptic feedback can provide resistance and guide the hand of the surgeon.

The ubiquity of computing devices. Computation is no longer only on the desk—it is everywhere and used everywhere, in new and unforeseen contexts. The sparse visual real estate gives opportunities for innovation in information displays that does not crowd the already crowded but instead attempts to present itself in new and less crowded areas of interaction. The concept of ubiquity in computing is discussed further in the following section.

Multitasking. As more aspects of life become entangled with information technology, there is a tendency for people to do more and get more done with their devices. Equally so, the requirement and expectations for what these devices can deliver increases. This means that some channels of perception are occupied (often the visual and auditory) in a stressed situation, while others are not. Utilizing multimodal interactions with haptics can relieve or free up other channels of communication.

Virtualization of personal presence. As more people are able to work remotely, some elements of personal engagement (such as non-verbal cues, e.g.) are lost. Possibly even more so with interpersonal relationships, when the lack of bodily interaction and its impact can be questioned. Trying to recapture the essence of some of these physical bodily interactions (or create new ones) provide exciting opportunities for haptic research.

Information management. Too much information needs to be managed, filtered, and organized in the modern information age we occupy. The term *Information overload* (Speier et al., 1999) is becoming today's challenge, stressing the necessity for finding new ways of interacting and living with information. New innovative ways of perceiving and interacting with this information can be enabled through the proposition of new haptic interactions.

Fragmentation. The side effects of all of the above. Information needs to be timely and context-aware to mitigate intrusiveness, inappropriateness, stress, and reduced attention span. The discreetness and subtle qualities of haptics might help mitigate these symptoms.

The incentive for exploring new ways of engaging with various types of information underpins the motivation for this project. However, as MacLean (2008) points out—and as will be explored later in this project—even though design openings has been recognized, it is essential also to recognize the highly interdisciplinary nature of this challenge of creating useful, pleasing and efficient haptic interactions.

2.2.2 – Ubiquitous Computing and the Internet of Things

As briefly touched upon in the previous section, our devices are becoming increasingly more capable of detecting the world around them, sensing their surroundings and reacting to it in new innovative ways (O'Modhrain, 2004). Motion sensors, global and local positioning systems, and automatic object identification are just some of many technologies that have assisted this ongoing trend. We see more objects around us becoming digital, from new categories of product to old products brought back to life with new digital capabilities. These things can communicate with us, and each other, locally or over the internet—all becoming part of, and contributing to, what is known as the *Internet of Things* (IoT) (Kranz et al., 2010). The IoT relates to a broader concept within software engineering and computer science known as *ubiquitous computing* (Weiser, 1999), suggesting how computing in the 21th century would become ever more present, embedded in the everyday things we use, wear and occupy our world with, thus becoming an integrated part of our life and digital environment. O'Modhrain (2004) argues for how these connected things or *devices* can provide new opportunities and new ways of sensing and understanding the world around us, made possible through objects infused with embedded electronics and internet connectivity:

> "*These devices are also acquiring the ability to sense what is happening to them — how they are being held and moved. The coincidence of connectedness, awareness and richly multimodal input and output capabilities brings into the hand a device capable of supporting an entirely new class of haptic or touch-based interactions, where gestures can be captured and reactions to these gestures conveyed as haptic feedback directly into the hand*" (O'Modhrain, 2004, p. 139)

O'Modhrain suggests how this progression of technology provides new opportunities and challenges for haptic modalities, as a means to sense and interact with the world around us. As technology becomes increasingly ubiquitous, it is not only the things around us but also the things we wear; phones, glasses, watches, jewelry, clothes, e.g., that becomes infused with smart technology; sensing, adapting and communicating with their surroundings. Jones & Sarter (2008) suggest how the combining of mobile everyday wearable technology with touch-based input and output capabilities can create opportunities for the design of novel interactive solutions, as well as provide promising means for supporting communication and coordination in human to human and human to machine systems.

To the idea of sensing coordination through physical guidance, by the use of haptic technologies, as examined in this project, MacLean & Hayward (2008) argues how "*[...]tactile feedback can be used to provide a user with direct spatial guidance, either by leading with forces or orienting attention in a particular direction*" (2008, p. 106). They suggest how a user's attention can be guided by applying a discrete signal to a body location corresponding to the direction of interest, which can then cue visual attention in the same direction. This approach and similar projects are examined in *4 Related Work*.

2.2.3 – Tangible Computing Through Embodied Interactions

Relevant to the perspective adopted in this project is the notion of *tangible computing* through *embodied interactions*. With *tangible computing*, we refer to an area of HCI research by Ishii and Ullmer (1997), exploring how the interface can be moved 'off the screen' and into the real world. Generally speaking, tangible interfaces involves systems of physical artifacts as representations and interactive elements for the control, manipulation, and expression of digital information (Shaer & Hornecker, 2010). In contrast to graphical user interfaces (GUI), interaction with tangible computing is done through *tangible user interfaces* (TUI), such as by the use of physical objects to represent and manipulate digital data, using bodily movements as rich expressions, or by using spaces as reactive elements in which the action takes place (Shaer & Hornecker, 2010).

To help us analyze how a tangible approach to interaction design can be used to create environments for computational activity—in which we interact directly through physical artifacts rather than traditional graphical interfaces and interface devices—a different approach must be explored. To this, the notion of *embodied interactions* developed by Paul Dourish (2001) provides a valuable perspective on how meaning can be created and communicated when interacting with tangible and physical computational objects. Embodied interaction is not merely a form of interaction, but rather, it is "*an approach to the design and analysis of interaction that takes embodiment to be central to, even constitutive of, the whole phenomenon*" (2001, p. 102). To this, Dourish explains the relevance of embodiment in our interactions as "*the common way in which we encounter physical and social reality in the everyday world. [...] the key to their effectiveness is the fact that we, and our actions, are embodied elements of the everyday world.*" (2001, p. 100).
Designing with *embodied interaction* can be understood as the designer's ability to involve the users' physical body in interaction with technology in a natural way, such as through the use of gestures and tangible representations of information. Using this understanding helps us explore our experiences as embodied actors interacting in the world, participating

in it, and acting through it. Furthermore, this understanding is based on the realization that it is the user, not the system designer, that eventually create and communicate meaning through their interactions with the designed system and with each other. In essence, embodied interaction is "*the creation, manipulation, and sharing of meaning through engaged interaction with artifacts*" (2001, p. 126). Dourish suggests how this perspective lets designers offer new sorts of metaphors to take advantage of our physical skills (like using our hands to rearrange objects to suit our needs), motivating us to directly observe and respond to our physical activities and reactions to the world, when designing and prototyping.

The perspective on interaction design research set out by Dourish provides the vantage point to which tangible opportunities with haptic is understood. The aim here is not only to identify the digital trends and relevance, for which this project is situated, but also a relevant perspective to which this project is approached.

Chapter 3

Methodological Approach

This chapter outline the research design and methodological approach used, along with a short introduction to some practical methods and tools applied, during the construction of a series of research artifacts. Learnings and insights from similar projects have been collected through a literary review, used to narrow down and define the project research question. The design and construction of research artifacts have been anchored around this research question, as a means for knowledge gathering. The artifacts are further iterated and reflected upon, to explore possible solutions to the design of a haptic interface for spatial directional guidance.

At its core, the nature of this project is exploratory, starting with secondary research to help identify the problem/solution space and define the project research question. To provide the initial structure for the project, a process inspired by the *double-diamond design process* described below has been conducted. The research question has been examined through the practices of *research through design* (discussed later in this chapter) and used to explore alternative solutions to current problems identified in related work.

3.1 – The 'Double Diamond' Design Process Model

The basic framework for the research design used in this project is based on the double-diamond design process model originally developed through in-house research at the British Design Council in 2005. This diagram consists of two diamond shapes illustrating the problem space and solution space. The two spaces are further divided into two phases each, for a total of four distinct phases illustrating the divergent and convergent processes to which the design process can go through. These four phases are identified as the *discover* and *define* phases, followed by the *develop* and *deliver* phases comprising the two diamond shapes (British Design Council, 2005). The divergent and convergent phases illustrate the modes of design thinking used throughout these phases; from expanding knowledge of the problem identified—exploring all possible avenues of the problem—to converge to a single understanding of the problem space as defined by a problem statement. Norman (2013) outlines how, during the solution phase, "*designers diverge as they attempt to explore all possible solutions to the problem statement, expanding the solution space. Finally, the designers converge, reducing any number of suggested solutions, in order to find the right solution and the best fit for the problem*" (2013, pp. 220–221). It is essential to embrace the iterative nature of this creative process; as ideas are developed, concepts created and prototypes tested, the potential for new problems to be exposed and new solutions to be discovered, can present itself. Bad ideas are dismissed, and new ideas are examined. The process is refined and repeated based on the new knowledge gathered. This iterative cycle is an essential part of good design (British Design Council, 2005).

Even though definitions of the four phases by the British Design Councils differs significantly to how they are used in this project, the overall process—moving from the problem space to the solution space, through convergent and divergent phases and modes of thinking—it is still a useful construct as a foundation for the initial research design framework for which additional design methods, tools, and principles can be applied. As pointed out by Norman (2013), "*The double diverge-converge process is quite effective at freeing designers from unnecessary restrictions to the problem and solution spaces*" (2013, p. 221).

3.2 – Research through Design

Design activities using designed artifacts has become established elements of the design process for generating and communicating knowledge. This has become referred to as *research through design* or RtD for short, and is a term used primarily in academic work, especially with the fields of interaction design and HCI. In *the Encyclopedia of Human-Computer Interaction*, Stappers & Giaccardi notes that "*explicit theory about RtD is still in its formative stage. Given this, the involved communities are still struggling to find the right words, models, and practices.*" (Stappers & Giaccardi as cited in Soegaard & Dam, 2013).

Zimmerman (2003) argues that the nature of design itself is a form of research, in that both activities can result in the generation of new knowledge. Compared to traditional design practices that focus on making commercially successful products, design researchers engage in critical design with artifacts carefully crafted to answer design questions and advance "*discourse around a topic by challenging the status quo and by placing the design researcher in the role of a critic*" (Zimmerman et al., 2007, p. 4).

3.2.1 – Doing Design as a Part of Doing Research

The design artifact and applied design activities have become indispensable elements in the process of gathering and communicating new knowledge. The process of conducting research through design is to focus on the role of the prototype, using it as an instrument of inquiry for design knowledge (Keyson & Alonso, 2009). From interactive mockups to fully functional prototypes, Keyson & Alonso argues that the prototype can evolve as a means to develop and validate design knowledge. Using this approach, the designer can explore complex interactions and issues within a realistic user context. Furthermore, the researcher can reflect back on the process and decisions made, not only based on the observed user interactions and experiences of the prototype, but also through the designer's own reflections of working with the prototype. This experiential and often tacit knowledge obtained through the design activity, is an essential part of the design practice (Schön, 2011), as these observations can be used to guide further research as an iterative process, helping to shape the prototype and narrow the solution space. According to Schön (2011), the path between the designer's intention and the outcome is never certain: "*As you work a problem, you are continually in the process of developing a path into it, forming new appreciations and understandings as you make new moves*" (2011, p. 171).

3.2.2 – The Role of the Artifact

RtD consists of the development of a prototype, that being the research artifact, often through various methods of sketching and experimentation with design materials. Prototypes play several important roles in design. Stappers (2013) outline six aspects of prototypes for research, gathered from different design disciplines, suggesting that prototypes are:

- Unfinished, and open for experimentation
- A way to experience a future situation
- A way to connect abstract theories to experience
- A carrier for (interdisciplinary) discussions
- A prop to carry activities and tell stories
- A landmark for reference in the process of a project

Furthermore, prototypes can also be utilized as a way to direct the research design and as a way of formulating a research question, either by substantiating or challenging it (Brandt et al., 2011; Smith et al., 2016). In terms of specific activities, methods, and process to conduct RtD, there is great variety by which designers go about doing it, as there still is no single defined recipe by which it is conducted (Mattelmäki & Matthews, 2009; Soegaard & Dam, 2013; Wensveen & Matthews, 2015).

3.3 – From Sketching to Prototyping

Analogous to traditional sketching, this method is used within interaction design as a timely and inexpensive way to capture design concepts and identify unique attributes of interactive systems. In this project, the use of sketches as a tool for conducting research, is borrowed from the teachings of Bill Buxton and his work on the topic. In his book *Sketching User Experiences*, Buxton (2011) outlines the following traits of a sketch as: "*Quick, timely, inexpensive, disposable, plentiful, clear vocabulary, distinct gesture, minimal detail, appropriate degree of refinement, and suggest and explore rather than confirm ambiguity*" (2011, p. 136).

SKETCH		PROTOTYPE
Evocative	→	Didactic
Suggest	→	Describe
Explore	→	Refine
Question	→	Answer
Propose	→	Test
Provoke	→	Resolve
Tentative	→	Specific
Noncommittal	→	Depiction

Figure 2: Showing the characteristics and transition between a sketch and a prototype.

According to Buxton, the use of sketches usually dominates the early stages of exploring the solution space, whereas prototypes usually take up the later stages of the process, ending with preparation for testing (see *figure 2*). This is preferable due to the lower time and cost use associated with the sketching process compared to the construction and refinement of prototypes. Buxton suggests the practicality of how starting the design process with sketching enables the generation of ideas to be explored quickly and cheaply, followed by progressively more refined and higher fidelity prototypes, providing a basis for further testing at later stages in the process. Although he illustrates this design process from sketch to prototype—using the notion of a *design funnel* to emphasize the change in progress over time, from ideation to usability—he also stresses how this process should not be understood as a continuum. Instead the whole design process is iterative as ideas are explored and tested, gradually converging towards a solution. To clarify the distinction between sketches and prototypes, Buxton explains that "*it is as much a contrast of purpose, or intent, as it is a contrast in form*"

(2011, p. 140), emphasizing that the difference between the two is not merely an either/or proposition.

> "*Sketches and prototypes are both instantiations of the design concept. However they serve different purposes, and therefore are concentrated at different stages of the design process.*" (Buxton, 2011, p. 139)

3.3.1 – Sketching in Hardware

An essential aspect of sketching not yet mentioned, is that it is in no way limited to pen and paper, even though that is often the associating many have of the concept. Our understanding of sketching presented by Buxton (2011) holds true for sketching in hardware as well. Sketching in hardware—using cheap microcontrollers, and easily accessible sensors, actuators, other types of electronic circuits, as used in the artifacts presented in this project—is still quite a challenge for many that are new to programming and do-it-yourself electronics. The benefits of getting entangled in sketching with hardware might not always be clear, but with some dedication, it can become an efficient way to test interactive interfaces, exploring the interaction between hardware and software.

> "*…one typically has to look beyond the immediate results or outcomes to appreciate approaches like research through design and sketching in hardware.*"
> (Moussette, 2012, pp. 126–127)

Engaging with sketching in hardware also has the often-underappreciated benefit of providing the practitioner with skills and understandings of the material qualities and interactive expressions hard to come by through literature alone. This acquiring of tacit knowledge is not only useful when designing and exploring haptic interactions, but also essential when defining a solution space (Moussette, 2012).

3.4 – Prototyping

In *The Anatomy of Prototypes*, Lim et al. (2008) present a general framework for understanding the fundamental characteristics of prototypes. They propose the following three characteristics as useful reference points for designing efficient prototypes:

Fundamental prototyping principle: The activity of prototyping in its simplest form, is a manifestation of the qualities and characteristics of the design, without compromising the understanding of the whole.

Economic principle of prototyping: The most efficient prototype is one that makes the possibilities and limitations of design idea visible and measurable, in the simplest most efficient way.

Anatomy of prototypes: Prototypes are filters of the design space for which design ideas are conceptualized and concretized (Lim et al., 2008).

According to Lim et al. (2008), the activity of prototyping should be focused on navigating and filtering the design space and allowing the evaluate and measure of design ideas by their tangible manifestations with which others can interact. The focus of prototyping is the expression of ideas, as either being a possible problem-solution fit or one that can be a source of insights for further iteration.
In the view of Houde & Hill (1997), prototypes are seen as representations that designers can engage with in order to explore different questions, for different purposes. Mousette (2012) argues that constructing prototypes is not only about building new artifacts; it is also about how one uses those artifacts to ask questions and to tackle or inform design activities at large.

3.4.1 – Experience Prototyping

Applicable to this project is the notion of an experience prototype. In Experience Prototyping, Buchenau & Suri (2000) suggests a category of doing prototyping that "*focuses on the resulting experience more than the qualities of artifacts that help deliver that experience*" (as cited in Moussette, 2012, p. 75). Moggridge (2007) suggests a more practical understanding, defining it as "*any kind of representation, in any medium, that is designed to understand, explore or communicate what it might be like to engage with the product, space or system we are designing*" (2007, p. 687).

> "*Experience is a very dynamic, complex and subjective phenomenon. It depends upon the perception of multiple sensory qualities of a design, interpreted through filters relating to contextual factors […] The experience of even simple artifacts does not exist in a vacuum but, rather, in dynamic relationship with other people, places and objects. Additionally, the quality of people's experience changes over time as it is influenced by variations in these contextual factors*" (Buchenau & Suri as cited by Buxton, 2011, p. 135).

A holistic approach to defining prototypes that encompasses the experiential characteristic is suggested by Houde & Hill (1997), noting that the 'look & feel' of a prototype is "*the concrete sensory experience of using an artifact—what the user looks at, feels and hears while using it*" (as cited in Helander et al., 1997, p. 369). This is only one dimension of any prototype, the other two being the role, referring to the question about what functionality the prototype could have in a user's life; and the *implementation*, referring to questions about the components and technicalities in the prototype. They are all important to consider, although some dimensions of what makes up a prototype design will always be more relevant than others for any given project, including this one.

3.5 – User Testing

> "*The only way to really know whether an idea is reasonable is to test it.*" (Norman, 2013, p. 227)

As part of the Deliver phase of the project, a usability test was conducted with an exploratory focus; to evaluate the final prototype by testing the haptic interaction design concept and evaluate its promise (see *5.4.2 User testing the final prototype*). The purpose of performing a usability test is to examine how people perform specific tasks, to guide the definition and implementation of its functionality (Goodman et al., 2012).

Goodman et al. suggest four main types of usability testing:

- **Exploratory**, to test preliminary concepts and evaluate their promise
- **Assessment**, to test features during implementation
- **Comparison**, to assess one design against another
- **Validation**, to certify that features meet certain standards and benchmarks late in the development process

(2012, p. 274)

The purpose and the expected outcome of the test for this project were to:

test

1. to do a preliminary evaluation of the design in terms of efficiency as a haptic modality for spatial directional guidance.
2. to observe how users interacted with it in specific scenarios.
3. to gain qualitative feedback on the users' experience with the interaction.

The results and findings of the test are summed up in *6 Findings*.

3.5.1 – Pilot Tests

Pilot tests are small, useful preliminary tests of a methods or procedure to be used on a larger scale if the pilot study demonstrates that the methods and procedures can work, or to search for possible effects and associations that may be worth following up in a subsequent more extensive study (Thabane et al., 2010). Thabane et al. (2010) suggest that the rationale for a pilot study can be grouped under the following classifications:

- **Process testing** to test the feasibility of the steps that need to be taken.
- **Resources testing** to assess time and resource costs issues that can occur.
- **Management testing** to discover potential human resource and data optimization problems.
- **Scientific testing** to test the variables that constitute good scientific practices, such as reliability and safety (2010, pp. 2–3).

Several pilot tests were conducted during this project as part of the sketching and prototyping stages, but also during the early defining stages of the project. The tests were mainly related to the necessary testing of reliability, comfortability, and affordance of the haptic stimulation and materials used in the constructions. Having conducted this project by myself and thus spending many hours experimenting with various types of vibrating actuators at various intensity, strapped to my skin, it was essential to get a second opinion on many of the variables that go into constructing a wearable haptic prototype. Fortunately, enough, this project was, for the most part, tested at the IT University of Copenhagen, allowing me timely access to several students interested in helping me lower the potential for research bias.

Chapter 4

Related Work

In this chapter, I highlight some of the related work found through a literature review on the topic of haptics in HCI, touching on the design of vibrotactile interfaces with a focus on wearables and directional guidance. Several studies in the field of Haptic IxD are examined, covering topics like haptic modalities for guiding spatial awareness and non-visual location-based navigation. This literary review provides the foundation for defining the problem/solution space for this project, as well as to relate the construction of a series of hardware sketches as the experimental approach to addressing the project research question.

4.1 – Designing Haptic Interfaces

There is a growing trend in interface research towards multimodal human-computer interfaces (Tan et al., 2003). This is partly due to a common problem with screen-based mobile devices related to their limited screen space and output capabilities, making interface design for these devices difficult (Brewster & Brown, 2004, p. 3). To overcome this, Brewster & Brown (2004) suggest exploring other display modalities to reduce demands on visual displays, or even replace them, in situations where visual screen-based information is not practical or desirable.
One promising approach is to take advantage of multimodal perception when designing, such as through the use of multimodal interfaces, which have been demonstrated to have potential over unimodal systems that involve a single recognition-based technology (Oviatt, 1999). One reason is that humans are natural experts in combining input from multiple senses at once to form a coherent understanding of their interactions. Various modalities can also be used interchangeably for the same overall purpose, providing flexibility to suit different needs in changing contexts. Cognitive research has shown that such multimodal communication, can result in an increase in successfully transmitting information compared to unimodal communication (Miller, 1956), which has the potential to enable more natural and efficient human-computer interactions (Tan et al., 2003).

Oakley et al. (2006) describes how efforts to make use of this potential has led to a wide variety of haptic technologies, as well as how its use in mobile environments has resulted in a general recognition "*that non-visual cues have an important role to play in the interfaces to handheld or wearable computing devices*" (Oakley et al., 2006, p. 27). Furthermore, they argue for the practicality of vibrotactile interfaces, presenting a technical relevance to the expanding mobile domain for being simple to construct, "*small, cheap, robust, reliable, and consume modest amounts of power*" (Oakley et al., 2006, p. 27). Today's use of this technology in commercial interfaces range from vibratory to electrical, to pneumatic, and now ultrasound for mid-air vibrations (Long et al., 2014).

4.2 – Using the Skin for Haptic Sensing

To interact with a haptic interface utilizing vibrotactile feedback requires using the body's skin as a source for accessing information. The skin, being the largest organ in the body, has long been accepted to have considerable potential as a conduit for information, leading to a history of research focused on investigating how this organ can be effectively utilized (Oakley et al., 2006). Consequently, studies on the placement of vibrations on various parts of the body for vibrotactile feedback has also been studied extensively. Some successful applications include wearing belts around the *abdomen* (Panëels et al., 2013a; Tsukada & Yasumura, 2004; van Erp et al., 2005). Others have tried *shoulder pads* (Toney et al., 2003) or used vests to stimulate the front and back of the torso (Ding et al., 2010). Similarly, the *wrist* and *forearm* have been tested using different types of armbands (Hong et al., 2017; Ng & Man, 2004; Panëels et al., 2013b; Sergi et al., 2008). Vibrations have also been applied on the *fingertip* and to the *hand* (Carbonaro et al., 2014; Horvath et al., 2014; Leonardis et al., 2015; Sokoler et al., 2002). Some studies have attempted even larger areas of the body, such as using a wearable data suit or vest stuffed with actuators at specific locations on the body (Jansen et al., 2008; Lindeman et al., 2006). A key design challenge for many of these studies has been on selecting the appropriate location to wear and feel the tactile signal. One important aspect to this is that the most sensitive areas of the body are often inappropriate and off-limit, such as the lips, tongue, or even hands and fingers can easily conflict with user tasks and social norms depending on the context. Alternative locations that have proved easier to perceive—in terms of being able to localize a point of tactile vibrations on the body—is when this location is near anatomic reference points such as the wrist, elbow, spine, and navel (Cholewiak et al., 2003; Cholewiak & Collins, 2003), although these less sensitive areas of the body can still be considered inconvenient and inappropriate. Concerning this conflict of interests, Jonas & Sarter (2008) suggests that there must always be a trade-off decision to be made between sensitivity versus feasibility and acceptance when designing. Another suggestion is to integrate wearables into everyday devices, that are regularly on or near us. One such approach has been explored by (Wade & Asada, 2006) suggesting to integrate tactile technology into fabrics, e.g., as in watches, headsets, belts, and in the seatbelt.

4.2.1 – Feasibility of Wrist-Worn Haptics

As mentioned in the previous, many researchers have already looked at wrist-worn haptic applications specifically with the focus of its use for haptic guidance (Guo et al., 2009; Schatzle et al., 2006; Sergi et al., 2008; Weber et al., 2011). Although the wrist is not as sensitive as the hand and fingers, it does seem to offers a great balance of tactile acuity in localizing spatially distributed vibrotactile stimuli (Cholewiak & Collins, 2003), while also providing a small but decent surface area that is at the same time convenient (hands free) and is socially acceptable (Hong et al., 2016), since the artifact can resemble, or be integrated into, a wristband, watchband or another type of bracelet.

Oakley et al. (2006) looked at experiments examining the quality of vibrotactile displays placed on the forearm. They noticed that placing tactors (i.e., vibrating actuators for tactile stimuli) at different locations and in different arrangements around the skin resulted in different levels of performance. They also found that increasing the size of the stimulated area resulted in an increased perception of intensity. Their overall conclusion about the use of forearm tactile input was positive. Similar findings were reached by Chen et al. (2008), studying the ability to identify the location of a single point of vibration delivered to the upper and lower forearm near the wrist. The wrist near the hand joint was considered a suitable candidate for receiving vibrotactile stimulation compared to other areas closer to the elbow, as well as the advantage of the wrist as a convenient place for a wearable mobile device. The use of the wrist for haptic stimulation was also considered by the ease of keeping a haptic interface in place and close to the skin, such as by the use of a wristband, as was used in their study (Chen et al., 2008).

Another study by Heikkinen et al. (2009) involved seven focus group sessions, discussing the various uses of the haptic modality in mobile communication. During these sessions, the topic of wearability and where to locate the haptic feedback on the body was an important topic that came up regularly. The most often suggested device by the focus group participants, was a watch-like device or some kind of bracelet worn on wrists, with some participants suggesting how "*it would be unobtrusive, mobile and constantly in contact with the user's skin while leaving both hands free for other activities*" (Heikkinen et al., 2009, p. 6). Handheld devices were also suggested, but according to Heikkinen et al., it was not the preferred design for this many of the participants.
Particularly for navigational purposes, Karuei et al. (2011) explored the potential and limitations of vibrotactile displays in wearable applications, finding that the wrist was amongst the most preferred body locations. Lee & Starner (2010) also examined the reaction time to perceive alerts on the wrist, concluding that paying attention to these alerts was not easily deteriorated by visual distraction, indicating that wrist-mounted tactile displays can be appropriate for enabling mobile multitasking.

The idea of mounting a haptic display on the forearm near the wrist is an appealing one, with considerable potential if made sufficiently small, robust and discreet for its use. As summed up by Oakley et al. (2006), "*…of all possible body sites, it is the most attractive for such a purpose as it is both physically and visually accessible to users, and is an easy, established and acceptable part of the body on which to wear an electronic device*" (2006, p. 33).

4.2.2 – Tactor Arrangements on the Wrist

In terms of where and how to place tactors for a wrist-worn vibrotactile display, several researchers have examined the efficiency of different arrangement, both over, under, and around the forearm circumference near the wrist.

Psychophysical studies have also been conducted trying to identify the ideal alignment, number, and type of tactors to use on a vibrotactile wristband. Such study was done by Schatzle et al. (2006) suggesting that a configuration of six tactors distributed evenly along the circumference of the arm near the wrist is a good compromise between the number of feedback locations to perceive from, and being able to reliably distinguish the location of these, when compared with tests using configurations of four and eight actuators.

Work by Cholewiak and colleagues (Cholewiak et al., 2003; Cholewiak & Collins, 2003) also found that when placing actuators along the arm, the ability to localize vibrotactile stimuli was generally higher near bodily landmarks, such as near joints, suggesting that these placements should be considered when designing vibrotactile devices. Another study by Piateski & Jones (2005) examined a 3 by 3 array of tactors placed on the underside of the forearm, in order to study the ability to recognize simple patterns including systematic activation of lines of tactors moving vibrations along or across the arm. They observed that it was easier for the participants in the test to recognize tactile stimulation moving across the arm than along the arm, possibly due to the use of the edges of the arm (area along the arm separating the lower and upper arm) as bodily landmarks. This corresponds with Chen et al.'s (2008) study also examining arrangements of 3 by 3 tactors but on both the dorsal, the volar, and both sides of the wrist at once, with findings suggesting the usefulness of using vibrotactile input on both sides of the wrist.

In Oakley et al.'s (2006) paper on the subject of determining the feasibility of forearm mounted vibrotactile displays, they studied the simple act of placing tactors in an array mounted across the forearm—in line with the strap of a watch, instead of along the forearm—to determine if localization rates could be improved above what was reported in studies of similar uni-dimensional tactor placements in belts and around the torso. To this placement they argue for "*[the] practical advantage to such a laterally arranged array is that it is natively smaller and easier to wear than one mounted along the arm*", suggesting that "*[if] sites on both the top and bottom of the forearm are employed this study suggests that as many as six tactors could be attached to a single band, and good localization performance be maintained*" (Oakley et al., 2006, p. 33).

Consequently, the design of a vibrotactile wearable device, and how to appropriately place tactors in specific arrangement on the wrist, not only rely on the preferred technology and technicalities of the tactors used, such as output, dimensions, weight, power consumption, reliability, e.g. design considerations based on the type of information and haptic expression of the device also has to be considered. A grid-like arrangement might be suitable for the display of a broad range of low-resolution haptic patterns, while a uni-dimensional layout around the wrist can be sufficiently useful for conveying information using the circumference of the wrist as a mental plane of reference. These arrangements of tactors, in turn, influences the design possibilities, aesthetics, and wearability of the device, which has to fit the user and use.

4.3 – Applications for Vibrotactile Guidance

Several projects have used vibrotactile displays for various types and purposes of guidance using methods of sensory substitution or by communication of complex messages through skin stimulation. To distinguish between some of these projects, and to see how haptic guidance can be applied to different use cases, Weber et al. (2011) present three useful categorizations of haptic guidance; attention guidance, movement guidance, and spatial guidance, as presented below:

Attentional guidance, such as with the use of vibrotactile warning signals to alert of critical events, usually by directing attention towards the direction, as relevant in the context of driving (Ho et al., 2005) and applicable to air traffic control (Olivari et al., 2014).

Movement guidance, such as physical interactions in remote environments (Tsetserukou et al., 2009), training in posture or handling of instruments (van der Linden et al., 2009) or rehabilitation recovery.

Spatial guidance by vibrotactile stimulation has been used effectively in many use cases and contexts, to guide human operators towards a specific target. This type of vibrotactile feedback for spatial guidance has proven to be helpful for surgeons when complex hand movements have to be followed (Jones & Sarter, 2008). It was also found to support marksmanship (Oron-Gilad et al., 2007) or to aid soldiers in navigating through unfamiliar environments (Elliott et al., 2010). Vibrotactile displays are also used to guide actors in a virtual studio, to help them interact with virtual objects (Wöldecke et al., 2009). Driving (Tilak et al., 2008) or walking (Panëels et al., 2013b; Pielot et al., 2009, 2012; Sokoler et al., 2002; Tsukada & Yasumura, 2004; van Erp et al., 2005) using turn-by-turn or waypoint navigation, has also been supported by vibrotactile devices. Finally, there are use scenarios where the spatial frame of reference is disturbed (as will be discussed later), causing difficulties for the user to orient themselves in their environment, such as in maritime scenarios (van Erp & Self, 2008), in weightless environments in space (Traylor & Tan, 2002), in the cockpit of an aircraft (Rupert, 2000), in virtual environments (van Erp, 2001a) and in patients suffering balance disorders (Piateski & Jones, 2005).

4.3.1 – Sensing Direction

Haptic researchers have developed several attempts to communicate directional information in a mobile setting using tactile stimuli. Arrays of tactors has been used to successfully communicate direction cues and have been built into wearable devices including belts (Tsukada & Yasumura, 2004; van Erp, 2005) and vests (Tan & Pentland, 1997), in vehicle chairs (Tan et al., 2003) and steering wheels (Kern et al., 2009). Examples of handheld or fingertip-based devices include those that use inertial forces to communicate direction (Sokoler et al., 2002; Winfree et al., 2009), and others utilizing shear forces, slip, or skin stretch at the fingertip (Gleeson et al., 2010; Leonardis et al., 2015; Tsetserukou et al., 2014).

There are several proposed applications of tactile displays where users have to identify an object in 3D space, assisted only through vibrotactile stimulation on the body (van Erp, 2005, 2001b) or as assistive devices for turning the users attention towards a visual target based on a spatially tactile cue (Tan et al., 2003). Weber et al. (2011) and Sergi et al. (2008) studied wrist-based haptic guidance for 3D hand movements with a relatively small set of target directions (4 and 6 possible direction). Hong et al. (2016) used 32 possible directions, however indicating that knowledge about how precisely users might interpret an arbitrary number of directions on the skin and execute a corresponding interaction is still not yet known. According to van Erp (2001b), perceiving information about an external direction can be indicated by a single point of tactile stimulation on the body.

The most ubiquitous digital interface of all, the smartphone, has also been explored as a source for interacting with spatial information about the users' physical presence and that of their surroundings, also as a means to provide directional and navigational guidance. To this, Fröhlich et al. (2011) describe two predominant approaches and interactive metaphors—the *magic wand* and *sixth sense*—that can utilize the benefits of haptic interactions in a mobile device. These are explained in the following two sub-sections.

4.3.2 – The Magic Wand

The *magic wand* metaphor refers to the use of a handheld device (i.e., a smartphone) to point at a distant object to get information about it. This has become technically possible due to the combination of GPS and an internal digital compass in the device, being able to estimate what object or direction the device is being pointed at. Various implementations of this design have utilized haptic feedback in the handheld device to give information about the object or direction being pointed towards, such as in applications for pedestrian navigation (Robinson et al., 2010) and sensing of virtual objects that are geographically grounded (Williamson et al., 2010).

In terms of using the magic wand concept for navigational purposes, one considerable design challenge is in determining the appropriate precision of the handheld device towards the target location. With this, we understand the specific angle between the pointing direction of the device and the direction towards the target location that the user is trying to reach. A narrow angle size (or "low tolerance") can appear preferable in situations where the user expects to use the device to learn the exact direction towards their target. However, a smaller angle size also puts a higher demand on the user aiming the device, in order to know when the device is pointing close enough towards the target and within the specified angle size.

One such study by Magnusson et al. (2010) looked at the influence of tolerances in angle size on navigation performance, by testing different intervals of angle sizes with a handheld smartphone, to guide pedestrians between waypoint locations around an open park area. Between each waypoint, the participants' devices used a randomly assigned angle interval and located the next randomly assigned waypoint to be guided towards. Contrary to the teams expectations, Magnusson et al. found that, "*users were not very sensitive to the angle interval*" (Magnusson et al., 2010, p. 4), finding that even though narrow intervals provide more exact track following, it also results in slower walking and require more attention/concentration from the user. In contrast, wider angle intervals result in less exact track following but allow users to walk faster and be more relaxed. The conclusion is that there is no single preferred angle interval—instead, the appropriate angle depends on the task. Their observations, however, support the notion that "*using this type of pointing gesture for navigation is intuitive and easy to use*" (Magnusson et al., 2010, p. 1).

Another aspect of using the magic wand, while being mobile and requiring navigation support, is that it allows users to stay aware of the general direction of their travel by actively scanning the environment with the device while at the same time maintain visual attention to their surroundings. This approach to navigation has been demonstrated to be both intuitive and allows users to effectively reach a given destination (Robinson et al., 2010). However, the intuitiveness of using a handheld pointing device using haptic feedback is traded with the drawback that it requires active pointing gestures and holding of the device. This style of interaction may not be suitable in cases where a user's hands are full, such as while carrying a bag or performing other tasks that require hand free navigation (Crossan et al., 2008). To this, Panëels et al. suggest to use a wearable device instead, to provide feedback in an unobstructed manner (Panëels et al., 2013b).

4.3.3 – The Sixth Sense

The *sixth sense* metaphor describes interaction techniques that use multimodal feedback to inform the user about changes in the environment (Fröhlich et al., 2011). These changes can be related to the user's current geolocation and orientation, such as direction towards travel destination or notifications about waypoint navigation hints. The sixth sense metaphor comes from the fact that the user might receive this information discreetly and effortlessly through a haptic display.

For the purpose of guided navigation, the sixth sense concept has been applied by issuing turning instructions either by using vibration patterns to specific locations on the skin corresponding to the users location and direction to move (Lin et al., 2008; Pielot et al., 2009, 2012; Tsukada & Yasumura, 2004; van Erp et al., 2005) or by cueing the direction through tactile representation of directional messages (Brock et al., 2014; Gleeson & Provancher, 2012; Pielot et al., 2011b, 2011a; Sokoler et al., 2002). If abstract messages are communicated, these solutions would require the users to learn and memorize the *haptic language* (the distinct patterns of vibrations to which specific meanings are made implicit) before it can be used efficiently.

The advantage of the sixth sense approach compared to the magic wand solution described in the previous is that the user is not required to search for spatial entities via active pointing gestures actively. This makes the approach suitable for passive cutaneous sensing of information, such as the use of vibrotactile feedback in a wearable.

4.4 – Frame of Reference

In the context of mobile applications, world-centered actions relate to the movement "*of the person, with the device, in the world*" (O'Modhrain, 2004, p. 143). As such, designing mobile navigational applications requires considerations about what external frames of references there is in any given context of use to appropriately understand and place the user in time and space. To this, O'Modhrain (2004) explains how many such applications are piggybacking on existing infrastructure, such as networks for mobile telecommunications, or the global positioning system (GPS), or other systems, such as museum exhibits, use indoor positioning system (IPS), i.e., by utilizing physical, electronic tags placed at various locations. The importance of these systems is in how they provide means of interpreting aspects of people moving through space and use this interpretation as a way to reveal information relating to their immediate physical surroundings (O'Modhrain, 2004).
When dealing with directional navigation using haptics, having a mental model of the environment as a frame of reference is crucial to the interpretation of any movement and change in orientation. Gleeson & Provancher (2012) argues how "*A thorough understanding of the mental transformation of haptic stimuli will help engineers and designers to develop haptic interactions that are suitable for mobile and handheld applications*" (2012, p. 175).

In previous examples of using devices with haptic feedback based on the orientation of the device, the user has to interpret not only their place in the environment but also the reference frame of the device used to navigate the environment. The human system can, and often does, encode objects through multiple reference frames simultaneously, through the act of mental rotation (Volcic et al., 2009). Depending on the frames of reference and degree of rotations involved, this act can either be done instinctively or require considerable mental computation relative to the complexity of the interaction.

The context of navigating an environment using a map exemplifies the cognitive demand of both paying attention to the world frame, the body frame, the hand frame, as well as the mental frame of what is depicted on the map. This can be observed when tourists try to rotate a map and/or their body to match the orientation of the map with their unfamiliar environment, in order to reduce the cognitive load of navigation.

4.4.1 – The Rotation Problem

One issue that can influence the user's interpretation of directional perception of haptic stimuli from a device is when that device itself is rotated in space, thus having a different frame of reference than the user holding it. This mental transformation of haptic stimuli between different reference frames—referred to as the *rotation problem* (Panëels et al., 2013b, p. 119)—poses "*an important problem inherent to many types of haptic communication*" (Gleeson & Provancher, 2012, p. 171). This problem is related to the cognitive load necessary to mentally transform haptic cues from the location and orientation of the skin where they are perceived, to the world-centered frame, where they are applied (Gleeson & Provancher, 2012). Volcic & Kappers (2008) found that variable hand orientation did cause errors in the perception of the orientation of the haptic stimulus, indicating that the mental processes interpreting the haptic representation of space are tightly linked to their reference frames in which these internal representations are coded. The adverse impacts of variable hand orientation have also been documented in control of virtual reality environments using haptics (Ware & Arsenault, 2004). "*These results warn that variable hand orientation could potentially interfere with the accurate perception of haptic direction cues*" (Gleeson & Provancher, 2012, p. 171). These findings—when designing mobile interactive applications utilizing spatial directional guidance—is of considerable relevance when the aim is to create an intuitive and naturally embodied interaction dealing with multiple changing frames of references.

Logically, the adverse effects of the rotation problem are only influenced by how much rotation actually occurs. This raises the question about context and real-world use cases. Panëels et al. (2013b) experimented with the impact of the rotation problem using a wrist-worn haptic guidance bracelet with four actuators to provide tactile stimulation on the top, right, bottom and left of the wrist, to indicating front, right, back and left movement directions respectively. This test of user interpretation was done while performing everyday poses like talking on the phone, looking at the phone, hands in pockets, carrying a bag, and a default resting pose. Additionally, the team conducted the tests in both static (standing) and mobile (walking) conditions. The results showed that the first test group, who were asked to locate the source of the vibration on their wrist while standing still took generally less time to interpret the vibration, than the second test group, who were asked to indicate the direction while walking (Panëels et al., 2013b). The more demanding situations was when the "*direction was not clearly defined* *in the participant's mind*" (Panëels et al., 2013b, p. 121) as noticed when the test subjects' wrists were in their pockets or while talking on the phone, compared to when they were looking at the phone or holding a bag and having the reference frame of the bracelet aligned to their direction of walking.

Although Panëels et al. (2013b) identified that "*some confusion is experienced when the user needs to associate the vibration to a perceived direction*" (2013b, p. 122), it was also argued that, "*the orientation of the user's wrist does not have a strong effect on the presentation of tactile directional cues*" (2013b, p. 125). The study was concluded with a questionnaire to the participants, about the difficulty in localizing vibrations and associating directions from the bracelet, as well as final remarks on the prospect of using the wrist as a place for sensing directional stimulation:

> "*Overall, we can conclude after this experimental validation, combined with positive feedback from our participants, that the wrist is an excellent candidate for the provision of passive vibrotactile feedback*"
> (Panëels et al., 2013b, p. 125)

Despite research on the possible adverse effects of the rotation problem, the study provides insights into how users can successfully interpret two-dimensional directional stimuli, using four directional cues on a wearable bracelet in various hand poses and while walking. The study examines efficiency (in terms of reaction time and accuracy) of interpreting directional cues—not the feasibility of actually guiding a user towards the direction using this method of navigation. To deal with the rotation problem, it is worth considering how today's sensors already used in modern smartphones (i.e., gyroscopes, accelerometers, and magnetometers), can be used to reduce the complexity of the rotation problem, by orientating the display of a device to the world frame, in an attempt to parallelize the reference frames for a more intuitive and less demanding interactions.

4.5 – Privacy Concerns

The unique traits of touch-based communication being close to the body allow for the creation of private displays. This a critical affordance when information is private or even confidential, or inappropriate to other people (Jones & Sarter, 2008). The most common example is the use of vibrations in smartphones when ringtones and sound alerts are inappropriate.

In a study focus group, examining expectations and experiences with haptic interactions, the participants emphasized the need for maintaining control over the privacy of haptic communication more than with other communication channels (Heikkinen et al., 2009). The reason being that touch was considered "*such a private sense that the user must be able to control who can communicate via the haptic modality with them*" (2009, p. 7), considering haptics as a one-on-one type of communication between only the most trusted and close friends.

Another aspect of privacy concern is related to how a person must move and act physically in order to interact with a product or complete a specific task. O'Modhrain (2004) argues for the importance of considering the role of body motion and proprioceptive cues in interacting with mobile digital artifacts. Small finger gestures might be irrelevant to consider, but if the interaction requires large gestures and arm movements, then these can create social concerns of being awkward or inappropriate. Instead, the use of small and hard to notice ways of communicating, such as squeezing, tapping or touching with the fingers alone, can be used to communicate privately and discreetly (Heikkinen et al., 2009).

Chapter 5

Process

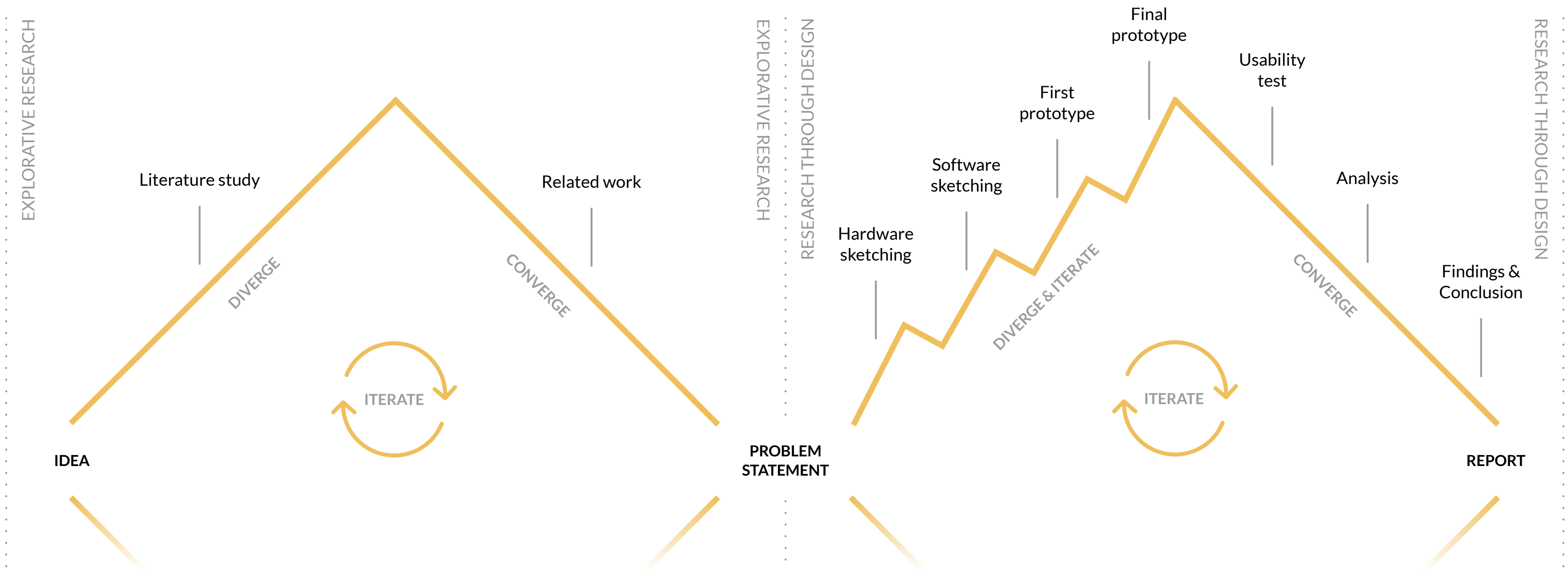

Figure 3: Illustration of the project process based on the double-diamond model.

The process framework used in this project is based on the basic double-diamond model described in *3.1 The 'Double Diamond' Design Process Model*. The following process chapter is structured accordingly, based on the four phases in this model (see *figure 3*):

- In the **Discover** phase, I discuss the initial curiosity and motivation for conducting this project, followed by an exploration of the issue and shortcomings of personal navigation with and without haptics.
- In the **Define** phase, I describe the desk research conducted, analyze my findings, and define the final research question.
- In the **Develop** phase, I open up the solution space, exploring possible solutions to the research question using a sketching and prototyping methodology.

- In the **Deliver** phase, I explore the final research artifact designed, also through a usability test and analysis of the results.

The result of this process is summed up in *6 Findings* and further discussed in *7 Discussion*.

5.1 – Discover

Before any design can take place, a problem—or an idea leading to a problem—first has to be discovered and understood. In this section, I will briefly describe the initial curiosity and motivation that was the starting point, for what eventually lead to this project.

This motivation is based on a self-observation of how the use of mainstream everyday mobile technology for personal navigation can still be problematic. The most commonly used approach is the use of one's smartphone and a map-based service and try to navigate from A to B while paying attention to both the map and the environment. Several researchers have argued how this approach can be both problematic and potentially a safety risk, especially when traversing urban and traffic-heavy environments (Panëels et al., 2013a, 2013b; Pielot et al., 2012; Renaudin et al., 2017; van Erp et al., 2005). Screen-based handheld navigation can in some cases be hard to read due to sunlight reflections, or the device itself can be problematic if the hands are already occupied. Looking down on the device while walking can also pose a serious security risk, as it takes the user's attention away from the ongoing traffic. Audio-based navigation can be used, and privately, using headphones or earpieces. However, this approach can introduce counterproductive effects, e.g., by isolating the user from the ambient sounds of the traffic or interfere with communication between other pedestrians (Renaudin et al., 2017). Another challenge lies in the difficulties of verbally communicating walking instructions that are both detailed, timely, and contextual, due to the pace and freedom of movement compared to, for example, car navigation.

Traditional navigation solutions depend on the visual and auditory senses, which happen to interfere with the same sensory channels already occupied during walking, navigating, and paying attention to traffic. The sense of touch, however, is hardly used when scanning the environment, thereby providing opportunities to supplement the other senses (Pielot et al., 2012). The idea of examining the body's distinct sensory channels involved in pedestrian navigation is supported by Renaudin et al., stating that "*Haptic technologies can potentially be useful in this context since they provide information while freeing the users' hands,* *ears and eyes."* (Renaudin et al., 2017, p. 184). Exploring the use of haptics for navigational purposes has already been proven efficient in reducing distractions, reaction time and attentional load (Pielot et al., 2011a, 2012), as well as a potential use for mainly the elderly and people with impaired sight (Renaudin et al., 2017). The question then, is not so much about the potential of haptics in navigational applications, but more so a question on how to appropriate the technology in ways that it is both continuously available for everyday use, while also being useful, accurate, robust, and acceptable to everybody, both ethically and aesthetically (Renaudin et al., 2017).

Next to exploring uses of the ubiquitous smartphone, another prospect for a device with a haptic potential, that also fit the affordance of being *continuously available for everyday use*, is the increasing popularity of smartwatches, currently expected to grow sales by an average of 20 percent each year (Lamkin, 2018a). Most modern smartwatches afford communication through haptics on the wrist, unlike smartphones that either needs to be actively held in hand for optimal use or sensed through the fabric of a pocket, purse, or bag. This device can be paired to work with the user's smartphone, taking advantage of each other's multiple sensors, computation, and connectivity.

5.1.1 – Haptic Navigation Using a Smartwatch

To get a better understanding for how haptics in a smartwatch can be used to assist personal navigation, an opportunity for self-observation presented itself one day, when I tried to navigate to a social event on foot, carrying a bag in one hand through an unfamiliar neighborhood, while also paying attention to the good company I was in. I was in charge of guiding us to our destination address. This was a scenario for which hands-free and eyes-free navigation could be the preferred choice, so an attempt was made to guide us using the haptic feedback navigation feature on my smartwatch. The point of this navigation feature is to provide turn directions on the wrist using haptics. However, the *haptic language* expressed by my smartwatch—that is, how it *communicates* through a series of vibration patterns—was not conceivable to me at first. I felt vibrations usually when we reached an intersection or crossroad and needed to decide on which direction to go. However, the vibrations on my wrist caused confusion and insecurity of whether or not I was on the right track. I later learned that others had experienced similar problems[2], but through a search online while stopping for a break, I found that '*two taps three times in a row*' meant turn left, '*twelve steady taps*' means turn right, and a long vibration means I've arrived[3]. Even with this knowledge in my head, it was still necessary to

[2] WATCH map turn directions / haptic feedback mystery solved! https://forums.macrumors.com/threads/watch-map-turn-directions-haptic-feedback-mystery-solved.1871693/

[3] How to use Maps on Apple Watch: https://www.macworld.co.uk/how-to/apple/how-use-maps-on-apple-watch-3609161/

regularly and visually confirm on my smartphone that I was on the right path, as well as to check whenever we encountered situations that were hard to decide solely by left or right turn instructions. This was more common than expected, such as when navigating non-perpendicular road layouts, navigating smaller contoured paths, shortcuts or open areas, e.g., crossing a park and a playground. I've since tried to rely on haptics for other walking, running, and bike riding purposes, but with less than satisfying results.

The point here is not to critique the design behind this specific haptic solution. After all, this is an optional navigation feature identical for any navigational input (i.e., walking, biking, driving)—not a feature advertised as an eyes-free substitution for pedestrian navigation[4]. Other products (e.g., Wayband™)[5] relying on this same approach for navigational purposes, utilizing distinct patterns of vibrations as haptics on the wrist to deliver navigational messages. Instead, the issue with this approach appears to revolve around the profoundly disembodied interaction, of neglecting the spatial sense of presence and physical location relative to one's destination goal, by instead following stiff turning directions blindly, hoping to eventually and suddenly reach the final destination.
Although the use of turn-by-turn instructions is known to have noticeable disadvantages for pedestrians (Pielot & Boll, 2010), the turn-by-turn navigation paradigm is readily appreciated in car navigation systems since turning instructions are more convenient to interpret on clearly defined roads, intersection, and exits. The most direct path is also not always the fastest route due to traffic, speed limits, one-way streets, e.g.; these examples are restrictions that modern car navigation can help navigate, however, they are at the same time not as relevant for pedestrian navigation. Inaccuracies in location technology like GPS is also easier to manage in car navigation systems when the location and driving direction can be constrained to the road grid, and the average speed of the vehicle can be approximated. For navigation on foot, this is more of a problem to compensate for due to the use of unmapped shortcuts, greater freedom of movement with sudden changes in direction and speed, and deficiencies in indoor navigation systems. Indeed pedestrian navigation differs widely from the navigation of motorized vehicles (Renaudin et al., 2017).

Typical navigation systems that have taken up the challenge of personal mobility are either adaptations of car navigation systems or systems that do not appropriately take into account the human factors involved in the interactions and use of the system. Despite a decade of research and the adaptation of the smartphone used as a navigation device, Renaudin et

[4] Get directions on Apple Watch: https://support.apple.com/guide/watch/get-directions-apdea7480950/watchos

[5] Wayband™ website: https://www.wear.works/wayband

al. argue that to their time of writing, "*no universal personal navigation system has been successfully introduced and adopted to improve personal mobility*" (Renaudin et al., 2017, p. 177).

5.2 – Define

In this section, the research question for the project is defined, based on the issues and shortcomings of personal mobility using smartphone navigation, as well as the potential of utilizing the haptic modality as discussed in *4.1 Designing Haptic Interfaces*. This is supported by my own observations with personal mobility using haptics, and the notion put forward by Renaudin et al. (2017) suggesting that more research is needed in this area.

Alternative solutions and approaches to vibrotactile interfaces design, with a focus on particularly wearables for directional guidance and spatial awareness, is examined in *4.3 Applications for Vibrotactile Guidance* based on a literary review. Navigating through the literature, the apparent benefits of eyes-free navigation using multimodal or haptic only interfaces is a noticeably relevant topic, with numerous pieces of work trying to address the issues of this technical, ethical and design-related challenge. One reason for this is the interest in exploring new interactive communication channels within HCI, combined with the insights around the potential value of haptics for creating more intuitive, private, and convenient interactions.

Key relevant insights from the related projects examined in this thesis are listed here, as to provide an overview of what has helped define the project research question:

- It has been demonstrated that multimodal interfaces are effective (Oviatt, 1999) and humans are natural experts in combining input from multiple senses at once.
- We see that multimodal interfaces have the potential to enable more natural and efficient human-computer interactions (Tan et al., 2003).
- "*The skin, the largest organ in the body, has considerable potential as a conduit for information. Correspondingly, there is a substantial history of research investigating how it might be effectively utilized*" (Oakley et al., 2006, p. 27).
- The placement of vibrotactile feedback on various parts of the body has been studied extensively.
- Many researchers have already looked at wrist-worn haptic applications, also specifically for haptic guidance (Guo et al., 2009; Schatzle et al., 2006; Sergi et al., 2008; Weber et al.,

2011).

- The wrist seems to offers a great balance of proximity (Cholewiak & Collins, 2003) and provides a small but decent surface area, that is at the same time convenient (hands-free) and is socially acceptable (Hong et al., 2016)
- In a focus group study about the expectations of haptic interactions, a watch-like device or "*some kind of bracelet worn on wrists*" was the most often suggested (Heikkinen et al., 2009, p. 7)
- Another discussed benefit of using a wrist-worn device is that it would be "*unobtrusive, mobile and constantly in contact with the user's skin while leaving both hands free for other activities*" (Heikkinen et al., 2009, p. 7).
- To that point, it was noted that handheld haptic devices that require the user to keep the device actively held in hand, is "*not a preferred design for many*" (Heikkinen et al., 2009, p. 7).
- Oakley et al. (2006) expressed that, "*…of all possible body sites, it* [referring to the wrist] *is the most attractive for such a purpose as it is both physically and visually accessible to users, and is an easy, established and acceptable part of the body on which to wear an electronic device*" (2006, p. 33).
- Psychophysical studies trying to identify the ideal alignment, number and type of tactons to use on a vibrotactile wristband, concluded that a configuration of six tactons distributed evenly along the circumference of the arm near the wrist, is a good compromise between the number of feedback locations and being able to reliably distinguish the location of these (Schatzle et al., 2006).
- As was concluded by Oakley et al. (2006), "*…a simple uni-dimensional array mounted across the wrist could result in localization rates that are still greater [than previous tests]" … "Using a single wrist strap, it is possible to position three or more tactors. If sites on both the top and bottom of the forearm are employed this study suggests that as many as six tactors could be attached to a single band, and good localization performance be maintained*" (2006, p. 33).
- Studies on spatial directional sensing has been conducted with tactile cues to successfully direct user attention towards a visual target (Tan et al., 2003), or by guiding a user's hand in 3D Weber et al. (Hong et al., 2016; Sergi et al., 2008; Weber et al., 2011).
- According to van Erp (2001b), perceiving information about an external direction from a single point of stimulation on the

body is quite intuitive, also noting how the illusion of apparent location (the percept of one point stimuli located in between two simultaneously presented stimuli) is as good as that of real points. This is also referred to as the *cutaneous rabbit illusion* (Geldard & Sherrick, 1972).

- Concepts like the *Magic Wand* and the *Sixth Sense* metaphors have been discussed (Fröhlich et al., 2011; Panëels et al., 2013a), providing interesting alternatives to turn-based instructions.
- The *rotation problem* was examined. Even though the negative cognitive load of interpreting devices rotated relative to the users reference frame has been documented (Gleeson & Provancher, 2013; Volcic et al., 2009; Volcic & Kappers, 2008; Ware & Arsenault, 2004), tests to simulate everyday use cases of a handheld haptic device showed that "*the orientation of the user's wrist does not have a strong effect on the presentation of tactile directional cues*" (Panëels et al., 2013b, p. 125), although some confusion is found relative to the degree of rotation (Gleeson & Provancher, 2013).
- Privacy concerns associated with the use of the haptic technology has briefly touched upon, recognizing not only the opportunity for its use as a private communications channel but also recognizing privacy issues associated with accessing this highly intimate sense of touch (Heikkinen et al., 2009).

The literature contains a sufficient body of research indicating the usefulness of using the wrist as a place for vibrotactile interactions with unique benefits over visual and auditory communication. These findings are timely, as the adoption rate of smartwatches is on the rise, potentially becoming the next ubiquitous device to accompany the smartphone (Fingas, 2019; Lamkin, 2018b). This affordance of being always available and with us at all times is an important one, and partly the reason watches have become 'smart' in the first place (Rawassizadeh et al., 2014).

The smartwatch provides a means for haptic communication that—although still simple in output—is always available, always in touch with the skin in a convenient, discreet and socially acceptable manner. It is both ubiquitous computing embedded in a watch, which for watch owners mean that no additional device must be carried; and it is a multi-purpose device, which means even when one feature is not needed or used, it can still serve other purposes, justifying its day-to-day presence. Modern models include embedded sensors, and connectivity features closely matching that of the smartphone but is also able to work seamlessly in pair with the smartphone to exchange data and work as an extension of each other. At the same time, it is worn in a place that is easily accessible for screen-, touch- and voice-based input, able to detect hand movement and gesture input using technologies like a built-in accelerometer, gyroscope, and magnetometer. The smartwatch can be used to assist in navigation—and using haptics, as has been observed—but the turn-by-turn navigation still adheres to the same shortcomings as the smartphone, although being strapped to the wrist. Clearly, an alternative to haptic turn-by-turn navigation for pedestrians is needed to improve personal mobility.

5.2.1 – An Alternative Approach to Turn-By-Turn Navigation

The unique benefit of map-based navigation is not only to learn when to take a turn—it involves the mental practice of positioning oneself in the landscape with the target destination, recognizing landmarks as a way of creating a mental model and spatial awareness, to form a sense of which direction to go. This spatial framework provides opportunities to pick any preferred route and do multiple directional turns or shortcuts towards the goal, as long as the sense of direction is maintained. This sense of direction and ability to spatially orient oneself are essential components of the human capability for wayfinding (Cornell et al., 2003).

Attempts to embody this sense of direction is exemplified in devices designed to use the haptic modality to deliver 'the sixth sense' metaphor to the skin (see *4.3.3 The Sixth Sense*). This is done by using a uni-dimensional tactor placements placed horizontally around a part of the body, such as around the torso (van Erp, 2005) and head (Kerdegari et al., 2016) to deliver vibrotactile stimulation to the area of the body closest to the direction of the target to navigate towards. When the user moves and rotates their body, the vibrotactile stimulation updates accordingly to always target the area of the skin closest to the target location. It is made possible using location and orientation-based technology, to always calculate and estimate the egocentric location and orientation of the device worn, relative to the target location, thereby estimating the direction towards the target and which tactors on the worn device to vibrate to conceive this sense of direction. The embodiment of the sixth sense metaphor provides an alternative approach or supplement to turn-by-turn directions for personal mobility that has—to the knowledge of this author—not yet been sufficiently examined in a wrist-worn device for personal mobility and navigational purposes.

5.2.2 – Defining the Research Question and Project Scope

The challenge of pedestrian navigation goes well beyond just knowing in what direction to go. Concurrent navigation systems are required to do so much more when the ambition is to provide a service that is easy and efficient to use, accessible, effective, reliable, flexible, private, and safe. This undertaking of mobile personal navigation includes both engineering challenges, human challenges, legal and ethical challenges (Renaudin et al., 2017)—all of which are essential considerations, but also beyond the scope of this project. To name some of these considerations, still relevant in a haptic use context: Conveying distance information and estimating time of arrival, transition to other transportation types during travel, meeting demands of the elderly and people with disabilities or impairments, indoor navigation, navigating stairs, lifts, elevators, doors, etc., running navigation, data usage, and battery consumption.

This project aims to explore how the sense of direction can be conceived in a suitable wrist-worn wearable like a smartwatch using the unique capabilities of haptics for private eyes-, ears- and hands-free navigation. This focus was chosen as the basis for examining alternatives to the contemporary turn-by-turn paradigm, thereby considering an alternative style of navigation that takes advantage of using spatial directional stimuli through haptics using the sixth sense metaphor. The following project research question is hereby defined as:

"By utilizing the unique capabilities of haptics for spatial directional guidance, how can a sense of direction towards a point of interest be appropriated in a wrist-worn wearable for personal mobility purposes?"

By *unique capabilities of haptics,* we understand the unique traits and advantages of the modality over typical visual and auditory interactions, as described in *2.1 The Sense of Touch*.

By *spatial directional guidance*, we understand the ability of a user to sense—through the use of a haptic display—in what direction a point of interest is, relative to them.

By *appropriated in a wrist-worn wearable*, we understand the design constraints of limiting solutions to that which could potentially be embedded in a typical wrist-worn wearable like a smartwatch, without significantly compromising the existing affordances of such wearable.

Finally, the *for personal mobility purposes* defines the relevance of conducting this research, as to address the issues with personal mobility, notably for pedestrian navigation purposes.

To best answer the research question presented, requires investigation and familiarization of the haptic modality and haptic interface technology.

Moussette (2012) argues for using research through design with hardware sketching as a means to explore haptics. According to Moussette, this is best approached by sketching with haptics, using uncomplicated and accessible technology and tools, to "*best learn, understand and seize the full potential of this new* [haptic] *modality*" (2012, p. 25). He argues that the benefits are in the level of exploration and unexpected discoveries gained (compared to typical haptic research activities), as well as the technical expertise gained by understanding design materials and mechanisms, through the act of sketching and continuously building stuff (Moussette, 2012).

This practice of sketching with hardware and haptics by adopting an RtD methodology to explore possible solutions to the research question is described in the next section.

5.3 – Develop

With the research question defined, we begin this phase by examining the solution space using haptics as part of the initial sketching process. We start by focusing first on the challenge of how the skin on the wrist area could be stimulated appropriately and how the direction of the stimulation is perceived. The exposed area on the wrist was understood as to where a typical watch strap would be in contact with the skin just above the wrist joint.

5.3.1 – Testing Wrist Sensing

A simple exercise was used to get an initial understanding of how various sensations could be provoked when different materials and techniques were applied to the wrist. Three volunteers were used and asked to look away while their wrist of choice was stimulated in different ways. This was done, while at the same time questioning them, in what direction they perceived the source of stimuli. Sensations such as tickling, squeezing, and pressuring, and using sharp and sticky objects were quickly discarded for being unpleasant or dangerous. Applying electricity and temperature change to the skin was also not tested due to lack of appropriate and safe means of testing. Tapping on their wrist gently with a finger, using the bottom of a pencil, and using a simple coin vibrator[6], was the preferred techniques used. Here it was noted that tapping on the wrist was considered to be in direction of where the tap was applied (not opposite of that, as if the wrist was pushed by the taps). However, pulling the wrist gently using a thread was considered the same direction as the wrist was being pulled, even though the threads actual contact with the skin was opposite of the pull direction. This was likely due to the causation of actual applying movement to the hand, in contrast to sensations that allowed the hand to remain still. The idea of applying enough force to move a person's hand involuntarily was, however, discarded as being impractical and unpleasant.

The exercise provided a useful means of gaining tacit knowledge about the sensation and general sensitivity of the skin on the wrist, as well as reaffirming how sensations can be applied to the wrist area electronically using a simple and small coin actuator, and in a way that is still comfortable. One volunteer noted how the sensation was even pleasantly intriguing due to unfamiliarity with the sensation. A voltage regulator was used with the coin vibrator to adjust an appropriate intensity of the vibration. Here it was noted that the intensity of the sensation caused by the vibration varied significantly depending on how tight the vibrator was held to the skin—something worth considering during the design of future experiments.

[6] https://www.precisionmicrodrives.com/vibration-motors/coin-vibration-motors/

5.3.2 – Using Multiple Tactors to Perceive Change in Direction

To create a haptic display that can emulate the sensation of vibrations traveling around the circumference of the wrist, as a means to express changes in the direction of the stimuli. Multiple tactors can be used in sequence, by controlling which tactor to vibrate at any time depending on changes in orientation. While it can appear favorable to use as many tactors as possible to achieve a higher fidelity of haptic feedback, this is not only impractical due to the weight of components, it is also not necessary when exceeding the limits of tactile acuity on the wrist (see *4.2.2 Tactor Arrangements on the Wrist*). Furthermore, designers of haptic interfaces can exploit the *cutaneous rabbit illusion* for this purpose to give the illusion of perception of points of stimuli between two neighboring points (Geldard & Sherrick, 1972; van Erp, 2001a). By spacing tactors in a linear arrangement around the wrist circumference with some distance between each one and alternating the intensity of the vibration from one tactor to the next it is possible to "*simulate a higher spatial density of tactors than is actually present in a display*" (Jones & Sarter, 2008, p. 97). Using this alignment, Schatzle et al. (2006) examined between four to eight evenly distributed actuators, recommending the use of six as a good compromise between being able to distinguish the location of individual actuators, while also using as few actuators as possible to reduce weight and cost of the device.

The effect of rotating the vibrotactile stimulation around the wrist was examined using a hardware sketch consisting of a smartwatch wrist-band, and initially four tactors being coin vibrators, placed evenly spaced between the watch band and wrist (see *figure 4*). An Arduino Uno[7] microcontroller was used to control and provide power to the individual tactors. This simple setup provided the opportunity to quickly write short programs to test the sense of multiple sources of haptics working together to form a unified sensing experience. By gradually varying the individual voltage output of each tactor using a sinus curve, this setup demonstrated the cutaneous rabbit phenomenon very convincingly, as the experience was perceived as one unified source of vibration rotating in circles around the wrist traveling between the tactors. Varying the speed of these rotations exposed a potential problem, when the speed was either too fast or too slow. Too fast, and the sense gradually felt as if the whole wristband was vibrating. Too slow, and the cutaneous rabbit effect was lost, exposing the vibration of each individual tactor.

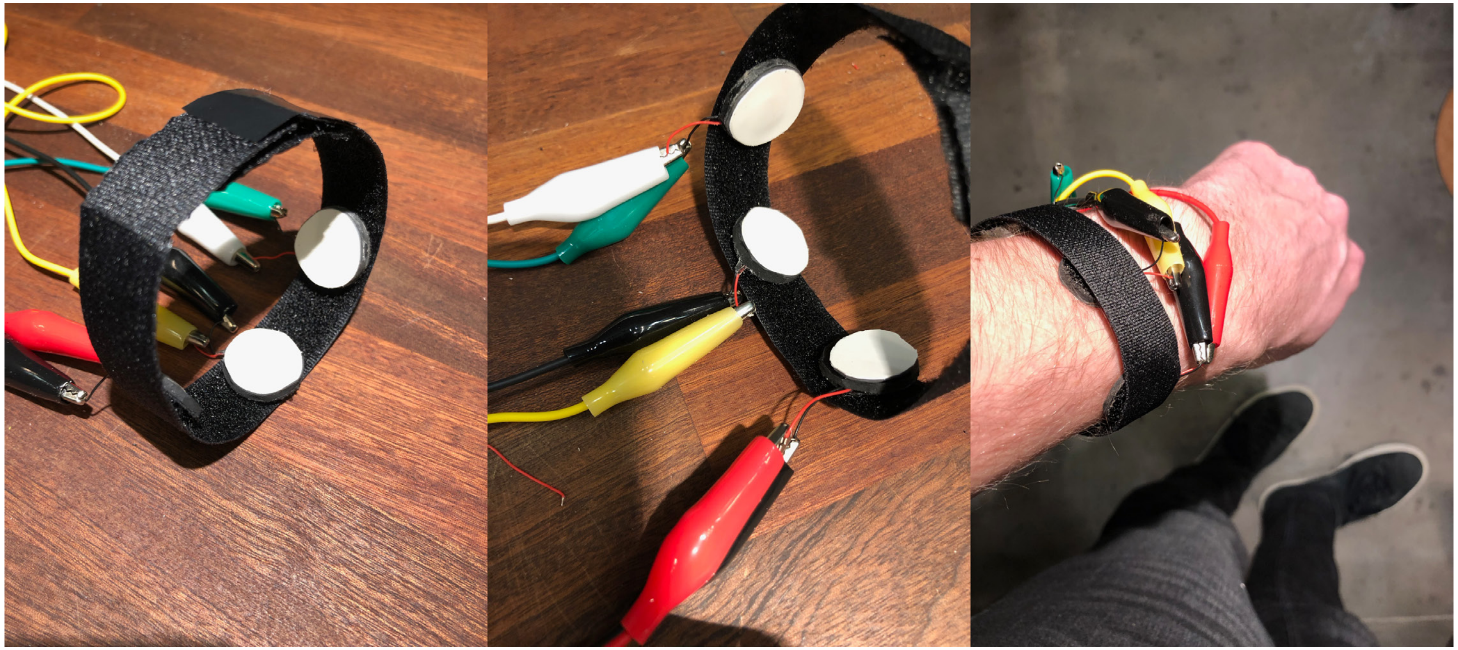

Figure 4: Four coin vibrators enclosed in rubber isolations and placed on a wrist band.

[7] https://en.wikipedia.org/wiki/Arduino_Uno

This, however, was considered more of an issue related to the number of tactors initially used (only four) and a question of appropriately regulating the transition of intensity between the tactors.

Rotating the source of stimulation on the wrist, based on the rotation and location of the wrist towards a target, is easy to conceive in a two-dimensional frame of reference when the wrist's circumference plane is also horizontally aligned to the world. One can imagine a person holding their hand down parallel to their body, and how the direction of stimuli can be perceived as a point on the circular circumference of the wrist pointing towards the target (see *figure 5*). Even if the wrist is rotated while the hand is still pointing downwards, this rotation can be compensated for, using a digital compass attached to the wrist, as discussed earlier. However, what should happen when the wrist circumference is not parallel to the ground, such as if a person is talking on the phone, holding their wrist up near the head; or if carrying a box with the hand

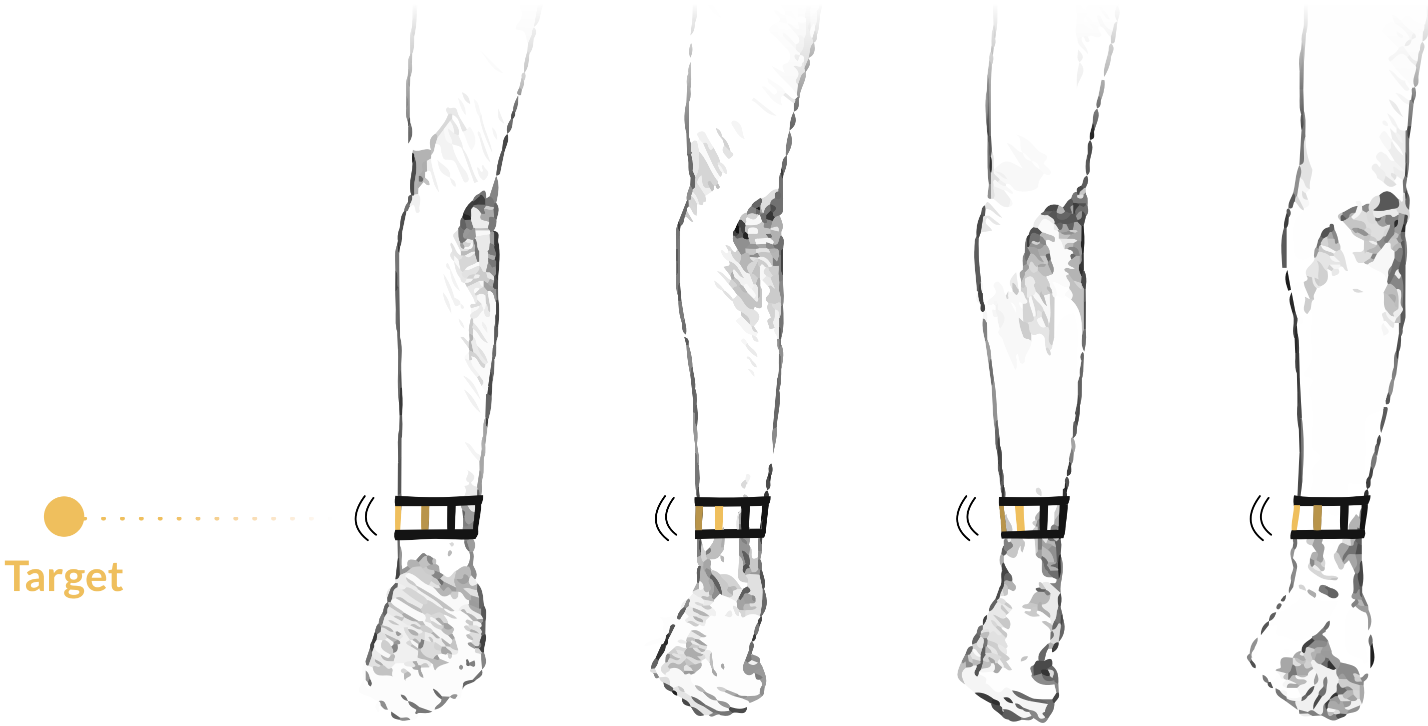

Figure 5: Showing different rotations of the wrist. Note how closest tactor to target is always vibrating.

and wrist pointing forward towards the walking direction? Any unpredicted orientation of the wrist during everyday unforeseeable use must be expected in the design of the interface. This is the challenge of rotating frames of reference, as discussed in *4.4.1 The Rotation Problem*.

5.3.3 – Dealing with Wrist Rotations

The relevant projects already discussed that uses tactors placed around the torso and head for directional stimuli, does not deal with this problem, since the plane of rotation of the torso and head rarely changes significantly while walking or sitting. This is not the case with the wrist. The design approach used for a wrist-worn display must compensate for all angles of rotation if the affordance of a hand-free solution should be maintained. This issue of rotation presents an essential component in answering the research question.

While brainstorming practical solutions to this problem, it was considered how we humans are quite adapted at explaining a direction to others by merely pointing our finger in the given direction. This pointing gesture is something we learn intuitively from an early age and is deeply embedded in our spatial perception and communication of spatial information. Using the concept of pointing while exploring possible solutions to how the different tactors on the wrist should vibrate during wrist rotations, the idea of using a simple string-bound in a loop around the wrist, was used. The loop was loose enough that it could easily rotate, matching the direction of pulling the string (see *figure 6*).

The other end of the string was attached to an arbitrary point of interest, indicating the direction towards it. Using this analogy of the string as an arrow pointing in the direction of the target, and the location of the knot connecting the loop as the indicator for where vibrations should be felt, this *string model* provides a useful concept to how and where various rotations of the wrist should be conceived using vibrations on the wrist. Using this model as the basis for interpreting this interaction, also naturally aligned with how the gesture of pointing should be perceived. The very embodied act of pointing at a far-away object rarely does not involve also moving the forearm in the same direction. The gesture of pointing, and using this string model, suggests the alignment of the string parallel to the forearm (and wrist). Ideally, in this position, all possible knot locations are equally close to the point of interest, meaning all knot (tactors) should vibrate equally. By this analogy, it was conceived that the incident of sensing rotation while pointing did not have to be an issue, but rather an opportunity for interaction. This notion was further inspired by the magic wand metaphor discussed previously (see *4.3.2 The Magic Wand*), using the same act of pointing a device towards a target, to get information about it. The consideration here was that both the sixth sense and magic wand metaphors could be embraced simultaneously based on rotation. Using this analogy of a sting pulling the hand and guiding movement creates the basis for a truly embodied interaction using natural gestures.

5.3.4 – Software Sketching Tactor Behavior

In order to explore how this concept of a string to guide direction, could be used to convert rotation data into vibration output, a more convenient method of working with, and visualizing, the behavior, was needed. For this purpose, a software sketch running on a smartphone was used, taking advantage of the build-in gyroscope and screen for data visualization. The software sketch consisted of a live website that could be visited through the browser on any smartphone (see *figure 7*). The website displays a large circle representing the circumference of the wrist, with the center crosshair illustrated the pointing direction. Tac-

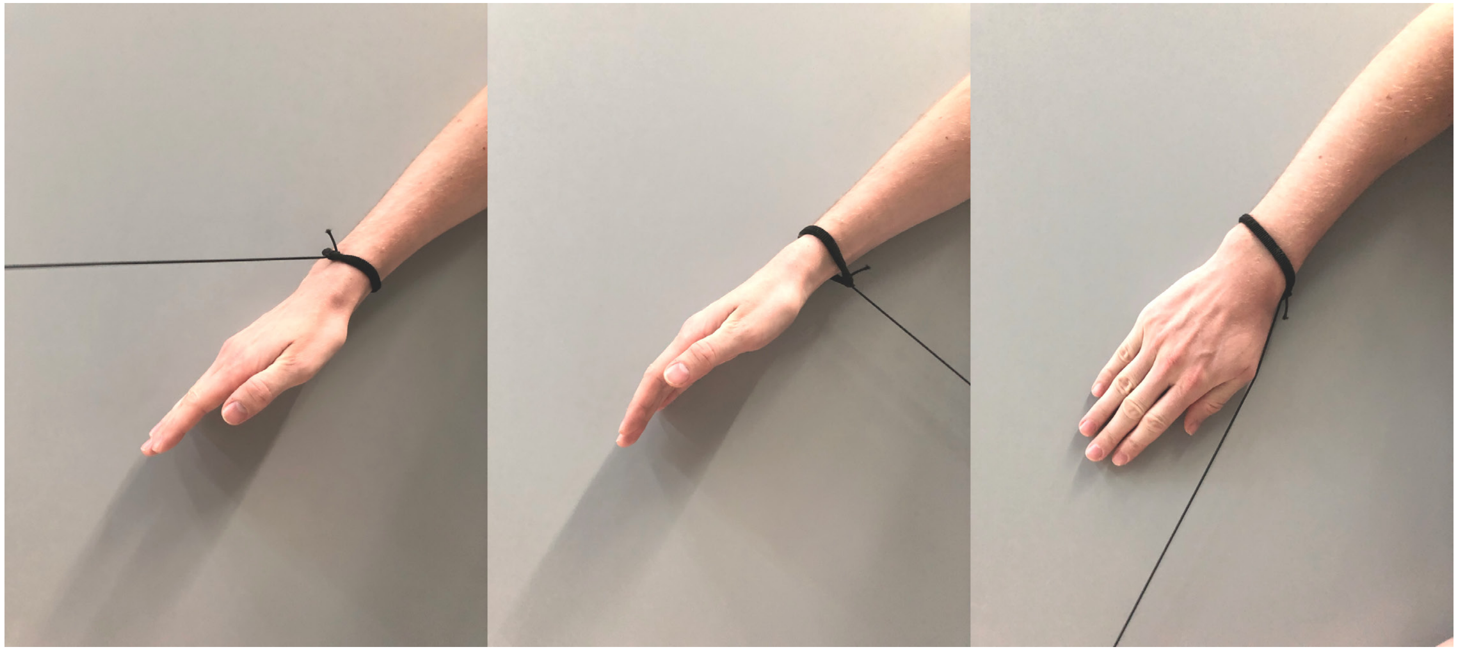

Figure 6: Testing various positions of wrist rotations with a string indicating the direction towards a point of interest.

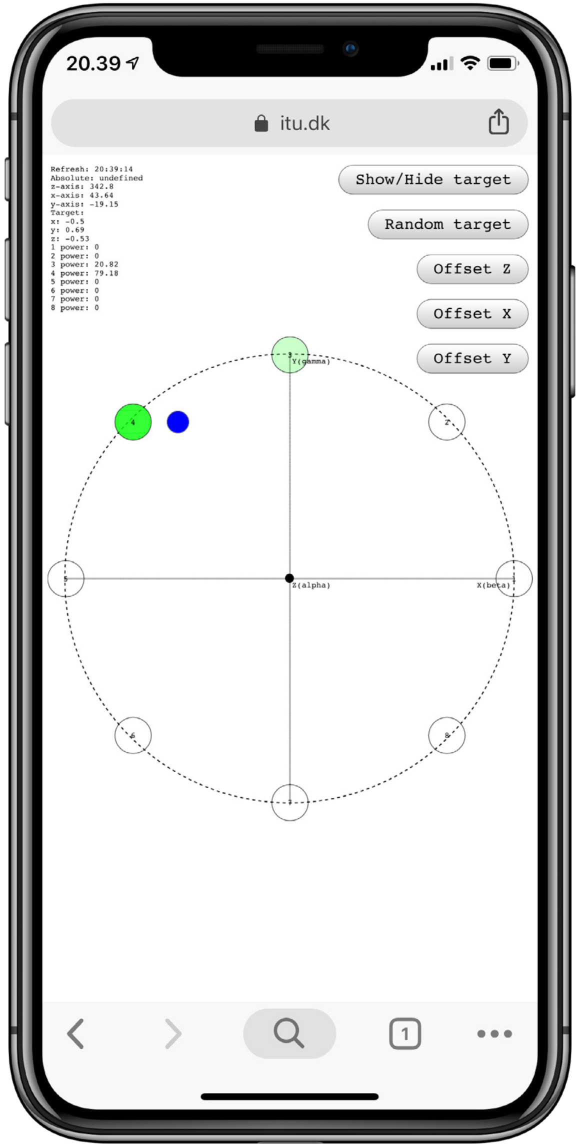

Figure 7: Software sketch running on an iPhone. See *Appendix A*.

tors are visualized as smaller circles placed on the wrist circumference. Power applied to the tactors is illustrated by the circles turning green. The target (point of interest) is illustrated by an orange circle which can be moved around in 3D by rotating the device, thereby also influencing the power distributed to the individual tactors. Various statistics used to debug and work with the code is also depicted, as well as buttons to hide, adjust, or randomize the target location. The number of tactors could be adjusted as well, although a number of eight was used for most of the testing for better visualization.

By physically placing the smartphone on the wrist and moving the wrist around, it is possible to emulate how various positions would influence the voltage supplied to individual tactors. Using a smartwatch with web browsing capabilities also meant that the same sketch could be viewed directly on the wrist, taking advantage of its motion-sensing capabilities. During the programming and pilot testing with volunteers using the sketch (with the target hidden so only tactor vibrations would be visualized), two potential issues were identified that made locating and hitting the target (i.e., locate the point of interest) more difficult. The first issue was in lack of communicating how close or far off the user was to hitting the target. Regardless of rotation, one tactor would always be the closest to the target and vibrate. This meant that although users know in what direction to rotate, they do not know how far, or at what speed, they should move their wrist to find the target without overshooting it. It was observed how this unintendedly challenge made the interaction appear playful. The second issue observed was the need for an appropriate effect of actually hitting the target. This should work both as a confirmation to the user, that they are on point, but also to limit the issue of flickering vibrators caused by small hand shaking near the target, which was also observed at a 180-degree angle directly opposite of the target.

To work around both of these issues, an additional parameter was added to the interaction, inspired by the magic wand metaphor. The new behavior meant that as a user approaches the target direction, all other tactors would gradually start to vibrate as well, although at a lower voltage not to conflict with the tactor guiding the direction. Only if the aim was on point would the result be that all tactors would vibrate

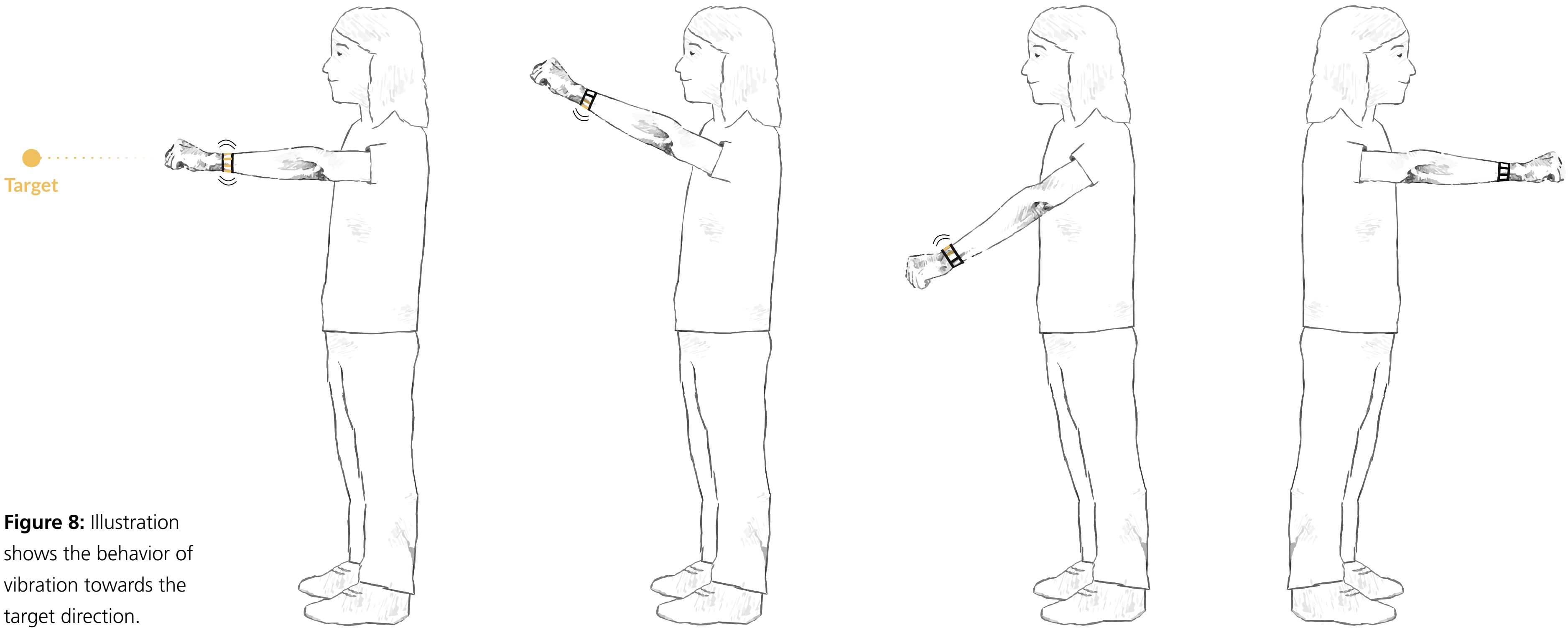

Figure 8: Illustration shows the behavior of vibration towards the target direction.

equally. Moving the hand away from the target again would lower the vibration of all tactors except the one guiding towards the target. The opposite effect was also implemented for when the rotation was far off target. If the user pointed directly opposite and away from the target, the intensity of the vibrations would become very weak, to indicate that the user was in the opposite direction of the target. Rotating the wrist towards the target again and the guiding tactor would gradually start to vibrate again (see *figure 8*).

The result of this addition to the change in behavior (although still only visually represented on-screen) was that now the user could not only interpret the direction when the wristband was parallel to the ground but also reach out and interpret the direction based on how the wrist should rotate—and how far it should rotate—to point in the direction of the target. The interesting consequence of this approach to the rotation problem was that now not only the horizontal but also the vertical aspect of sensing a direction could be interpreted from the device,

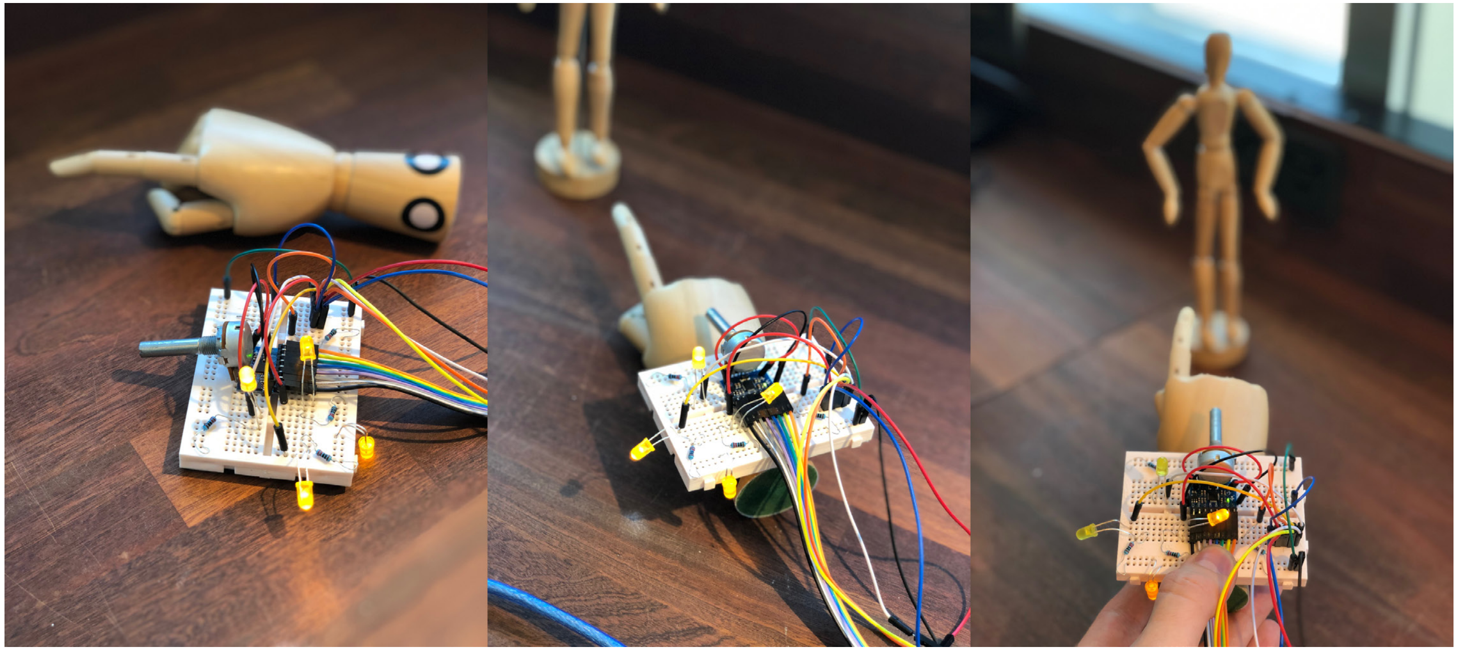

Figure 9: Working with the MPU-6050, LED's was initially used to verify the sensor and coded behavior from the software sketch.

depending on how the device was rotated.

Before moving this behavior onto a physical wristband, the JavaScript code from the website software sketch was rewritten to run on the Arduino Uni used previously. A 6-axis MPU-6050[8] motion tracking device (3-axis gyroscope and 3-axis accelerometer) was connected to the Arduino as a means to sense changes in rotation. LEDs were initially used to indicate varying voltage to the tactors, as these were easier to interpret while working on the code (see *figure 9*).

When the Arduino code and MPU-6050 were working as intended, the setup was eventually transferred to the first physical prototype using haptics.

5.3.5 – First Prototype

The shortcomings of the first hardware sketch using haptics meant that examining the perception of direction was done mostly while holding the wrist in a steady position. This was due to the wiring and difficulty in keeping the coin vibrators well in place and close to the skin. Gluing the tactors to the wristband and tightening the band presented another dilemma of vibrations passing through the stiff material of the wristband. This caused vibrations from one tactor to carry over, through the material, to nearby tactors where the vibrations could also be felt. To cope with these issues, a flexible elastic band was used in an attempt to minimize the displacement of vibrations and to compensate for the uneven circumference of the wrist not being a perfect circular shape. Another consideration and argument for using an elastic band were observed when testing the sketch on volunteers with varying sizes of wrists circumferences, due to the difficulty in keeping the tactors evenly spaced around the wrist, when the length of the band had to be adjusted.

To address these findings and work with the motion sensor used in the software sketch, a prototype was constructed providing more flexibility for experimentation (see *figure 10*). The design of the prototype used a broader elastic band with an adjustable hook-and-loop fastener to compensate for variances in wrist circumference. The prototype used ten sewn pockets on the wristband to hold and experiment with different types and arrangements of tactors. The wiring was eventually sewn into the elastic band, ending in one cable going from the wristband sensor to the Arduino and portable power supply, making this prototype easier to wear while performing various hand and body movements.

This first prototype proved useful for working with different parameters

[8] https://www.invensense.com/products/motion-tracking/6-axis/mpu-6050/

and tactors of the display while also experiencing the haptic feedback of what was first conceptualized in the software sketch.

The smaller coin vibrators were replaced with larger pill-shaped encapsulated vibrator[9], also based on the eccentric rotating mass (ERM) principle, but with the direction of rotation being upright to the skin surface (compared to the coin vibrators being parallel to it). Although the new vibrators were significantly larger in size and weight, the importance of being able to have more control over the intensity of the vibrations was considered a higher priority. Coin shaped linear resonant actuators (LRA)[10] was also considered, and likely would have been optimal due to their linear and focused vibration perpendicular to its surface. However, they were discarded due to the requirements of additional components and development time to operate them efficiently. The number of actuators used was also increased to six to improve the sensation of vibrations moving around the wrist.

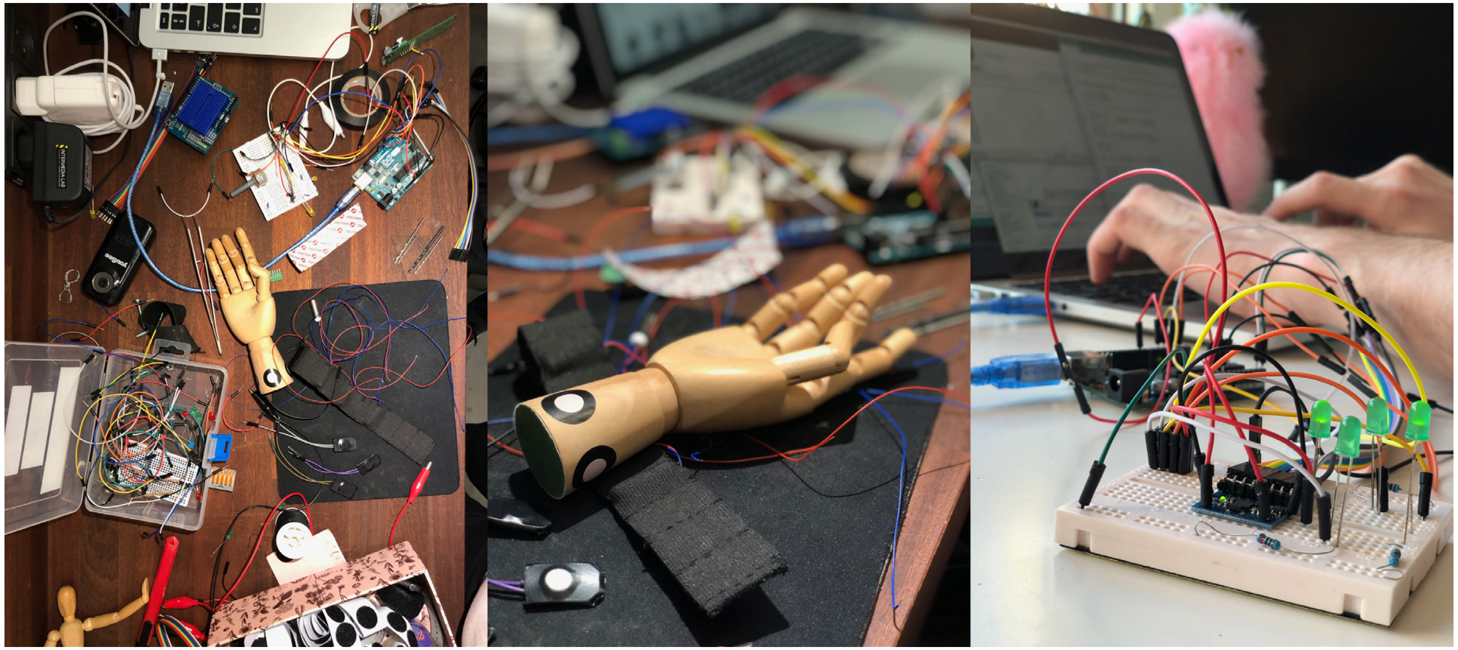

Figure 10: Photos from the process of building the software sketch and the first prototype.

[9] https://nfpshop.com/product/nfp-7c-fs0725-7mm-encapsulated-vibration-motor-25mm-type

[10] https://www.precisionmicrodrives.com/vibration-motors/linear-resonant-actuators-lras/

It was noticed how the solution of adjusting the intensity of tactors in the software sketch (visualized by colored circles and later LEDs) did not communicate well to the haptic prototype. The reason is that the skin is less sensitive for observing precise changes in vibrations than visual verification of changes in color and brightness. This is made even more difficult due to the influence of vibrations from nearby tactors through the material. An alternative solution of using changes in frequency instead of amplitude was used. The tactors were instead turned on and off rapidly in a frequency, with a delay between the frequencies depending on the proximity of the rotation to the target direction. This behavior was similar to the warning tones used in modern car parking assistants to signal proximity to outside object[11]. Switching tactors on and off continuously in concise bursts, was a noticeably better signifier for proximity than the previous method of adjusting the intensity by voltage regulation. With the new method, each vibration will always vibrate a minimum of 150ms, but the delay between the vibrations range from 300ms to 0ms delay (constant) depending on the rotation towards the target (from 0 to 180 degrees). This new method was noticeably better at expressing a sense of proximity to the target intuitively, as the small changes in delays between the vibrations, depending on the remaining distance, was less difficult to distinguish than changes in the amplitude of vibrations.

The combination of changing frequency based on proximity, with the cutaneous effect of vibrations moving around the wrist surface, and based on direct manipulation of the sensory input using wrist rotation with no noticeable lag between the input to the sensor and output from the tactors, had resulted in a natural and intuitive interaction with the display. An interesting sense was felt when circling the wrist around the direction towards the point of interest, causing the source of vibration to move around the wrist accordingly, giving the objective experience of sensing a cone-like structure that could be felt and grasped mid-air—this was the sense of direction as manifested in the embodied interaction of actively reaching out and feeling the source of vibrations on the body, as a tangible indicator of which direction the device was communicating. Although it was clear that a general sense of direction could be felt, the acuity of this sense—especially when trying to determine the orientation of direction without actively pointing towards it—was difficult to locate reliably, where precisely on the wrist the vibration was felt. The issue was partly caused by the encapsulation of the tactors in the sewn pockets on the elastic band, and the now larger tactors used, making the band stretch and becoming stiff and uncomfortable to wear. A design flaw that required another iteration, using a different approach to the design of holding the tactors and improving the precision of the displays output.

[11] Example of Park Distance Controller beeping: https://www.youtube.com/watch?v=8LY8R-z5aM6A

5.3.6 – Final Prototype

The purpose of the final prototype was to focus on optimizing the acuity of the haptic stimulation, thereby allowing for a more precise perception of direction. The prototype was also intended to be used in a potential user test, so comfortability and flexibility of using the device also considered. The look of this prototype was, for the most part, deprioritize in favor of exploring the interactive experience. It was an experience prototype, with the purpose of delivering the experience of sensing directions on the wrist, through the display. The implementation was done using relatively cheap and easily accessible materials and components. The elastic band from the previous prototype was replaced with a new structure using two soft cloth hair elastics as straps running in parallel around the wrist (see *figure 11*). Between the straps is the pill-shaped tactors inside thin closed cloth pockets running in parallel, evenly spaced out around the wrist, and only attached at both ends to each strap. The purpose of this design was that the soft straps provide the primary

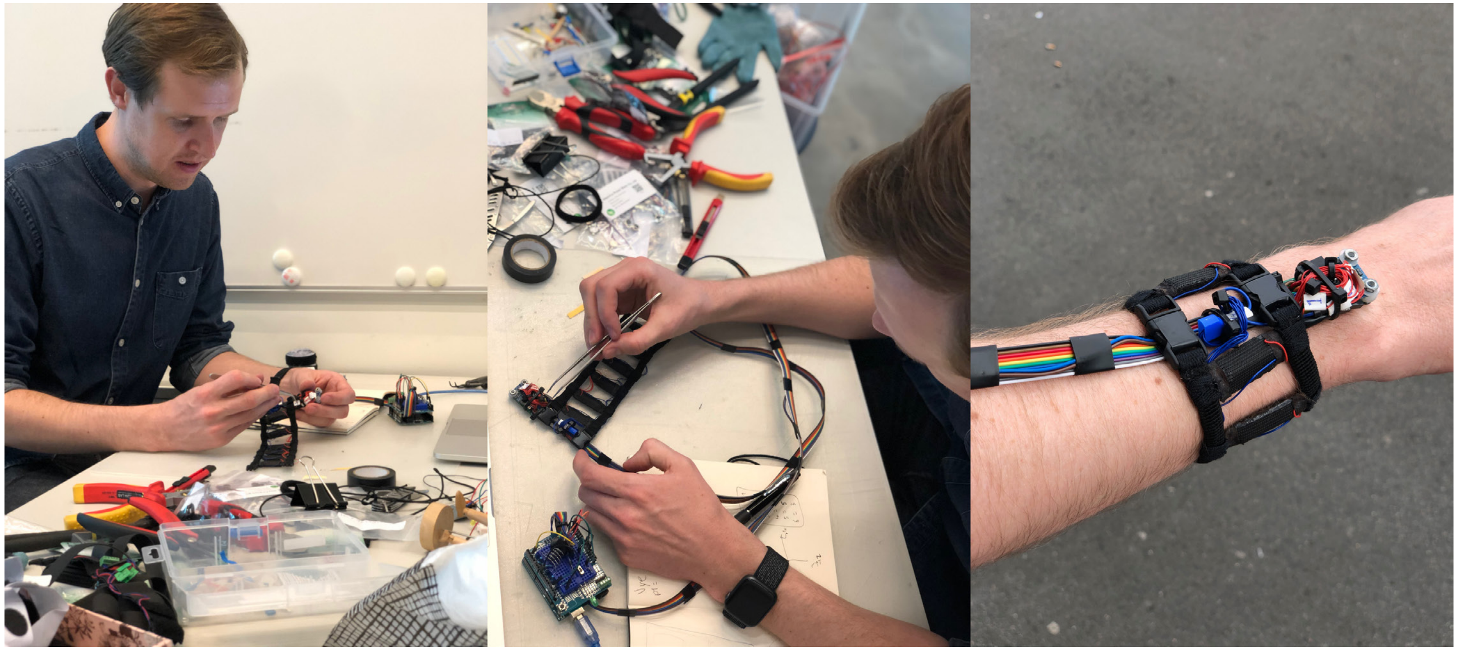

Figure 11: Photos from the process of building the final prototype.

structure and contact with the skin, being stretchable to accommodate the difference in wrist sizes, while the tactors are held in place between the straps but still close to the skin. Any vibrations traveling between tactors has to travel along with the cloth pockets and up through the strap, thereby greatly reducing the spread of vibrations in the device. The wiring from individual tactor runs through the straps up to the motion tracker, which was moved in front of the wristband, closer to the wrist joint, due to its size and to reduce potential interference with the vibrations while still keeping it as close to the wrist skin as possible. The wiring from the device runs along the upper forearm and down to a portable base holding the Arduino and power bank (see *figure 12*).

The Arduino base itself was equipped with a button and a switch. The button is for manual on/off switching of the vibrations. The toggle switch was used to switch the behavior of the program between two states: (1) The default with a virtually fixed point of interest, and; (2) The 'find target'-program, which, whenever the point of interest was located by pointed at it (within a 10-degree radius), it would change position to a new randomly generated direction. This made it easy to try to repeatedly locate multiple randomly generated directions around the user, as a means to test the efficiency and acuity of locating directions. A 'confirmation' vibration pattern (lasting 2500ms) was also added to indicate when the user had successfully found the target direction (after pointing at it for minimum 500ms to decrease the chance of accidental hits), and to alert that a new random direction has been generated.

In terms of the experience of use, the new design was a noticeable improvement from the previous prototype; it was both easier and faster to perceive the location of the vibration to a specific area of the skin, and easier to detect the differences in vibrations between the tactors. Overall, the sense of direction was improved, not only in terms of quickly locating a point of interest by pointing but also when holding the wrist in various positions without pointing, such as while walking around, using a smartphone or carrying a bag. Using the 'find target'-program, it was acknowledged how the precision of the device had become sufficient for sensing not only the horizontal but also (if need be) the vertical direction towards points of interest, such as if the direction should be used to indicate going up and down stairs, or point at a specific nearby object.

The experience afforded by this design—including the interactive potential of the haptic display—presents a potential answer to how spatial directional guidance can be expressed, interacted with, and appropriated in a wrist-worn wearable utilizing the unique capabilities of haptics. This prototype represents the research artifact to which the research question was explored and answered.

In the final phase of the project process, this potential answer to the research question is examined using the design of a usability test, which is examined in *5.4.3 Analysis of the user test*.

5.4 – Deliver

In this final phase of the process, the answer to the research question is examined by testing user interactions with the final prototype using a small-scale usability test. The purpose of this test was to be explorative; to uncover potential issues with the design, to verify or disprove its ability to sense directions, and as an opportunity to gain insights into how the interaction design could be interpreted. This testing purpose suggests both a qualitative and quantitative evaluation of observing and questioning test participants, and to measure their ability to detect and locate directional stimuli successfully.

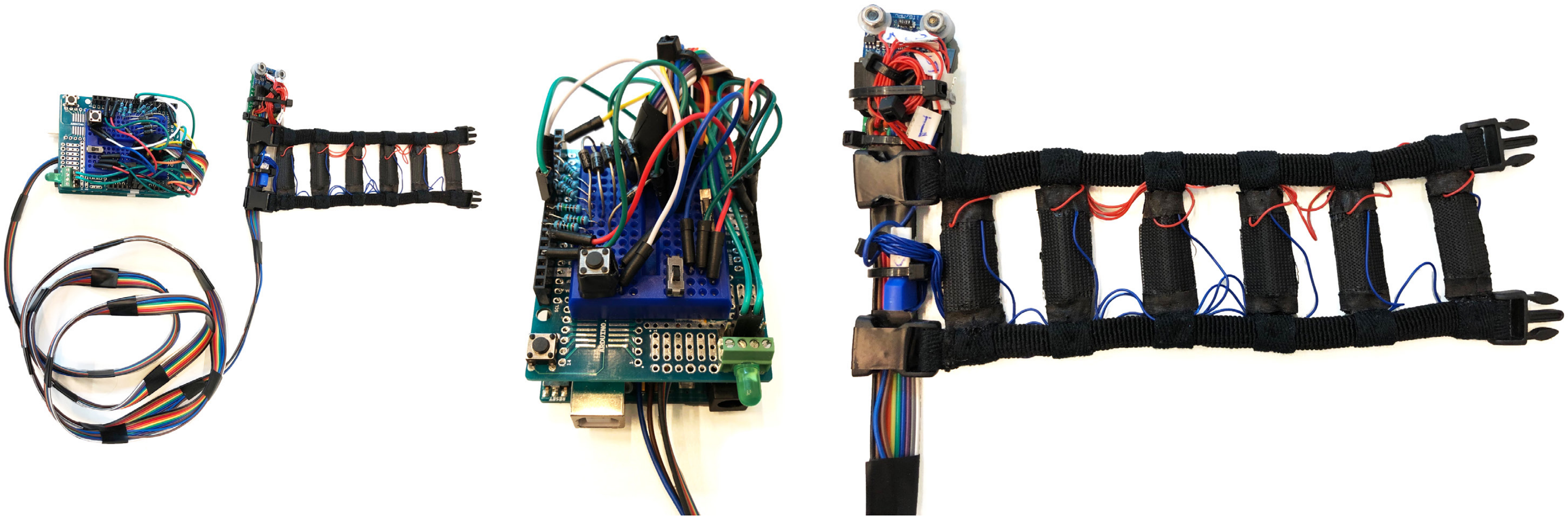

Figure 12: The final prototype

5.4.1 – Pilot Testing the Process

To prepare the testing process, a preliminary pilot test was conducted with voluntary participants in 1-on-1 interviews. The participants were first asked about their general opinion and experiences of using haptic feedback, then their impressions of the prototype before, during and after having it equipped, and were asked to describe the sense of directional stimuli when moving freely and trying various poses.

The 'find target'-program on the Arduino was used to observe the participants ability to detect and find directions. This worked well in most cases, but issues with using randomly assigned directions were observed. One issue appeared when the rotation of a new random direction happened to be very close to the previous direction identified. This led to situations where participants would accidentally locate multiple locations repeatedly and be confused by the repeated confirmation vibration. The issue was removed programmatically, by making sure new random direction would not be within a 30-degree radius of the previous. A second issue was observed when directions appeared pointing mostly vertically. The act of locating something directly under you or directly above you was unexpected and led to confusion and silly postures. To make the directions appear more in line with practical applications, this issue was also solved programmatically, by preventing new directions to appear in an angle of 30 degrees above or below horizontal. To verify that participants were indeed able to locate directions, an LED was added to the Arduino to light up whenever a location was found.

Other observations include the realization that time should be given to the users to familiarize themselves with the haptic stimuli using the default program, before trying the 'find target'-program. Trying to sense direction in various positions was also easier to explain and attempt when the participants were given real objects to hold and use during the test. Various ways of explaining how to use the prototype, with as few instructions as possible to still allow for self-exploration, was also practiced. The prototype was also packed to hide exposed components and electric wiring to make it appear less intimidating and fragile, and the Arduino and power bank was packed to wear on a belt or from a pocket. The findings from the pilot tests were used to prepare an interview guide for the upcoming user test.

5.4.2 – User Testing the Final Prototype

The user test was conducted at the IT University of Copenhagen, with volunteers recruited ad hoc at the location, by setting up a booth with a sign to attract potential volunteers (see *figure 13*). No specific recruiting criteria was used, except the willingness to participate and try wearing the prototype. Ten participants (three females, seven males) were used between the age of 21 and 39, most of which were expected to be students at the university and relatively experienced with IT. The tests were video recorded with permission from each participant, being informed that it was only for internal use to document the process and that any images used for this report would be anonymized. Each test took around 15 minutes, following a predefined interview guide.

- The participant is greeted and introduced to the project and test. Name and age are noted.
- The participant is interviewed about their experiences of using haptic feedback, to uncover biases and presumptions.
- The participant is introduced to the prototype and help with getting it properly equipped.
- The participant is given some time to experience and explore the prototype themselves.

Figure 13: Photos from the user testing session of the final prototype.

- The participant is asked questions about their experience and if they perceive being able to sense in what direction to go.
- These same questions are asked, while the participant tries a variety of arm poses while carrying a bag, and while pretending to be on the phone.
- The next phase involves the participant trying to locate ten directions using the 'find target'-program, while the time between each find was timed using a stopwatch.
- Finally, the participant can unequip the prototype and is asked three final questions about:
    - o Their general opinion about the sensation of feeling a direction using haptics.
    - o Their perception about the difficulty in perceiving the directions.
    - o If they felt tired mentally or physically at the wrist after the exercise.
    - The participant was asked for any final remarks.

The Arduino code used can be seen in *Appendix B*. The interview guide can be seen in *Appendix C*. Notes and video recordings from the user test were collected for further analysis as a way to compare the results and find possible trends in the data. The findings of this analysis are described next.

5.4.3 – Analysis of the User Test

Note: In this section, the citations from test participants (cited as 'Tester #') have been translated from Danish to English.

The user test went well, with all participants expressing enjoyment and gratitude for having participated, and willingness to discuss their experiences.

The general opinion about haptics (before trying the prototype) was as expected, with most participants being either neutral, thinking that haptics works fine, or expressing their appreciation of haptics in games and when the phone is in silent mode. Some also stated that it could, however, be annoying if it was overdone or came unexpectedly.

After trying the prototype on, and becoming familiar with the interaction, the consensus was that the experience was overall enjoyable and interesting. All participants used positive adjectives to describe the experience, such as "*Funny*", "*Playful*", "*Feels nice*", "*Feels weird*", "*Very fascinating*", "*Tickling*", "*Very funny!*", and one describing the experience as "*I can feel that I have to move, as if it is trying to move* *me*" (Tester #9).

For some, the stimulation was more intuitive than for others, but overall, it was learned quite quickly. One participant stated this as, "*Yes, it can be hard at first, but when you solve the riddle* [of how it works]*, it becomes completely natural*" (Tester #6), and another saying, "*It was only* [difficult] *in the beginning, but then you learn it very fast. In the end, it gets very easy*" (Tester #4), and, "*You first have to tap into it. It's like a new sense!*" (Tester #2). A participant initially had the mapping inverted, "*I felt at first that I was moving the vibration, but then it flipped side, so I learned that it controlled where I should move*" (Tester #5).

Some aspects of the experience were compared to games and how it could be used in games, "*It feels somewhat like a game of 'hot and cold*[12]" (Tester #3), and, "*It is very intuitive where you have to go, especially if it was in a game, where you had to feel where to go*" (Tester #7). One participant who played golf as a hobby suggested, how the device could be useful to allow gold players to sense the direction of a hole, even if bushes or trees was in the way, also noting its potential use for retrieving golf balls.

When trying the prototype in various poses, 8 out of 10 expressed how it was easier to point the hand outward to feel the direction, than sensing the direction while holding the hand down near the body. The hardest pose for 9 out of 10 participants, was to sense the direction while pretending to be talking on the phone, with one saying, "*It's a little harder. It is as if I can feel it more clearly on my underarm*" (Tester #1). Just one participant found this pose equally easy, noticing that, "*Yes, I can feel it as a 2D plane*" (Tester #7).

During the 'find target' exercise of trying to locate ten random targets, it was noticed how the participants were significantly more focused than previous explorations of the haptic interface, possibly due to the game-like aspect of the exercise and the new assignment of trying to point directly at the sensed direction, with one participant expressing it as "*I needed more concentration to feel the direction precisely*" (Tester #10), while another found the exercise more playful, saying afterward that, "*It is very funny. It is funny that you don't have to look. Super funny!*" (Tester #6).

Although the act of pointing outwards to locate a direction precisely (as was also required in the 'find target' exercise), it was observed that all ten participants preferred to hold their arm out straight, and away from

[12] How to Play Hot and Cold: https://considerable.com/hot-and-cold/

the body, even from the very first chance of trying the prototype on. When later asked about any signs of fatigue after having conducted all exercises, 8 out of 10 expressed that they felt tired from holding their hand raised for so long, while 7 out of 10 also expressed some sign of prolonged exposure to the vibration on the wrist, with some saying that, "[I'm] *Not tired, except for holding the hand out for too long*" (Tester #4), "*Not really, but only tired of holding my arm up for so long*" (Tester #2), and, "*Tired of holding my hand high, but the wrist is okay, but can feel it buzzing a bit*" (Tester #7).

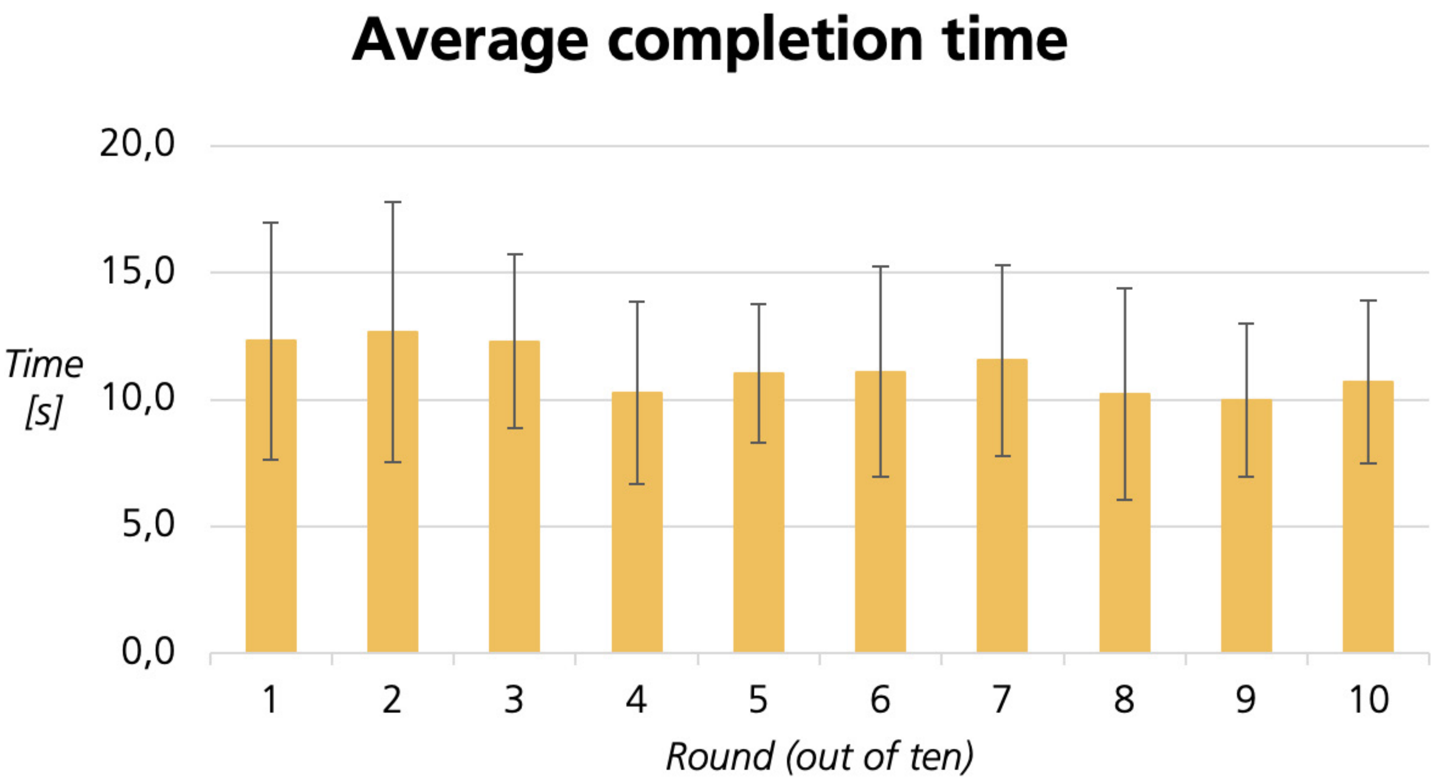

Figure 14: The results from the 'find target' user test, showing the participants average for each round.
Error bars showing standard deviation. See (Appendix D)

In terms of efficiency to locate targets by pointing, it was noticed how some participants took the exercise more seriously than others, with the fastest participant averaging a time of 8,7 seconds between hits, while the slowest was almost double that, at 16,3 seconds. The mean speed amongst all participants was 11,2 seconds between hits, with a standard deviation of 3,6 seconds. Amongst the 100 data points collected, the fastest time was 5,7 seconds. It is important to note, however, that each hit was measured by stopwatch, by watching the LED on the Arduino to verify hits visually, although the participants had also been asked to say "hit" when finding a target direction. Each hit was measured as the time since the hit before it. Between these hits, the participants essentially had to endure a dead time of first; the 2,5 seconds confirmation vibration before it stops, before a new target direction is generated and revealed haptically, and second; the 0,5 seconds of holding the device steady over the target direction for it to be verified as a hit by the Arduino. In other words, this leaves the theoretical minimum time between hits, using this program, at a minimum of 3 seconds, not including human reaction time. The participants could not get information about the new target location before after 2,5 seconds into each round after the confirmation vibration was replaced with the normal directional vibration.

This user test concludes the solution-phase of the process. The result of this analysis, findings, and overall process are summed up in *6 Findings*.

Chapter 6

Findings

The findings presented are based on observations made during the design, testing, and development of the presented sketches and prototypes during the project solution phase. Several of these findings have already been discussed during the sketching and prototyping process and have been relevant to the understanding of the process decisions made throughout. As such, this chapter works in part as a summary of these findings leading to the discussion.

From the user test, it was observed how participants were able to efficiently locate points of interest using the haptic modality alone, through the haptic display presented by the final prototype. The fastest participants were able to locate a random point of interest within a 10-degree radius threshold (set programmatically), in under 3,5 seconds after the direction of vibration was announced to them. For practical reasons, these randomly generated points would only appear between 30-degrees above or below sea level, and never within a 30-degree radius of the one generated before it. To lower the chance of accidentally registering a hit, by swiping past a point, participants had to hold the direction towards a point of interest at least 0,5 seconds to confirm the hit.

To perform this sensing meant that users were required to actively point directly at the point of interest to confirm its location, often also pointing using the finger in the process, although for no added effect. When exploring the haptic modality, the participants were observed to prefer holding the arm straight out from the body and use the shoulder joint as the point of rotation. After 10-20 minutes of testing, several participants expressed signs of beginning discomfort with the prolonged raise of the arm.

The novelty of the experience was expressed by all participants, appreciating the tangibility of being able to '*reach out and touch*' the output from the device. The novelty of this interaction and the increased precision of sensing the direction both vertically and horizontally could be a reason for the preference in raising the arm, although this was not specifically questioned. A longitudinal study could potentially be used to minimize the 'novelty effect' commonly seen in studies focusing on sensor-based systems (Sears & Jacko, 2009), to reveal if the more relaxed hands-down style of navigation would eventually be more appreciated in everyday use of navigation.

It was observed on a few occasions, when participants tried to locate points of interest above the horizon level (max 30-degrees above sea level), that this gesture had the unfortunate resemblance of a Nazi salute[13], also noticed during preliminary testing with volunteers. Although the practicality of being able to locate a point of interest in a higher altitude can be questioned and eliminated programmatically (and if need be, other gestures can be used instead), this observation signifies the importance of being aware and concerned with what actions of movement the haptic interface can potentially provoke in users.

The haptic display was also programmed to provide constant stimulation to the wrist, and in a higher intensity to make sure participants with less sensitive skin could also feel the vibrations. However, during the duration of testing, some participants expressed concerns related to vibration fatigue and beginning discomfort. If the display were to be embedded in an actual commercial navigational device, like the watchband of a smartwatch, the vibrations would need to be limited to only when needed and desired—an important consideration for any haptic design.

Challenges in the process of designing the wearable were also observed. For the display to efficiently convey direction stimuli around the wrist, the source of stimuli must be placed sufficiently close to the skin and evenly around the wrist circumference. It must be held in place to avoid offsetting the stimuli, but at the same time not be uncomfortable to wear and accommodate varieties in wrist sizes. The intensity of the haptic output is easily influenced by small changes in pressure towards the skin, indicating that changes in haptic amplitude were less efficient at conveying information than changes in vibration frequency.

The subjectivity of sensing haptics can be difficult to communicate verbally and textually, representing an epistemological challenge of how to understand, organize, and communicate this knowledge. As such, several self-observed findings while constructing, interacting with, and reflecting on the devices build, has resulted in tacit knowledge and experience working with the haptic modality. Experiences and knowledge that is difficult to express and can vary significantly between individuals. Interacting with the haptic prototype must be felt.

This project exemplifies the importance of doing actual and tangible work with haptics (such as in the form of sketches and prototypes) as a medium to convey meanings—a view also shared by (Moussette, 2012; Wensveen & Matthews, 2015; Zimmerman et al., 2007) and others.

[13] https://en.wikipedia.org/wiki/Nazi_salute

Chapter 7

Discussion

Although the focus of this project is on the haptic modality and the potential of a wrist-worn haptic display to stimulate directional guidance, the driving argument for the relevance of this research, has been on personal mobility and pedestrian navigation, as also defined in the research question. The discussion presented here is devoted not only to reflect on the process of this project and the achieved solution and findings but also to reflect on how the process could have been carried out differently.

While working on the haptic display and challenges in how to appropriate it into a wrist-worn wearable, the idea of using virtual points of interest instead of physical real objects or locations was appreciated during the initial design and sketching process. Using this setup, the now strictly virtual points of interest to which the interface would attempt to guide the user towards, now only existed mathematically on the Arduino as angles of rotation in a three-dimensional grid. Using an illusionary point of interest as the target location, it was conceived as if the target was simply out of sight for the moment, and far away, enough that small changes in user movement, such as walking around the room, would not have a meaningful impact on the direction to the target. Changes in hand and arm movement was much more impactful, and thus, that was were the focus of the sketch and prototyping process was. The use of virtual points of interest controlled by the Arduino also meant that they could easily be manipulated programmatically, as was the case in the 'find target' exercise of the user test. This approach to the design leaves the question, of how the study would have gone differently, if more focus was put into exploring changes in location—not only in the user approaching the target but also to explore the effect of the target itself is mobile, e.g., if the target was a person? Considerably more development time and testing would be needed to add the relevant aspect of the location, using location-based services with the prototype. Some aspects of this experience could be faked using Wizard of Oz[14] techniques using an observer to manually control (by the use of a joystick) the direction transmitted to the user wearing the interface, thereby being able to control the user navigating using its output.

Although the aspect of a user's change in location relative to the navigational goal (and handling of intermediary waypoints) is an essential aspect of almost all navigation types, it was considered to be outside the scope of this thesis—something that can hopefully be revisited in another project.

Another aspect of the study that was questioned was the use of the 'string model'-concept (see *5.3.3 Dealing with Wrist Rotations*) for gui-

[14] https://en.wikipedia.org/wiki/Wizard_of_Oz_experiment

ding the expression of the haptic design and overcome the rotation problem. This model presented a convenient solution for conceptualizing directional navigation in three-dimensional space using a uni-dimensional wrist design and without compromising the possibility for sensing two-dimensional directions when the circumference of the wristband is closer to parallel with the ground in a resting position. This model introduced a powerful interaction of being able to both vertically and horizontally detect the direction towards a target that—during the user testing—was observed to dominate over other preferred sensing postures. Even after having conducted the test and observed the efficiency of a user being able to locate a virtual point in space, the question to ask is: Is this information needed for pedestrian navigation purposes? How important is it to know the height above ground level of something you need navigation towards? By imagining a future of potentially improved positioning systems and IoT devices with ambient intelligence and communicating their location, the ability to sense precisely where lost objects have gone missing, or on what shelf in the supermarket the next item on your shopping list is found, could be useful. This application could also be used for more pressing matters, to assist the visually impaired in locating nearby objects, finding avalanche victims under the snow, assist in locating a public defibrillator in a building to help a heart attack victim, assist soldiers sensing the location of someone needing rescue without compromising their visual or auditory senses, etc. It can be questioned whether or not the ability to locate points of interest in three-dimensional space, is an affordance appreciated by pedestrians, or if the concept could have been situated in other contexts, addressing different needs.

Most of the research conducted was confined to the research lab, with the pilot tests and final testing also being conducted in a controlled environment. The artifact was never tested outside this domain, with the unpredictable nature of everyday situations. Moving the research out into the real world could potentially provide insights into how the interaction design could (and should) be embodied in the everyday encounter with "*real users, in real settings, doing real work*" (Dourish, 2001, p. 19). Something that I hope to revisit in a future project.

Chapter 8

Conclusion

By adopting the methodological approach of conducting research through design, and using simple *do-it-yourself* electronics, sensors, components and cheaply available hobby materials, several research artifacts were built and iterated upon, as a means to explore potential answers to the defined project research question. The practice of sketching in software and hardware, and prototyping, was used to create the final design, consisting of a wrist-worn wearable with a haptic interface providing spatial directional stimuli.

To express directional guidance using vibrotactile stimulation on the wrist circumference, the 'string model' approach was used as a conceptual model to guide the interface design. Interacting with the interface provides a tangible and direct manipulation of the haptic expression, to provide the sense of being able to actively reach out and feel the sense of direction around the wrist.

The design was successfully tested in a small-scale user test at the IT University of Copenhagen, with a focus on the displays ability to guide user attention towards a specific direction while compensating for changes in body, arm and wrist rotations. Although the design was unanimously deemed conceivable, usable, and interesting by the test participants, concerns were also raised about prolonged exposure to vibrations and fatigue due to holding the hand raised. Alternative approaches to the research design have been discussed, addressing shortcomings in the scope and focus of the project concerning the broader issues of personal navigation. To this note, further research was suggested, as well as exploring other applications for the design, with a need for real-world location-based testing of the proposed design.

The final design presents an alternative approach to personal mobility that has not yet been sufficiently researched. This approach presents an alternative to the predominantly visual smartphone-based turn-by-turn paradigm. The proposition to using the wrist area for haptic navigational purposes is timely, with the growing popularity of smartwatches, providing a convenient place to embed a haptic display and take advantage of the already available connectivity, sensors, and computation on the wrist. Combining this technology can lead to a truly discreet, private, and unobstructed *sixth sense* navigational experience.

Acknowledgements

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Thanks to the many students and strangers at ITU who volunteered for testing and feedback, and for allowing me to strap silly-looking vibrating electronics on your body.

Last but not least, thanks to Regitze Puck for documenting the process, typesetting and creating the visuals.

[15] AirLab website: https://airlab.itu.dk/

Chapter 9

Literature

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Appendix A

Software Sketch Website

Available online at: https://itu.dk/people/gbro/index.html

Note: Visit the website on a device that has a with motion sensor.

Appendix B

Final Prototype Code

```
/*

 =====================================
 Title: Bachelor Project
 Date: 15. May 2019
 Location: IT University of Copenhagen
 Author: Gabriel Brodersen
 Email: gbro@itu.dk
 =====================================

*/

//https://github.com/ericbarch/arduino-libraries/tree/master/MPU6050
#include <helper_3dmath.h> //Used for calculating quaternion math

//MPU6050 Library:
// I2C device class (I2Cdev) demonstration Arduino sketch for MPU6050 class using DMP (MotionApps v2.0)
// 6/21/2012 by Jeff Rowberg <jeff@rowberg.net>
// Updates should (hopefully) always be available at https://github.com/jrowberg/i2cdevlib

/* ============================================
 I2Cdev device library code is placed under the MIT license
 Copyright (c) 2012 Jeff Rowberg

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 OUT OF OR IN CONNECTION WITH THE SOFTWARE OR THE USE OR OTHER DEALINGS IN
 THE SOFTWARE.
 ===============================================
*/

// I2Cdev and MPU6050 must be installed as libraries, or else the .cpp/.h files
// for both classes must be in the include path of your project
#include "I2Cdev.h"
```

```
#include "MPU6050_6Axis_MotionApps20.h"
//#include "MPU6050.h" // not necessary if using MotionApps
include file

// Arduino Wire library is required if I2Cdev I2CDEV_ARDUI-
NO_WIRE implementation
// is used in I2Cdev.h
#if I2CDEV_IMPLEMENTATION == I2CDEV_ARDUINO_WIRE
#include "Wire.h"
#endif

// class default I2C address is 0x68
// specific I2C addresses may be passed as a parameter here
// AD0 low = 0x68 (default for SparkFun breakout and InvenSense
evaluation board)
// AD0 high = 0x69
MPU6050 mpu;
//MPU6050 mpu(0x69); // <-- use for AD0 high

/* ==========================================================
===============
  NOTE: In addition to connection 3.3v, GND, SDA, and SCL, this
sketch
  depends on the MPU-6050's INT pin being connected to the Ar-
duino's
  external interrupt #0 pin. On the Arduino Uno and Mega 2560,
this is
  digital I/O pin 2.
  ===========================================================
============== */

// See the actual quaternion components in a [w, x, y, z] for-
mat:
#define OUTPUT_READABLE_QUATERNION

#define INTERRUPT_PIN 2 // use pin 2 on Arduino Uno & most boards
#define LED_PIN 13 // (Arduino is 13)
bool blinkState = false;

// MPU control/status vars
bool dmpReady = false; // set true if DMP init was successful
uint8_t mpuIntStatus;  // holds actual interrupt status byte
from MPU
uint8_t devStatus;   // return status after each device opera-
tion (0 = success, !0 = error)
uint16_t packetSize;  // expected DMP packet size (default is
42 bytes)
uint16_t fifoCount;   // count of all bytes currently in FIFO
uint8_t fifoBuffer[64]; // FIFO storage buffer

// orientation/motion vars
Quaternion q;       // [w, x, y, z]     quaternion container
VectorInt16 aa;      // [x, y, z]      accel sensor measurements
VectorInt16 aaReal;   // [x, y, z]      gravity-free accel sen-
sor measurements
VectorInt16 aaWorld;  // [x, y, z]      world-frame accel sen-
sor measurements
VectorFloat gravity;  // [x, y, z]      gravity vector
float euler[3];     // [psi, theta, phi]  Euler angle container,
[x, y, z]
float ypr[3];      // [yaw, pitch, roll]  yaw/pitch/roll contai-
ner and gravity vector
```

```
// ============================================================
======
// ===         INTERRUPT DETECTION ROUTINE         ===
// ============================================================
======

volatile bool mpuInterrupt = false;   // indicates whether MPU
interrupt pin has gone high
void dmpDataReady() {
 mpuInterrupt = true;
}

// ************************************************************
******
// ***            MY PIN MAPS             ***
// ************************************************************
******

//Haptic vibrator power pins:
int hapticPin1 = 11;           //Analog OUT, PWM wave
int hapticPin2 = 10;           //Analog OUT, PWM wave
int hapticPin3 = 9;            //Analog OUT, PWM wave
int hapticPin4 = 6;            //Analog OUT, PWM wave
int hapticPin5 = 5;            //Analog OUT, PWM wave
int hapticPin6 = 3;            //Analog OUT, PWM wave

//Green LED pin:
int greenPin = 8;              //Digital OUT

//Program Toggle button read pin:
int switchPin = 12;            //Using PullUp

//Vibration click button read pin:
int clickPin = 7;              //Using PullUp


// ************************************************************
******
// ***            MY VARIABLES            ***
// ************************************************************
******

//Hold debug integer value read from serial monitor input
boolean calibrateReady = false;      //Set to true after cali-
bration is done
boolean enableVibrate = false;       //Set vibration on/off
boolean vibrateSwitchReady = false;     //Hold vibrate toggle
by button click
const long timeToCalibrate = 5000;     //Default: 20000 millis
(20 seconds to fully calibrate)
boolean clickPinValue;          //Hold click button state: true
= pressed, false = not pressed
int SerialValue;             //Hold Serial input for debugging
int program = 1;             //State 1 = default, state 2 = find
target game

//Alpha (z), Beta (x) and Gamma (y)
double alpha;               //(z-axis)
double beta;               //(x-axis)
double gamma;               //(y-axis)

//Point setup and useful constants
const int points = 6;           //number of points(actuators)
```

```
const int r = 1;              //each points distance to coordi-
nate origin
const double angleBetweenPoints = 360 / points; //AngleBetween-
Points (in degrees)

//Target 3D location (point to direct user towards)
const double defaultTarget[] = {0, r, 0}; //[x, y, z] default
fallback coordinates of target
double target[] = {0, r, 0};       //[x, y, z] coordinates of
target
double offsetX;               //target X offset in degrees
double offsetY;               //target Y offset in degrees
double offsetZ;               //target Z offset in degrees

//To hold new target
double newTarget[] = {target[0], target[1], target[2]};//De-
fault, but will be overwritten

//Actuators Array with points in [x, y, z] coordinates format,
using 6 points (actuators)
double pArray[][3] = {
 {sin(PI / 6), 0, cos(PI / 6)},      //point1 = 30 degree on
Y-plane
 {sin(PI / 2), 0, cos(PI / 2)},      //point2 = 90 degree on
Y-plane
 {sin(5 * PI / 6), 0, cos(5 * PI / 6)}, //point3 = 150 degree
on Y-plane
 {sin(7 * PI / 6), 0, cos(7 * PI / 6)}, //point4 = 210 degree
on Y-plane
 {sin(3 * PI / 2), 0, cos(3 * PI / 2)}, //point5 = 270degree
on Y-plane
 {sin(11 * PI / 6), 0, cos(11 * PI / 6)} //point6 = 330degree
on Y-plane
};

const double pointing[] = {r, 0, 0};   //Point coordinate tow-
ards hand pointing direction
double pArrayPower[points] = {};      //Array to keep track of
power for individual points (0 = off, 100 = 100% power)
double pAllPower;              //Power on all points based on
distance to target (0 = turned off, 100 = full

double angleToTarget;            //Hold value of angle between
target and pointing direction
const int anglePointingPrecision = 10;  //Enter precision of
angle TOWARDS pointing direction (default = 30)
const int angleAwayPrecision = 45;    //Enter precision of ang-
le AWAY FROM pointing direction (default = 45)
const int pTransitionRange = 100;    //Increase power of neig-
hbour actuators when angle moves between points (default 100);
//Note: If range is 0 then actuators share the combined 100%
power when angle is between them (e.g. 50%/50% when target is
exactly between points)
//Note: IF range is 100 then two neighbour actuators can both
have 100% when target is between them


/* VIBRATION CONTROLS */
const int minVibration = 0;         //From 0-255 (up to 50 is
almost undetectable, but makes sounds and can start rotating
with movement)
const int maxVibration = 255;        //From 0-255 (255 is max
vibration power)
const int confirmationDuration = 150;   //Duration to send a
```

```
haptic confirmation pattern (default = 150)
const int maxtimeBetweenVibrationss = 300;    //Set max time
between vibrations (default = 500)
int timeBetweenVibrations;          //Hold current time between
vibrations
boolean confirmationVibration = false;  //True if in verify vi-
bration mode, false if not
long pauseStart;              //Hold time since pause started
long confirmationStart;           //Hold time since confirmation
vibration started


/* BULLSEYE VARIABLES: */
const int bullseyePrecision = 10;     //Enter precision of angle
towards target for Bullseye
const int timeToRegisterBullseye = 500;  //Time in millis user
must stay in Bullseye to register hit (default: 500)
long timeSinceBullseyeStarted;      //Count millis since Bull-
seye started
long timeBeingInBullseye;          //Hold millis duration the
user is pointing within Bullseye

boolean blinking = false;          //Hold if blinking is active
long blinkingDuration;           //Hold time duration in millis
blinking has occured
long timeSinceBlinkingStarted = 99999999; //Hold millis() time
since blinking started

/* Random target offsets for game program */
double randomXAngle;           //Hold random X angle
double randomYAngle;           //Hold random Y angle
double randomZAngle;           //Hold random Z angle
int lastRandomZAngle;           //Hold last random Z angle to
prevent getting the same random target location twice
const int randomVerticalAngle = 30;     //Set rangle for new
random vertical target angle +/- from 0. Default = 30 (60 to-
tal range)
const int randomHorizontalAngle = 60;    //Set minimum hori-
zontal angle +/- from last random target (within 360 degree).
Default = 60 (240 range possible)

//Quaternion objects (using #include helper_3dmath.h):
Quaternion qReadings;
VectorFloat vTarget;


// ==========================================================
======
// ===           INITIAL SETUP           ===
// ==========================================================
======


void setup() {
 // join I2C bus (I2Cdev library doesn't do this automatically)
#if I2CDEV_IMPLEMENTATION == I2CDEV_ARDUINO_WIRE
 Wire.begin();
 Wire.setClock(400000); // 400kHz I2C clock. Comment this line
if having compilation difficulties
#elif I2CDEV_IMPLEMENTATION == I2CDEV_BUILTIN_FASTWIRE
 Fastwire::setup(400, true);
#endif

 // initialize serial communication
 // (115200 chosen because it is required for Teapot Demo out-
```

```
put, but it's
 // really up to you depending on your project)
 Serial.begin(115200);
 while (!Serial); // wait for Leonardo enumeration, others con-
tinue immediately

 // initialize device
 Serial.println(F("Initializing I2C devices..."));
 mpu.initialize();
 pinMode(INTERRUPT_PIN, INPUT);

 // verify connection
 Serial.println(F("Testing device connections..."));
 Serial.println(mpu.testConnection() ? F("MPU6050 connection
successful") : F("MPU6050 connection failed"));

 // wait for ready
 //Serial.println(F("\nSend any character to begin DMP program-
ming and demo: "));
 //while (Serial.available() && Serial.read()); // empty buffer
 //while (!Serial.available());          // wait for data
 //while (Serial.available() && Serial.read()); // empty buffer
again

 // load and configure the DMP
 Serial.println(F("Initializing DMP..."));
 devStatus = mpu.dmpInitialize();

 // supply your own gyro offsets here, scaled for min sensiti-
vity
 // get values by calibrating running this sketch: http://
wired.chillibasket.com/2015/01/calibrating-mpu6050/
 mpu.setXAccelOffset(-77); //Last calibration: -77
 mpu.setYAccelOffset(-3774); //Last calibration: -3774
 mpu.setZAccelOffset(2877); //Last calibration: 2877
 mpu.setXGyroOffset(61); //Last calibration: 61
 mpu.setYGyroOffset(55);  //Last calibration: 55
 mpu.setZGyroOffset(64); //Last calibration: 64

 // make sure it worked (returns 0 if so)
 if (devStatus == 0) {
  // turn on the DMP, now that it's ready
  Serial.println(F("Enabling DMP..."));
  mpu.setDMPEnabled(true);

  // enable Arduino interrupt detection
  Serial.print(F("Enabling interrupt detection (Arduino exter-
nal interrupt "));
  Serial.print(digitalPinToInterrupt(INTERRUPT_PIN));
  Serial.println(F(")..."));
  attachInterrupt(digitalPinToInterrupt(INTERRUPT_PIN), dmpDa-
taReady, RISING);
  mpuIntStatus = mpu.getIntStatus();

  // set our DMP Ready flag so the main loop() function knows
it's okay to use it
 Serial.println(F("DMP ready! Waiting for first interrupt..."));
  dmpReady = true;

  // get expected DMP packet size for later comparison
  packetSize = mpu.dmpGetFIFOPacketSize();
 } else {
  // ERROR!
  // 1 = initial memory load failed
```

```
  // 2 = DMP configuration updates failed
  // (if it's going to break, usually the code will be 1)
  Serial.print(F("DMP Initialization failed (code "));
  Serial.print(devStatus);
  Serial.println(F(")"));
 }

 // configure LED for output
 pinMode(LED_PIN, OUTPUT);

 //Haptic pins:
 pinMode(hapticPin1, OUTPUT);
 pinMode(hapticPin2, OUTPUT);
 pinMode(hapticPin3, OUTPUT);
 pinMode(hapticPin4, OUTPUT);
 pinMode(hapticPin5, OUTPUT);
 pinMode(hapticPin6, OUTPUT);

 //Green LED pin:
 pinMode(greenPin, OUTPUT);

 //Program switch pullup:
 pinMode(switchPin, INPUT_PULLUP);

 //Vibration click pullup:
 pinMode(clickPin, INPUT_PULLUP);

 //Use serial input for debugging. Remove default 1000 delay
after serial read:
 //Serial.setTimeout(0);
}
```

```
// ==========================================================
======
// ===            MAIN PROGRAM LOOP           ===
// ==========================================================
======

void loop() {
 // if programming failed, don't try to do anything
 if (!dmpReady) return;

 // wait for MPU interrupt or extra packet(s) available
 while (!mpuInterrupt && fifoCount < packetSize) {
  if (mpuInterrupt && fifoCount < packetSize) {
   // try to get out of the infinite loop
   fifoCount = mpu.getFIFOCount();
  }

  // OTHER CUSTOM PROGRAM BEHAVIOR STUFF HERE!!
   // ********************************************************
********
  // ***           MY SERIAL INPUT            ***
   // ********************************************************
********
  /*
   //Use serial input for debugging (also uncomment in setup!)
   if (Serial.available()) { //If serial input received:
    SerialValue = Serial.readString().toInt(); //Get full in-
teger
   }
  */
```

```
  // ********************************************************
********
  // ***           VIBRATION CLICK BUTTON         ***
  // ********************************************************
********

  //Set clickPinValue: click button state 1 = pressed and 0 =
not pressed
  digitalRead(clickPin) == LOW ? clickPinValue = true : click-
PinValue = false;

  //Use click button to toggle between vibration on/off
   if (vibrateSwitchReady && clickPinValue) { //If button is
ready to switch and button is clicked
    calibrateReady = true; //Circumvent calibration for quick
start!
   enableVibrate == true ? enableVibrate = false : enableVibra-
te = true; //Toggle vibrations
    vibrateSwitchReady = false; //Prevent additional switches
until click button is released
  } else if (!vibrateSwitchReady && !clickPinValue) { //If but-
ton is not ready and is not being clicked
    vibrateSwitchReady = true; //Make button ready to toggle
vibration on/off
  }

  // ********************************************************
********
  // ***            MY CALIBRATION             ***
  // ********************************************************
********

  if (!calibrateReady) { //Run this while calibration is not
done yet
   if (millis() >= timeToCalibrate) { //Run after calibration
    calibrateReady = true; //Calibration done
    //enableVibrate = true; //enable vibrations
    Serial.println("CALIBRATION DONE!");
   } else { //Blink until calibration is finished
    if (millis() % 100 >= 50) {
     digitalWrite(greenPin, HIGH); //ON green LED
    } else {
     digitalWrite(greenPin, LOW); //OFF green LED
    }
    Serial.print("Please wait: ");
    Serial.println(int((timeToCalibrate - millis()) / 1000));
   }
  }


  // ********************************************************
********
  // ***            MY PROGRAM LOOP           ***
  // ********************************************************
********

  if (calibrateReady) { //Only run main program if calibration
is done!

   //Check switching between programs:
   if (digitalRead(switchPin) == HIGH) { //if switchPin is HIGH
    if (program == 2) { //Reset coming from program 2
     blinking = false; //Reset/Cancel blinking
```

```
      lastRandomZAngle = 0; //Reset target last z angle
       resetTarget(); //Reset target [x, y, z] to default when
switching program
      digitalWrite(greenPin, LOW); //Reset green LED
      Serial.println("Switched to program 1");
     }
     program = 1; //Switch program to 1: DEFAULT
    } else { //Else if switchPin is LOW
     if (program == 1) { //Reset coming from program 1
      blinking = false; //Reset/Cancel blinking
      lastRandomZAngle = 0; //Reset target last z angle
       resetTarget(); //Reset target [x, y, z] to default when
switching program
      digitalWrite(greenPin, LOW); //Reset green LED
      Serial.println("Switched to program 2");
     }
     program = 2; //Switch program to 2: GAME
    }

   //Run main update loop! Update vibrator and pin values each
cycle with main update function:
   update();

  } //End main program loop

   // *******************************************************
********
  // ***           END PROGRAM LOOP          ***
   // *******************************************************
********
  // END OTHER CUSTOM PROGRAM BEHAVIOR STUFF HERE!!

   // if you are really paranoid you can frequently test in bet-
ween other
   // stuff to see if mpuInterrupt is true, and if so, "break;"
from the
   // while() loop to immediately process the MPU data

 }

 // reset interrupt flag and get INT_STATUS byte
 mpuInterrupt = false;
 mpuIntStatus = mpu.getIntStatus();

 // get current FIFO count
 fifoCount = mpu.getFIFOCount();

 // check for overflow (this should never happen unless our code
is too inefficient)
 if ((mpuIntStatus & _BV(MPU6050_INTERRUPT_FIFO_OFLOW_BIT)) ||
fifoCount >= 1024) {
   // reset so we can continue cleanly
   mpu.resetFIFO();
   fifoCount = mpu.getFIFOCount();
   Serial.println(F("FIFO overflow!"));

   // otherwise, check for DMP data ready interrupt (this should
happen frequently)
 } else if (mpuIntStatus & _BV(MPU6050_INTERRUPT_DMP_INT_BIT))
{
   // wait for correct available data length, should be a VERY
short wait
   while (fifoCount < packetSize) fifoCount = mpu.getFIFOCount();
```

```
  // read a packet from FIFO
  mpu.getFIFOBytes(fifoBuffer, packetSize);

  // track FIFO count here in case there is > 1 packet available
  // (this lets us immediately read more without waiting for
an interrupt)
  fifoCount -= packetSize;

#ifdef OUTPUT_READABLE_QUATERNION
  // display quaternion values in easy matrix form: w x y z
  mpu.dmpGetQuaternion(&q, fifoBuffer);

  //Read raw quaternion target values:
  //  Serial.print("quat\t");
  //  Serial.print(q.w);
  //  Serial.print("\t");
  //  Serial.print(q.x);
  //  Serial.print("\t");
  //  Serial.print(q.y);
  //  Serial.print("\t");
  //  Serial.println(q.z);

  //Get readings as a quaternion
  qReadings.w = q.w;
  qReadings.x = -q.x;
  qReadings.y = -q.y;
  qReadings.z = -q.z;

  //Get target vector point coordinates
  vTarget.x = target[0];
  vTarget.y = target[1];
  vTarget.z = target[2];

  vTarget = vTarget.getRotated(&qReadings); //Rotate vector by
quaternion

  //Set new target coordinates by recalculated vector
  newTarget[0] = vTarget.x;
  newTarget[1] = vTarget.y;
  newTarget[2] = vTarget.z;


  //Read new target values:
  //  Serial.print("target\t");
  //  Serial.print(newTarget[0]);
  //  Serial.print("\t");
  //  Serial.print(newTarget[1]);
  //  Serial.print("\t");
  //  Serial.print(newTarget[2]);
  //  Serial.println("\t");

  //Read individual vibrator values:
  //  Serial.print(pArrayPower[0]);
  //  Serial.print("\t");
  //  Serial.print(pArrayPower[1]);
  //  Serial.print("\t");
  //  Serial.print(pArrayPower[2]);
  //  Serial.print("\t");
  //  Serial.print(pArrayPower[3]);
  //  Serial.print("\t");
  //  Serial.print(pArrayPower[4]);
  //  Serial.print("\t");
  //  Serial.print(pArrayPower[5]);
  //  Serial.println("\t");
```

```
#endif

  // blink LED to indicate activity
  blinkState = !blinkState;
  digitalWrite(LED_PIN, blinkState);
 }
}


// ***********************************************************
******
// ***            MY FUNCTIONS            ***
// ***********************************************************
******

/* UTILITY FUNCTIONS: */
/* ------------------ */

//Function to return positive degrees between angles on same
plane
double disBetweenAngles(double circleAngle, double targetAng-
le) {
 int x = (int(circleAngle - targetAngle + 180)) % 360 - 180;
 x = x < -180 ? x + 360 : x;
 return abs(x);
}

//Function to measure distance between points a[x,y,z] and
b[x,y,z]
double disBetweenPoints(double a[], double b[]) {
 double x1 = a[0],
     y1 = a[1],
     z1 = a[2],
     x2 = b[0],
     y2 = b[1],
     z2 = b[2];
 return sqrt(pow(x2 - x1, 2) + pow(y2 - y1, 2) + pow(z2 - z1,
2));
}

//Function to convert degrees to radian
double degToRad(double deg) {
 return deg * PI / 180;
}

//Function to convert radian to degrees
double radiansToDegrees(double radianVal) {
 return radianVal * (180 / PI);
}


/* CORE FUNCTIONS: */
/* --------------- */

//Function to rotate target xyz coordinate using euler angles
void rotateWithEuler(double pitch, double roll, double yaw) {
 pitch = degToRad(pitch);
 roll = degToRad(roll);
 yaw = degToRad(yaw);
 double cosa = cos(yaw);
 double sina = sin(yaw);

 double cosb = cos(pitch);
 double sinb = sin(pitch);
```

```
 double cosc = cos(roll);
 double sinc = sin(roll);

 double Axx = cosa * cosb;
 double Axy = cosa * sinb * sinc - sina * cosc;
 double Axz = cosa * sinb * cosc + sina * sinc;

 double Ayx = sina * cosb;
 double Ayy = sina * sinb * sinc + cosa * cosc;
 double Ayz = sina * sinb * cosc - cosa * sinc;

 double Azx = -sinb;
 double Azy = cosb * sinc;
 double Azz = cosb * cosc;

 double px = defaultTarget[0];
 double py = defaultTarget[1];
 double pz = defaultTarget[2];

 target[0] = Axx * px + Axy * py + Axz * pz;
 target[1] = Ayx * px + Ayy * py + Ayz * pz;
 target[2] = Azx * px + Azy * py + Azz * pz;

 // Serial.print("New x: ");
 // Serial.print(target[0]);
 // Serial.print(", y: ");
 // Serial.print(target[1]);
 // Serial.print(", z: ");
 // Serial.println(target[2]);
}
```

```
//Angle in degrees between vectors of two points:
double angleBetweenVectors(double xyz1[3], double xyz2[3]) {
 double xyz1new[] = {xyz1[0], xyz1[1], xyz1[2]};
 double xyz2new[] = {xyz2[0], xyz2[1], xyz2[2]};
 double x1 = xyz1[0];
 double y1 = xyz1[1];
 double z1 = xyz1[2];
 double x2 = xyz2[0];
 double y2 = xyz2[1];
 double z2 = xyz2[2];
 double origin[] = {0, 0, 0};
 double length1 = disBetweenPoints(xyz1new, origin);
 double length2 = disBetweenPoints(xyz2new, origin);
 if (length1 * length2 == 0) { //Avoid zero division
  length1 = 0.01;
  length2 = 0.01;
 }
 return radiansToDegrees(acos((x1 * x2 + y1 * y2 + z1 * z2) /
(length1 * length2)));
}

//Calculate power value for each individual point based on
their angle to target on z plane:
void calculateDirectionalPower(double theTarget[]) {

 //Set individual power level for each point
 for (int i = 0; i < points; i++) {

  //Calculate angle between pointing axis and targets x and y
position
   double targetXAngle = radiansToDegrees(atan2(theTarget[1],
theTarget[2])); //NOTE: atan2() takes (y,x) not (x,y)
```

```
  //Calculate angle between targetXAngle and angle of point
p[i], which is i * AngleBetweenPoints
  double targetAngleToPoint = disBetweenAngles(targetXAngle, i
* angleBetweenPoints);

  //Set individual point power (pArrayPower[i]) based on de-
grees between point and target on z-plane
  //pArrayPower[i] = targetAngleToPoint < angleBetweenPoints
? map(targetAngleToPoint, 0, angleBetweenPoints, 100, 0) : 0;
  pArrayPower[i] = targetAngleToPoint < angleBetweenPoints ?
map(targetAngleToPoint, 0, angleBetweenPoints, 100 + pTransi-
tionRange, 0) : 0;
  pArrayPower[i] = constrain(pArrayPower[i], 0, 100);

 }
}


//Set all points power to parameter value (used for confirmation
blinking)
void setPowerForAllPoints(boolean onOrOff) {

 int value = 0;

 if (enableVibrate) { //Only set 'value' if enableVibrate is
true
  onOrOff ? value = maxVibration : value = minVibration;
 }

 analogWrite(hapticPin1, value);
 analogWrite(hapticPin2, value);
 analogWrite(hapticPin3, value);
 analogWrite(hapticPin4, value);
 analogWrite(hapticPin5, value);
 analogWrite(hapticPin6, value);

}

void resetTarget() {
 target[0] = defaultTarget[0]; //Reset target x value to de-
fault;
 target[1] = defaultTarget[1]; //Reset target y value to de-
fault;
 target[2] = defaultTarget[2]; //Reset target z value to de-
fault;
}


//Function to check for Bullseye (hitting target long enough)
and how to signal that to the user with vibrations
void checkBullseye(double angleBetweenTargetAndPointer) {

 //Check for Bullseye hit
 if (blinking == false) { //Only check if not already blinking

  //Checking if Bullseye:
  if (angleBetweenTargetAndPointer <= bullseyePrecision) {
   //Serial.print("hitting! ");
   if (timeSinceBullseyeStarted == 99999999) {
    timeSinceBullseyeStarted = millis();
   }
   timeBeingInBullseye = millis() - timeSinceBullseyeStarted;
   //Serial.println(timeBeingInBullseye);
```

```
  } else { //If not within Bullseye range
   timeBeingInBullseye = 0; //Reset time in Bullseye
    timeSinceBullseyeStarted = 99999999; //Reset time since
Bullseye
  }

  //Check if user stayed in Bullseye long enough (more than
'timeToRegisterBullseye' setting)
  if (timeBeingInBullseye >= timeToRegisterBullseye) {
   blinking = true;
  }
 }

 //If Bullseye hit long enough and is ready to blink (blinking
= true) -> start vibration pattern
 if (blinking == true) {

  //Control time of blinking
  if (timeSinceBlinkingStarted == 99999999) {
   timeSinceBlinkingStarted = millis();
  }
  blinkingDuration = millis() - timeSinceBlinkingStarted;

  //Set vibration pattern:
  if (blinkingDuration < 500) { //Pause before confirmation
   setPowerForAllPoints(false);
  } else if (blinkingDuration < 700) {
   setPowerForAllPoints(true);
  } else if (blinkingDuration < 800) {
   setPowerForAllPoints(false);
  } else if (blinkingDuration < 1000) {
   setPowerForAllPoints(true);
  } else if (blinkingDuration < 1500) {
   setPowerForAllPoints(false);
  } else if (blinkingDuration < 1700) {
   setPowerForAllPoints(true);
  } else if (blinkingDuration < 1800) {
   setPowerForAllPoints(false);
  } else if (blinkingDuration < 2000) {
   setPowerForAllPoints(true);
  } else if (blinkingDuration < 2500) { //Final pause before
new point
   setPowerForAllPoints(false);
  } else { //End vibration pattern and reset values

   Serial.print("Before X: ");
   Serial.print(target[0]);
   Serial.print(", Y: ");
   Serial.print(target[1]);
   Serial.print(", Z: ");
   Serial.println(target[2]);

   //Reset target
   resetTarget(); //Reset target [x, y, z] to default values

   //Set new random target
   randomXAngle = random(-1*randomVerticalAngle, randomVerti-
calAngle);  //Find random vertical angle between 60 degree
   randomYAngle = 0; //Not used
   randomZAngle = int((lastRandomZAngle + randomHorizontalAngle
+ random(0, 360-(2*randomHorizontalAngle))) % 359); //Shifting
new random angle based on previous angle
   lastRandomZAngle = randomZAngle; //Keep track of last angle
```

```
  //Print new values for new target position
  //  Serial.print("Angle X: ");
  //  Serial.print(randomXAngle);
  //  Serial.print(", Y: ");
  //  Serial.print(randomYAngle);
  //  Serial.print(", Z: ");
  //  Serial.println(randomZAngle);

   rotateWithEuler(randomYAngle, randomXAngle, randomZAngle);
//Takes angles for Y, X, Z (in that order)

  timeSinceBlinkingStarted = 99999999;
  blinkingDuration = 0;
  blinking = false;

  Serial.print("After X: ");
  Serial.print(target[0]);
  Serial.print(", Y: ");
  Serial.print(target[1]);
  Serial.print(", Z: ");
  Serial.println(target[2]);

 }
 }
}


/* CORE UPDATE FUNCTION */
void update() {

 //Measure angle to pointing direction:
 angleToTarget = angleBetweenVectors(pointing, newTarget);
 //Serial.println(angleToTarget);

 //Check Bullseye and run Bullseye vibration feature. If Bull-
seye blinking is false, then do the below code:
 if (program == 1) {
  if (angleToTarget <= bullseyePrecision) {
   digitalWrite(greenPin, LOW); //Signal program 1 by ON green
LED unless bullseye
  } else {
   digitalWrite(greenPin, HIGH); //If bullseye, turn LED off
  }
 } else if (program == 2) {
  checkBullseye(angleToTarget); //Signal program 2 by OFF green
LED unless bullseye
 }



 if (blinking == false) {
  //Power on/off on all actuators based on proximity to target:
  if (angleToTarget <= bullseyePrecision) { //Bullseye! if ang-
le is less than precision tolerance
   pAllPower = 40;
  } else {
   if (angleToTarget <= anglePointingPrecision) {
    //pAllPower = pow(map(angleToTarget, 0, anglePointingPre-
cision, pow(100, 0.333333333), 0), 3); //exponential^3
   } else if (180 - angleToTarget <= angleAwayPrecision) {
    pAllPower = -1 * pow(map(180 - angleToTarget, 0, angleAway-
Precision, 100, 0), 1); //exponential^1
   } else {
    pAllPower = 0;
```

```
   }
  }


  //Calculate power value based to distance to newTarget
  calculateDirectionalPower(newTarget);

  //Add pAllPower to all points individual points power in pAr-
rayPower[points], and constrain to max 100% power
  for (int i = 0; i < points; i++) { //points = number of ac-
tuators
    pArrayPower[i] = constrain(pArrayPower[i] + pAllPower, 0,
100);
  }


  //Control vibration pattern based on angle to target:
  timeBetweenVibrations = map(angleToTarget, 0, 180, 0, maxti-
meBetweenVibrationss);

  //Set vibrator pin values:
  if (!confirmationVibration || !enableVibrate) { //Disable vi-
brations

    digitalWrite(hapticPin1, 0); //Off
    digitalWrite(hapticPin2, 0); //Off
    digitalWrite(hapticPin3, 0); //Off
    digitalWrite(hapticPin4, 0); //Off
    digitalWrite(hapticPin5, 0); //Off
    digitalWrite(hapticPin6, 0); //Off

    if (millis() - confirmationStart >= timeBetweenVibrations) {
      confirmationVibration = true;
      pauseStart = millis();
    }
  } else if (confirmationVibration == true && enableVibrate ==
true) { //If vibrating AND enableVibrate is true

    analogWrite(hapticPin1, map(pArrayPower[0], 0, 100, minVi-
bration, maxVibration));
    analogWrite(hapticPin2, map(pArrayPower[1], 0, 100, minVi-
bration, maxVibration));
    analogWrite(hapticPin3, map(pArrayPower[2], 0, 100, minVi-
bration, maxVibration));
    analogWrite(hapticPin4, map(pArrayPower[3], 0, 100, minVi-
bration, maxVibration));
    analogWrite(hapticPin5, map(pArrayPower[4], 0, 100, minVi-
bration, maxVibration));
    analogWrite(hapticPin6, map(pArrayPower[5], 0, 100, minVi-
bration, maxVibration));


    if (millis() - pauseStart >= confirmationDuration) {
      confirmationVibration = false;
      confirmationStart = millis();
    }
  }
 }

 //Light green LED on or off when pointing in or out of bullseye,
depending on program:
 blinking ? digitalWrite(greenPin, HIGH) : digitalWrite(green-
Pin, LOW);
}
```

Appendix C

Interview Guide

Note: The interview guide has been translated from Danish to English

Test no.: ________________

Date: ________________

Name: ________________

1) Briefing

The test takes around 10 minutes to complete. My bachelor thesis aims at understanding how vibrations (haptic feedback) in a bracelet (for example the strap of a smartwatch) can give the user a better sense of direction with regards to objects nearby you. Thus, by excluding information from screens or sound I wish to research if only vibrations can make people sense a direction.

What is your previous experience with haptic feedback and equipment using vibrations? For example, vibrations in your smartphone, a joystick, etc.?

2) Give the test person the bracelet on

Explain shortly the test person about the construction of the prototype with regard to the vibrations through using six vibrators around the wrist. In addition, that the vibrations changes depending on the direction of the persons wrist. The test person is asked to stand within a specific area and can try moving his or her body and arms freely around, however without moving from the area in the room. After a while, when the test person has a sense of how it works, move on to step 3.

3) Questions

What do you experience?

How does it feel?

Through moving your hand, can you sense the direction that the bracelet guides you towards?

____

____

____

____

If you hold your hand straight and rotate it, can you then sense the direction?

____

____

____

____

If you try holding your hand down by your body and holds this bag while walking around in the room (away from the specific area), can you then sense the direction?

____

____

____

____

Finally, if you try holding this telephone as if you were speaking in it, can you then sense the direction?

____

____

____

____

4) Find Direction Exercise

Finally, I want you to try out a challenge. I switch to another program that generates random directions that you will need to locate. Every time you locate a direction, you will feel a confirming vibration, and then a new random direction is generated that you need to find.

Try to locate 10 directions.

First, you get to feel what I mean about generation of a new direction. When you are comfortable with the confirmation vibration let me know—then we start after the next confirmation you hit.

Note to oneself: Save screenshots of the stopwatch.

5) Debriefing

In general, what do you think about the experience of using haptics to sense a direction?

Did you find it difficult to locate the directions?

Do you feel tired in your wrist or mentally after the challenge I gave you? How do you feel right now?

Thank you for your participation!

Appendix D

User Test Data

	Round 1	Round 2	Round 3	Round 4	Round 5	Round 6	Round 7	Round 8	Round 9	Round 10
Tester #1	**10,8**	**9,7**	**12,7**	**10,0**	**11,2**	**11,6**	**11,4**	**9,5**	**17,7**	**10,9**
Tester #2	**14,7**	**13,3**	**8,5**	**5,7**	**12,5**	**10,5**	**9,4**	**6,1**	**7,1**	**14,3**
Tester #3	**16,2**	**18,7**	**15,7**	**15,2**	**11,8**	**10,2**	**10,6**	**18,9**	**8,3**	**11,0**
Tester #3	**6,9**	**6,6**	**7,3**	**7,0**	**7,9**	**6,5**	**19,2**	**5,9**	**10,3**	**9,3**
Tester #4	**19,9**	**22,9**	**16,9**	**16,6**	**14,1**	**20,5**	**17,8**	**10,3**	**9,9**	**14,3**
Tester #5	**8,1**	**8,3**	**15,8**	**8,8**	**9,5**	**12,7**	**7,5**	**17,1**	**9,2**	**7,1**
Tester #6	**6,1**	**13,8**	**13,7**	**8,9**	**7,2**	**7,6**	**10,2**	**9,2**	**7,8**	**16,2**
Tester #7	**19,1**	**6,4**	**8,3**	**14,7**	**12,7**	**8,6**	**12,3**	**8,9**	**6,9**	**5,9**
Tester #8	**10,6**	**16,1**	**14,8**	**8,1**	**15,7**	**6,9**	**9,0**	**6,6**	**10,0**	**9,3**
Tester #9	**10,9**	**10,9**	**9,3**	**7,8**	**7,6**	**15,7**	**8,0**	**9,8**	**12,7**	**8,7**
Average	**12,3**	**12,7**	**12,3**	**10,3**	**11,0**	**11,1**	**11,5**	**10,2**	**10,0**	**10,7**
SD	**4,7**	**5,1**	**3,4**	**3,6**	**2,7**	**4,1**	**3,8**	**4,2**	**3,0**	**3,2**