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Tilt-Watch: Inclination-Based Smartwatch Input in Relation to the Forearm

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Contents

Abstract xiii

Überblick xv

Acknowledgements xvii

Conventions xix

1 Introduction 1

2 Related Work 5

- 2.1 Interaction Challenges of Smartwatches . . . 5
- 2.2 Smartwatch Input Techniques 7
- 2.3 Inclination-Based Input 8

3 Tilt-Watch: Design And Implementation 11

- 3.1 Hardware Prototyping 11
  - 3.1.1 Sensor Selection 12

3.1.2 How Tilt-Watch Measures Inclinaton . 13

3.1.3 Tilt-Watch as Apple Watch Case . . . 15

3.1.4 Proof of Concept 16

3.1.5 Sensor Arrangement 18

3.1.6 Designing the Final Prototype 19

3.2 Software Implementation 21

3.2.1 Data Recording and Transfer 21

3.2.2 Calculating Inclination with Distance 23

4 Study: Maximum Degree of Inclination 25

4.1 Experimental Design 25

4.2 Participants 26

4.3 Apparatus 26

4.4 Study Procedure 26

4.5 Measurements 28

4.6 Results 28

4.6.1 Maximum Inclination 29

4.6.2 Does Firmness Matter? 30

4.6.3 Ease of Tilt 30

4.7 Discussion and Implications 31

4.8 Limitations 33

5 Preliminary Investigation: Performance During Movement 35
5.1 Measurements 36
5.2 Results 36
5.3 Discussion 37

6 Tilt-Watch Interaction Design 39
6.1 Inclination-Based Smartwatch Input 39
6.2 Tilt-Watch Applications 40

7 Summary and Future Work 43
7.1 Limitations of Tilt-Watch 43
7.2 Summary and Contributions 44
7.3 Future Work 45
  7.3.1 Improving the Prototype 45
  7.3.2 Future User Studies 46
  7.3.3 Further Interaction Possibilities 47

A User Study Questionaire 49

B Apple Watch Usage Guide 53

Bibliography 55

Index 63

List of Figures

2.1 Input modalities on smartwatches 7

3.1 Proof of concept schematics and picture . . . 17
3.2 Proof of concept worn on the wrist 18
3.3 PCB design for the rangefinders 19
3.4 Picture of Tilt-Watch including PCB connected to the ESP32 20
3.5 Bluetooth Low Energy stack on ESP32 22
3.6 Tilt-Watch raw sensor values for one inclination 24

4.1 Setup for userstudy 27
4.2 Average maximum inclination 29
4.3 Watchstrap firmness and average maximum inclination 30
4.4 Ease of tilt for eight directions 31

6.1 Demonstrator applications 40

A.1 User study questionnaire page 1 50
A.2 User study questionnaire page 2 51

B.1 Apple Watch usage guide 54

List of Tables

2.1 Related work smartwatch input space 9

5.1 Spreading per direction during movement . 36

Abstract

Smartwatches have gotten smaller over the past years, increasing wearing comfort but at the same time posing challenges in terms of human-computer interaction. Direct input via the touchscreen suffers from limited interaction space, content occlusion and the fat finger problem. Physical input modalities on smartwatches such as buttons or rotating crowns provide effortless and intuitive input, but only have limited expressiveness. Buttons only provide binary input and rotating crowns only provide one-dimensional input.

In this thesis, we present a novel input modality that enables two-dimensional continuous input while still providing an unrestricted view of the screen. Our proposed *Tilt-Watch* measures the distance of the smartwatch towards the wrist at nine points with which an algorithm calculates the inclination in two dimensions.

Previous research on inclination-based input on mobile devices found that users could accurately control the inclination and found it intuitive. To our knowledge, the presented implementation of inclination-based smartwatch input in relation to the forearm has not been explored already. Using a physical prototype that we produced, we were able to evaluate the proposed interaction in a user study. The study found that, on average, participants tilted the smartwatch to a maximum of 25 degrees and preferred tilting over the sides, rather than the corners. Feedback in the user study was generally positive and users quickly understood the interaction. Based on the study, we give design guidelines for future prototypes. Additionally, we implemented two applications to demonstrate the new input capabilities of *Tilt-Watch*.

Überblick

Smartwatches sind in den letzten Jahren immer kleiner geworden. Dadurch wurde zwar der Tragekomfort erhöht, gleichzeitig entstanden jedoch neue Herausforderungen in Bezug auf die Mensch-Computer-Interaktion. Die direkte Eingabe über den Touchscreen leidet unter dem kleinen Interaktionsraum, der Verdeckung des Inhaltes und dem *Fat-Finger-Fehler*. Physische Eingabemöglichkeiten an Smartwatches wie Tasten oder Kronen bieten eine einfache und intuitive Eingabe, haben aber nur eine begrenzte Ausdrucksstärke: Tasten ermöglichen nur binäre und Kronen nur eindimensionale Eingabe.

In dieser Arbeit stellen wir eine neue Eingabemodalität vor, die eine zweidimensionale, kontinuierliche Eingabe ermöglicht und dabei gleichzeitig eine uneingeschränkte Sicht auf den Bildschirm bietet. Unsere *Tilt-Watch* misst an neun Punkten den Abstand der Smartwatch zum Handgelenk und berechnet daraus die Neigung in zwei Dimensionen.

Frühere Forschung zur neigungsbasierten Eingabe auf mobilen Geräten ergab, dass die Benutzer die Neigung genau steuern konnten und sie als intuitiv empfanden. Unseres Wissens wurde die vorgestellte Implementierung der neigungsbasierten Smartwatch-Eingabe in Relation zum Unterarm bisher noch nicht untersucht. Anhand eines von uns hergestellten physischen Prototyps konnten wir die vorgestellte Interaktion in einer Nutzerstudie evaluieren. Die Studie ergab, dass die Teilnehmer die Smartwatch im Durchschnitt um maximal 25 Grad neigten und die Neigung zu den Seiten der Neigung über die Ecken bevorzugten. Das Feedback zu der neuen Eingabemodalität war generell positiv und die Benutzer haben die Interaktion schnell verstanden. Basierend auf der Studie geben wir Gestaltungsrichtlinien für zukünftige Prototypen vor. Außerdem implementierten wir zwei beispielhaften Anwendungen, mit denen wir die neuen technischen Möglichkeiten der *Tilt-Watch* demonstrieren.

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Conventions

Throughout this thesis we use the following conventions.

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

Definition:
Definitions

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

`myClass`

The whole thesis is written in American English. The first person is written in the plural form. Unidentified third persons are described in female form.

Chapter 1

Introduction

A smartwatch is a wrist-mounted wearable computing device that provides capabilities akin to a smartphone. Smartwatches are mainly used for quick information checks and allow the user to decide whether to switch to the smartphone for more details [Chun et al., 2018]. In addition to its technical utility, most people perceive smartwatches as both technology and fashion-like [Chuah et al., 2016]. An indicator for the popularity of smartwatches is presented by Strategy Analytics[1] , who compiled sale estimates and found that Apple sold more watches in 2019 than the entire Swiss watch industry combined.

Smartwatches are popular both in technology and fashion

Smartwatches have gotten smaller over the past years [Ni and Baudisch, 2009], increasing wearing comfort but at the same time posing challenges in terms of human-computer interaction: Direct touch input is intuitive and easy to use, but the interaction space is limited and the finger occludes a big portion of the small screen. Additionally, the interaction should be as efficient as possible to avoid the user having to hold up the watch longer than absolutely necessary. To expand the interaction space of smartwatches beyond touch-based interactions, current consumer devices often provide physical input modalities like buttons or rotating knobs on

Current smartwatch interaction has drawbacks

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[1] `https://news.strategyanalytics.com/press-releases/press-release-details/2020/Strategy-Analytics-Apple-Watch-Outsells-the-Entire-Swiss-Watch-Industry-in-2019` (Accessed: January 18, 2021)

the frame of the device. Furthermore, smartwatches are capable of offering voice input. However, physical input modalities have limited interaction expressiveness as they only provide binary input (e.g. button pressed or button not pressed) or one-dimensional input (e.g. crown turned clockwise for 1 second). Voice input on the other hand, can be expressive and efficient, but is not socially appropriate in many situations [Starner, 2002].

Displacement of smartwatch is used as input

In addition to the described interaction techniques, researchers have investigated alternatives to expand the input expressivity of smartwatches. Prototypes were built that utilize the physical displacement of parts of the watch or the whole watch on the arm as an input technique. Researchers complement existing inputs with omnidirectional panning, rotating as well as tilting of the display in relation to the body of the smartwatch [Xiao et al., 2014]. Displacing the whole smartwatch in relation to the arm was also investigated [Yeo et al., 2016]. For this interaction, the researchers use the integrated sensors of an existing smartwatch to detect omnidirectional panning and bi-directional twisting of the watch body. Nevertheless, the prototype only registers input when touching the screen and consequently some content will be occluded.

Inclination of smartwatch is used as input

Apart from displacement, inclination-based input on smartwatches was investigated to implement a space-saving keyboard [Götzelmann and Vázquez, 2015]. Here, the metaphor of gravity is used to select a letter by tilting the wrist and raising or lowering the elbow. This movement changes the inclination of the smartwatch. A user, then, has to tap on the screen to enter the currently selected letter.

Tilt-Watch enables inclination-based input in relation to the forearm

When already using both hands for the interaction, we imagined an input technique where one uses the second hand to manipulate the inclination of the watch, rather than moving the arm. In this work we present a novel input modality aimed to enable two-dimensional continuous input while still providing unrestricted visibility of the screen: Our proposed Tilt-Watch translates the inclination of the smartwatch in relation to the forearm to a continuous value input.

We built a prototype that uses nine photo-reflective rangefinders to measure the distance from the sensors on the back of the watch to the wrist, calculating the inclination of the watch. These sensors are built into a 3D printed case, that also encapsulates an Apple Watch to enable visual, auditory and haptic feedback. One of these rangefinders only measures 3×4 mm and are inexpensive, which allows to realize an array inside Tilt-Watch. We measure the distance toward the arm, instead of using the gyroscope to detect inclination in our prototype, leading to a more robust system against external movements like the slight up and down movements of the arm when walking.

Inexpensive photoelectric sensors are used to compute the inclination

We also conducted an initial user study to examine limitations like the maximum degree of comfortable inclination. Furtheremore, we discuss our insights from these studies, our plan for future improvements and future evaluations of our Tilt-Watch prototype. Also, we demonstrate the capabilities with two example applications built around the proposed interaction technique. In the first application, the inclination of the smartwatch is used as a two-dimensional remote control that can be used eyes-free. The second application demonstrates direct manipulation of onscreen content by implementing a marble balancing game.

We investigated limitations and built demonstrator applications

This work is structured as follows: In Chapter 2 an overview on user input on smartwatches is given and linked to the proposed inclination-based input. The design process of Tilt-Watch is presented in Chapter 3. After that, Chapter 4 presents an investigating into the maximum degree of inclination that was explored in a user study. Chapter 5 briefly presents a preliminary investigation into the performance of Tilt-Watch during movement. Chapter 6 explains the interaction design of Tilt-Watch in detail. Here, demonstrator applications are presented. Finally, in Chapter 7 we conclude the thesis and present limitations. We close the chapter with a discussion on what work could be done in the future.

Chapter 2

Related Work

In the following chapter we present the existing literature on smartwatch input. In the first section, we describe the unique interaction challenges of smartwatches. After this, a general overview is given of how researchers have been trying to solve these and come up with new, expressive input modalities. The last section focuses on research that specifically uses the inclination of the device as input.

2.1 Interaction Challenges of Smartwatches

Regarding output, available smartwatches already implement visual feedback via the screen, auditory feedback via loudspeakers as well as haptic feedback via vibration motors or linear actuators. However, looking at user input on smartwatches, the small form factor presents challenges in terms of human-computer interaction: Occlusion, *the fat finger problem* and limited expressiveness.

Occlusion is inevitable when operating a touchscreen

When operating a touchscreen, there will inevitably be occlusion. This is due to a direct manipulation of the on-screen content using your fingers, as opposed to a small, indirect target device like a mouse pointer. On smartwatches, the effect is intensified because screen diagonals often measure less than 5 cm [Baudisch and Chu, 2009]. Thus, a big portion of the screen is occluded when selecting a target which is not close to the edges of the screen.

Fat finger problem describes the decrease in selection accuracy for small targets in touch input

Another problem, which is directly connected to occlusion, is the *fat finger problem*, first explained by Siek et al. [2005]. During a button press task on touchscreen PDA devices, participants worried about pushing multiple targets at the same time because of the small target size in comparison to the size of the tip of the finger. Apart from occlusion, the *the fat finger problem* refers to a decrease in selection accuracy when the target is smaller than the fingertip. The problem can be illustrated best with the example of text input via an onscreen keyboard: On the diminutive display of a smartwatch, one has to estimate where exactly to press for a letter because the finger occludes multiple letters at a time and visual feedback is available only after selecting it.

Physical input modalities have limited expressiveness

Although high-resolution display technology, loudspeakers and sophisticated haptic engines allow for expressive output, input techniques are still limited in expressiveness. Despite the fact that touchscreens provide two-dimensional input, they suffer from problems as stated above. Because of this, current consumer devices often provide physical input modalities like buttons, rotating crowns or rotating bezels on the frame of the watch. Unfortunately, these input modalities have limited expressiveness: Buttons only have binary input (i.e. button pressed, button not pressed) and rotating crowns or bezels only have one-dimensional input (e.g. turned clockwise for 20 degree). In addition to that, physical input modalities on smartwatches are almost always reserved for system-wide functionalities (e.g. switching between applications, activating contactless payments) and thereby cannot be used for more general purpose input inside applications.

Another interaction challenge for smartwatches is mobility. Mobile devices can be used in various situations and are often operated while being on the move. However, when using a smartwatch on the move, one has to divide the attention between the environment and the device. Therefore, mobility restricts interaction with the smartwatch. Oulasvirta et al. [2005] investigate the cognitive resource

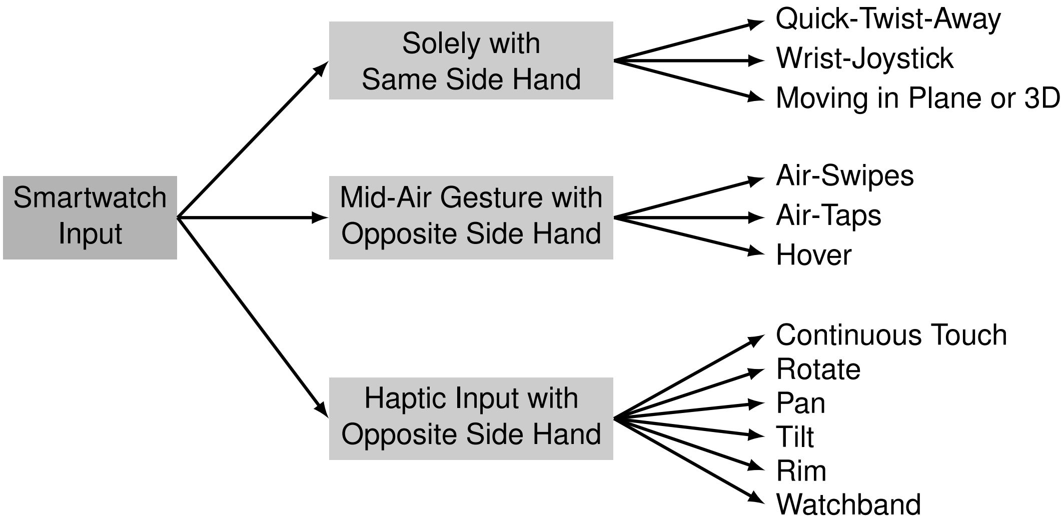

Figure 2.1: Diagram of input modalities of smartwatches that are proposed by related work

depletion caused by mobility. The researchers present that continuous attention to the device during movement is limited to bursts of 4 to 8 seconds. Visuri et al. [2017] present a broader analysis with more than 300 users and 800.000 screen usage events of smartwatches. Results showed that interactions have to be designed to be completed quickly or require minimal attention. Consequently, a novel interaction prosposal should not only be tested when sitting, but also during movement.

Mobility has to be considered during the design process

2.2 Smartwatch Input Techniques

With the aim to improve smartwatch interaction, researchers have investigated novel input techniques. The literature can be split by the mode of the input modality. There is literature on haptic input performed with the opposite side hand, mid-air gestures performed with opposite side hand, and input performed solely with the same side hand. This section gives a description on prominent input modalities for these categories. Figure 2.1 depicts an overview on smartwatch input techniques.

Same side hand gestures have appeared in several forms. Most are primarily targeted at simple discrete input commands like a quick twist of the wrist away from the body [Hinckley and Song, 2011, Müller et al., 2016, Arefin Shimon et al., 2016] or the assignment of finger postures to specific actions [Rekimoto, 2001, Dementyev and Paradiso, 2014]. Additionally, there exists approaches that implement two-dimensional input by means of using the wrist as a joystick [Gong et al., 2016] or moving the watch on a plane [Katsuragawa et al., 2016, Müller et al., 2016].

The second mode of input modalities are mid-air gestures. These are done with the opposite side hand, in proximity to the smartwatch, but without contact to it. Besides from simple air-taps or hover gestures [Withana et al., 2015, Arefin Shimon et al., 2016], there exists work on more expressive gestures like air-swipes [Kim et al., 2007, Arefin Shimon et al., 2016]. Kim et al. [2007] evaluated five mid-air gestures both stationary and on the go and achieved a recognition accuracy of 95.5% across all conditions. The authors note, that minimal training was needed and there was no statistically significant effect on accuracy when users were walking. This makes mid-air gestures suitable for quick, discrete input.

The third group of input modalities are interactions done with the opposite side hand like the manipulation of the touchscreen or pressing a button. There exists research on user input via the watch strap [Klamka et al., 2020, Saviot et al., 2017, Pasquero et al., 2011] and even via the skin next to the watch [Ogata and Imai, 2015, Schrapel et al., 2020]. Furthermore, touching the rim of the watch [Oakley and Lee, 2014, Ahn et al., 2017, Malu et al., 2019], rotating the watch face [Yeo et al., 2016] and panning the watch on the wrist [Xiao et al., 2014, Yeo et al., 2016, Singh et al., 2018] were investigated.

2.3 Inclination-Based Input

Using the inclination as input on a mobile device was first introduced by Rekimoto [1996]. The author presented a

	continuous value input	discrete value input
Two-dimensional	Touchscreen Pan [Xiao et al., 2014] Skin [Schrapel et al., 2020] Tilt with Tilt-Watch	Rotate [Ogata et al., 2013] Skin [Ogata et al., 2013] Tilt (*InclineType*) [Götzelmann and Vázquez, 2015]
One-dimensional	Touch [Yeo et al., 2016] Rotate [Yeo et al., 2016]	Click [Xiao et al., 2014] Rotate [Ogata and Imai, 2015] Frame [Ahn et al., 2015] Tilt [Xiao et al., 2014]

Table 2.1: Smartwatch input space of presented input modalities. Tilt-Watch is the first contribution that enables tilt-based two-dimensional continuous input on smartwatches. For every input modality one example contribution is given.

prototype which used a small external screen and an inertial measurement unit (IMU) to enable inclination-based input. Users were able to control the inclination with an accuracy of only 2 degrees, provided that visual feedback was displayed. Rekimoto implemented one-dimensional menu selection tasks, a two-dimensional map browser that changed the perspective view of the map as well as a three-dimensional object viewer that coupled the inclination of the display to the orientation of the object.

Users were able to control the inclination of a handheld device with an accuracy of 2 degrees

Oakley and O'Modhrain [2005] investigated inclination-based input on an iPaq touchscreen pocket PC and emphasize the importance of haptic feedback for this input technique. Additionally, the authors found that for menu items, position-based mapping of the inclination was more controllable than rate-based mapping. This means, each menu item is selectable by tilting the device to the corresponding fixed angular position.

Haptic feedback was emphasized

Xiao et al. [2014] presented the first research that included inclination-based input on smartwatches specifically. The authors build a smartwatch prototype using joystick sensors that sense the displacement of the display of the watch. The display could be panned, twisted and tilted on the smartwach body. While panning was implemented as two-dimensional input, twist input provided one-dimensional input and lastly tilt input was only detected binary in two directions (i.e. tilted to the left, not tilted, tilted to the right).

First inclination-based input on smartwatches was binary

Two-dimensional inclination-based input was used for keyboard entry

In order to solve the *the fat finger problem* for smartwatch keyboard input, Götzelmann and Vázquez [2015] presented *InclineType*, an inclination-based keyboard. Here, the inclination of the watch is controlled by raising or lowering the elbow and twisting the wrist. The two-dimensional inclination of the watch is used to select one of the letters distributed on the edges of the screen. While this alone would be classified as same side hand interaction, similar to the interaction presented by Gong et al. [2016], *InclineType* utilizes the second hand to confirm the selected letter and thereby enter it. The interaction facilitates the intuitive feeling of gravity and the authors explain that participants got familiar with almost no previous training. Regarding performance, it is noted that participants reached an average typing speed of six words per minute in average, which is on the lower end compared to other smartwatch keyboard approaches [Turner et al., 2020]. However, *InclineType* was specifically designed just for keyboard input. Going beyond keyboard input, the interaction reaches its limits based on physiological properties of the arm: When holding the arm in front of the body, it is only possible to twist the wrist very little towards the body. For more general two-dimensional input, this would limit the interaction range.

There has not been research on tilting the smartwatch with the opposite side hand

To the best of our knowledge, the direct manipulation of the inclination of the smartwatch with the opposite side hand has not been explored already. Table 2.1 lists different input modalities and groups them by expressiveness. One can see, that Tilt-Watch is the first contribution that enables two-dimensional continuous input via tilting.

In contrast to *InclineType*, we do not rely on moving the arm with the watch but only the watch itself is tilted. This also eliminates the disadvantage of only being able to tilt your wrist very slightly towards your body while still relying on the metaphor of gravity to make the interaction intuitive. The following chapter will explain, how we realized this inclination-based smartwatch input.

Chapter 3

Tilt-Watch: Design And Implementation

In the following chapter we present Tilt-Watch and describe its design process in detail. The chapter is split into two sections. In Section 3.1 we describe the exploration of different sensor types and explain why we settled for optical distance sensors (also called optical rangefinders) to detect the inclination of the watch. Then, we present different design iterations and decisions that led to the current prototype. Section 3.2 goes into detail on the software implementation of Tilt-Watch. Here we explain how the data from the optical distance sensors is used to calculate the inclination.

3.1 Hardware Prototyping

The following section describes the hardware implementation of Tilt-Watch. We start by going through different physical properties we explored in order to measure the inclination of the smartwatch in relation to the forearm. After that, we explain why we settled for photo-reflective rangefinders and we reason why we did not use different sensors, e.g. the IMU, to detect the inclination. We go on by providing insight in the prototyping process of Tilt-Watch and explain how the sensors are arranged and connected.

Definition: *intertial measurement unit*

INTERTIAL MEASUREMENT UNIT:
An intertial measurement unit (IMU) is a combination of multiple accelerometers and gyroscopes. Accelerometers measure linear acceleration and gyroscopes measure the rotational rate. Magnetometers that measure the magnetic field are often included, too.

3.1.1 Sensor Selection

Linux Watch with OLED display

Starting with the Linux Watch[1] presented in 2000, IMUs were built into smartwatches. The IMU makes the smartwatch aware of its position so that it can calculate if the user is currently looking at the watch face or whether the watch is facing away from the user. Also, researchers already used the IMU in a smartwatch to sense panning, twisting and rotation around the watch face [Yeo et al., 2016].

We discarded using the IMU to be robust against movement

Nevertheless, we decided against using the IMU for the proposed interaction. This is, because the smartwatch is a mobile computing device which is, in most cases, worn the whole day and often operated on the move [Oulasvirta et al., 2005]. Therefore, we wanted to build a system which is robust against movement. When walking or running, the arm is moved slightly with each step, which produces noise when using the IMU to calculate the inclination. The point is that with an IMU one would not measure the inclination in relation to the forearm but the inclination in relation to the earth.

Measuring the exerted force on the watch would limit the interaction

One could also measure the force exerted on the watch, as the user presses onto it to tilt the watch face. Unfortunately this would limit the interaction. We found that in some cases users do not touch the watch itself to manipulate the inclination, but only touch the watchband to drag the watch in the desired position.

When the watch is tilted on the wrist, one part of the watch body is pressed into the arm and the part on the opposite

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[1] `https://researcher.watson.ibm.com/researcher/view_group.php?id=5614` (Accessed: January 18, 2021)

side loses contact. Therefore, we explored measuring the force that is exerted on the arm in order to calculate the inclination of the smartwatch body. For this, we used a force sensing resistor (FSR). A FSR changes its value based on the exposed force. We built a prototype with one FSR on the bottom side of the watch and quickly discovered that detecting the exerted force comes with caveats, too. Although FSRs are cheap and can be built in a small form factor, the sensor values drift with time and would need regular recalibration. Also, one degree of inclination can have different levels of force, because one can hold the smartwatch at the same angle, while exerting less or more force onto the wrist. With this, the values are ambiguous and thus using an FSR is unsuitable for the proposed interaction.

Force sensing resistors produce ambiguous values

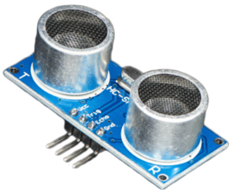
The most direct way to sense the inclination of the watch in relation to the wrist is to measure the distance from the watch to the wrist. With a minimum of four sensors, one on each side looking down, it would be possible to calculate the horizontal and vertical inclination of the watch. Therefore, we investigated using rangefinders (sensors that measure distance to a target) in our prototype. The following section gives an overview on several rangefinders we considered for the prototype and explains our choice of LED-based optical rangefinders for Tilt-Watch.

Sensing the distance towards the wrist is the most direct way

3.1.2 How Tilt-Watch Measures Inclinaton

For Tilt-Watch, we investigated rangefinders, searching for a small sensor with an update rate of at least 5 Hz (five times per second) and low current draw such that it can work on battery. An ideal sensor would be able to detect a range from 1 mm to about 5 cm to cover every possible inclination of the smartwatch.

There are several types of rangefinders, though all non-contact devices operate by interpreting a reflected signal. The distance to an object is either calculated by measuring the time between the emission of the signal and the arrival of its reflection or by measuring the reflection intensity (i.e. the intensity is lower, if the object is further away).



HC-SR04 Ultrasonic Sensor from Adafruit

An ultrasonic sensor measures the time between sending an ultrasonic soundwave and receiving its echo, thus calculating the distance to an object. While ultrasonic sensors have very low current draw and often operate with an update rate of at least 10 Hz, most ultrasonic sensors have a minimum range of 15 cm. While there are ultrasonic sensors for closer distances like the HC-SR04 with a minimum range of 2 cm, the sensor is too big to fit in a wearable prototype and the minimum range is still to high for our use case.

VL53L0X VSCEL on PCB from Adafruit

Ranging with a VCSEL is accurate, but complex

The second type of sensors we investigated were optical rangefinders based on vertical-cavity surface-emitting lasers (VCSELs). A VCSEL only emits laser beams perpendicular from its top surface. To be more precise, a VCSEL produces a lower divergence angle than regular lasers and thus requires less power. Ranging the distance to an object with a VCSEL works by measuring the time it takes the beam to travel to the object and bounce back to the sensor. Thus, VCSELs operate like ultrasonic rangefinders, but the emitted signal is a light beam rather than a sound wave. VCSEL-based rangefinders are already used in most smartphones to turn off the display during a call. Additionally to the low current draw and their small size, VCSELs have fast and accurate distance ranging. Having said this, a range finding VCSEL is a complex electronic component with an integrated microcontroller and a high precision clock. This makes integrating a VCSEL more complex and especially integrating several VCSELs in one body complicates circuits even more and thus would make prototyping harder.

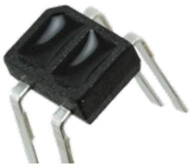


photo-reflective rangefinder QRE1113 from ON Semiconductor

Researching related work, we found several papers [Ogata et al., 2012, Ogata and Imai, 2015] that use another type of optical rangefinders to implement novel interaction proposals. Rather than measuring the precise time a light beam takes to travel to an object and back, one can measure the amount of light that is reflected by the object. Photo-reflective rangefinder include both, an infrared led and an infrared photo transistor in a footprint of 3×4 mm and detect distances from 1 to 10 mm. The infrared photo transistor converts infrared light into electrical current. Thus, if an object is closer to the sensor, more light is reflected onto the sensor and the output current is higher. Although powering an LED to measure reflected light requires more power compared to a VCSEL, photo-reflective rangefinders are inexpensive, have a small footprint and can be included in electronic circuits with little effort. Thus, we decided to use the QRE1113 from ON Semiconductor[2]. This photo-reflective rangefinder can measure distance in a range from 1 to 5 mm. Due to the low maximum range of the sensor, we decided to use several sensors per direction to be able to detect small as well as large inclinations.

Photo-reflective rangefinders are inexpensive, small and easy to integrate

Having chosen the sensor for Tilt-Watch, the next step was to integrate it into a smartwatch body. In the following section, we describe the prototyping process of Tilt-Watch. For this, we explain why we developed Tilt-Watch as a case for the Apple Watch and give an overview about different stages of the prototyping process.

3.1.3 Tilt-Watch as Apple Watch Case

We build an interactive prototype to evaluate the proposed human-computer interaction. To evaluate inclination-based smartwatch input, we set out to build a device that includes multiple photo-reflective rangefinder on the bottom. The prototype should be able to compute the sensor input as well as provide visual and haptic feedback to the user. Additionally, it was important that the prototype should roughly have the dimensions of a regular smartwatch, because users directly interact with the device itself.

Prototype should provide visual and haptic feedback

The sensors we chose are less than 2 mm tall. Because of this, we decided to built Tilt-Watch as a case for the Apple Watch. By using an existing smartwatch, we can provide rich visual feedback on the display and renowned haptic feedback via the built-in haptic engine. Unfortunately, the Apple Watch has no interface to connect the sensors directly. Thus, we decided connecting the sensors to a microcontroller with built-in Bluetooth and transmit the sensor data to the Apple Watch via Bluetooth.

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[2] `https://www.onsemi.com/products/optoelectronics/infrared/reflective-sensor/qre1113` (Accessed: January 18, 2021)

For the microcontroller, we decided using an ESP32 from Espressif Systems[3]. The ESP32 has integrated Wi-Fi and Bluetooth connectivity as well as 18 analog-to-digital converter (ADC) channels, which would theoretically enable connecting up to 18 photo-reflective rangefinders. Because of its low power consumption, the microcontroller from Espressif Systems is used in many internet of things (IoT) devices and wearable electronics Bachfeld [2019].

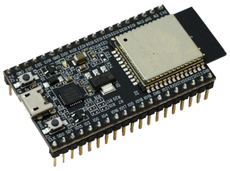

Image from Espressif Systems

ESP32-DevKitC with microcontroller ESP32 on the right

To enable fast prototyping, we used the ESP32-DevKitC development board. In addition to the microcontroller itself, the board contains controllers for USB programming, reset and boot-mode buttons and routes every important general-purpose input/output (GPIO) port to a breadboard-friendly pinout. Because of the small size of the ESP32 itself, one could theoretically include the microcontroller (without the development board) inside Tilt-Watch to build a cable-free prototype. For this, a rechargeable battery would also have to be included inside the prototype, which would make it thicker. As mentioned at the beginning of the Section, we set out to built a prototype that is similar to a regular smartwatch, because users directly interact with the smartwatch. That is the reason we decided to only include the sensors inside the case and move the microcontroller and battery outside.

3.1.4 Proof of Concept

As a proof of concept, we built the first prototype with only two sensors. A thin frame was 3D printed that allowed placing the sensors on opposing sides. The frame was then attached to the Apple Watch with adhesive tape as shown in Figure 3.1b. The two rangefinders were connected to the ESP32 on a breadboard in order to be able to try out resistors with different resistances.

The wiring diagram of the proof of concept is depicted in Figure 3.1a. As explained earlier, a photo-reflective rangefinder contains an LED and a photo-reflective transis-

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[3] `https://www.espressif.com/products/modules/esp32` (Accessed: January 18, 2021)

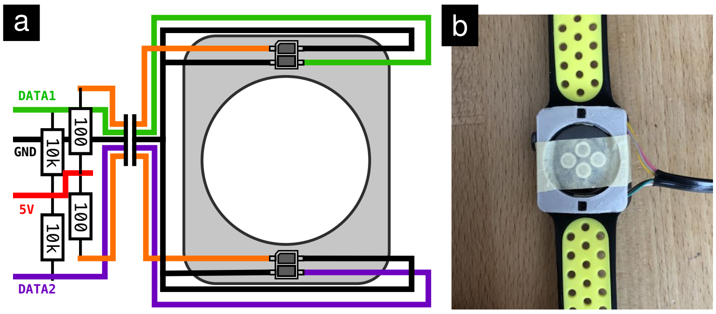

Figure 3.1: (a) Wiring diagram of the first proof of concept. (b) Picture of the prototype containing only two rangefinders.

tor. The 100Ω resistors limit the current of the LEDs to $1.4V$. The $10k\Omega$ resistors are pull-up resistors for the transistor as per documentation [Espressif Systems, 2020].

Pull-up Resistor:
A pull-up resistor ensures that the input of a microcontroller is always in a well-defined state. Without a pull-up resistor an indeterminate voltage could be read because the voltage would be influenced by electromagnetic noise. In our case, the absence of light would lead to unpredictable values when the program reads the state of a pin connected to a photo-transistor.

Definition: *Pull-up Resistor*

During early prototyping, the ESP32 was connected directly to a computer via the USB interface. This enabled us to experiment with the sensors, without implementing the Bluetooth stack for publishing sensor data. With the proof of concept, we learned important lessons about the placement of the sensors. Regarding vertical tilting (towards the top or bottom) we learned that the sensors are very far on the outer edge and thus showed high values in the resting position without user input. This is because the arm is round, and therefore the distance between the sensors and the arm becomes greater, the further away the sensors are moved away from the middle. Figure 3.2 shows the proof of concept attached to an Apple Watch worn on the wrist. In the picture, the sensors were too far on the outside, thus showed high values without input.

Proof of concept helped us better understand the impact of sensor placement

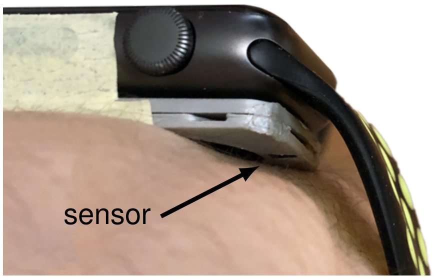

Figure 3.2: Proof of concept of Tilt-Watch containing two rangefinders. Sensor is too wide from the center, thus reporting high values without user input

Horizontal tilting worked well for small inclinations

With this prototype, we were also able to explore tilting to the left or right side by rotating the 3D printed base below the Apple Watch for 90 degree clockwise. After that, the two sensors are on the left and right side rather than on the top and bottom side. Tilting to the sides worked well for small inclinations. Unfortunately, the sensors reached their maximum value at around 10 degree inclination. Moving the sensors closer to the center solves this somewhat, but with the possible sensing range of 1 to 5 mm it is not possible to detect small as well as big inclinations. Therefore we decided to use multiple sensors per direction, to detect greater ranges of inclination. With the lessons learned, we decided how the sensors have to be arranged to enable two-dimensional tilt input with high value ranges.

3.1.5 Sensor Arrangement

After building and testing the proof of concept, we continued to develop Tilt-Watch. We decided to use a total of nine sensors for the next prototype. With each LED requiring $1.6V$ at maximum, we were able to connect 3 LEDs in series respectively via the 5V provided by the ESP32 development board.

Regarding the sensor arrangement on the bottom of the Apple Watch, we chose to place sensors on lines from the middle of the smartwatch towards all corners. The arrangement is depicted in Figure 3.3. Because of the nine sensors

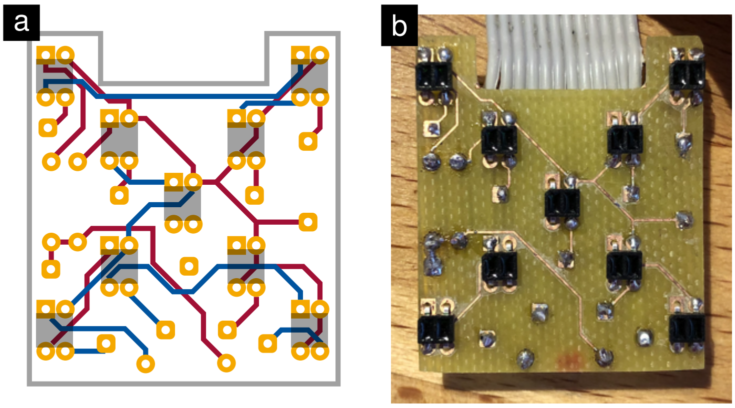

Figure 3.3: (a) PCB design for Tilt-Watch. Traces are marked red or blue according to the side they are on. (b) Picture of double-sided PCB with sensors. Three sensors are connected in series respectively.

with four pins each, it got difficult to wire the connections by hand. The following section describes the process of producing a printed circuit board (PCB) that holds the sensors and is attached to the Apple Watch.

3.1.6 Designing the Final Prototype

We designed the PCB for Tilt-Watch with KiCad[4]. KiCad is an open source platform for electronics design. We imported the schematic of the photo-reflective rangefinder into the schematic editor and defined how the rangefinders and the resistors are connected to each other. We decided to produce a double-sided PCB, in order to connect the high number of pins without having to use solder bridges.

To route the traces on the PCB, we relied on the open source autorouter software Freerouting[5]. We imported the schematics from KiCad and Freerouting automatically routed the traces on both sides of the PCB with minimal modification needed. Then, we exported the routing information as Specctra session file.

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[4] `https://kicad.org` (Accessed: January 18, 2021)

[5] `https://freerouting.mihosoft.eu` (Accessed: Jan. 18, 2021)

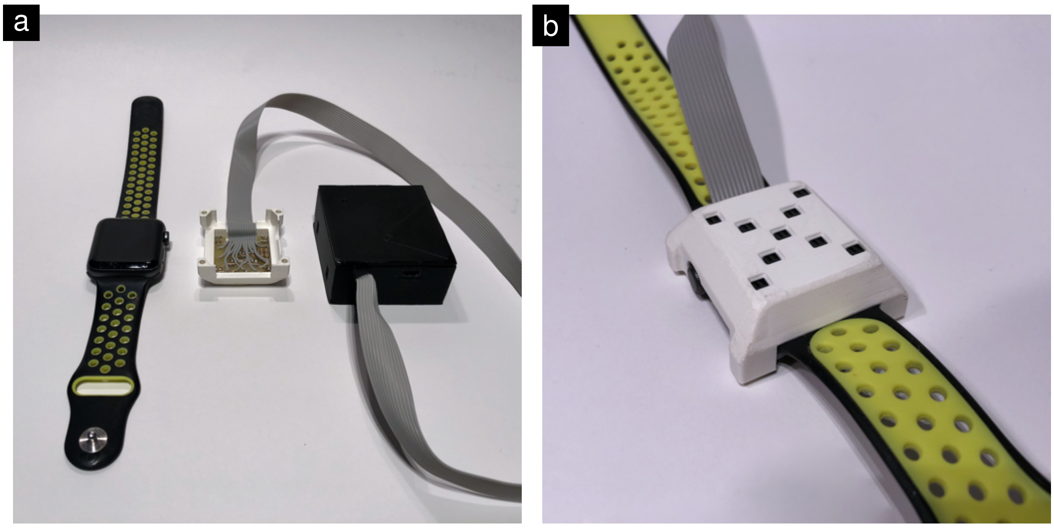

Figure 3.4: (a) Picture of Apple Watch next to Tilt-Watch case including PCB and black box containing ESP32. (b) Bottom of Tilt-Watch with the nine rangefinders.

This Specctra session file was imported into the KiCad software paltform. Here we generated drill files for the PCB mill. The mill is a LPKF Protomat S104 that can create PCBs from copper plated sheets of fibre glass. After the mill has finished drilling on the first side, we turned over the copper plated sheet for the machine to drill the second side. Finally, the nine photo-reflective rangefinders as well as three resistors were placed on the PCB and soldered together.

The sensors were mounted on a PCB and a case was 3D printed

To attach the finished PCB to the Apple Watch, we placed both together in a case, which is screwed tight from the top. Additionally, we designed a bigger PCB for the microcontroller and the pull-up resistors of the nine wsensors. These two components were then connected with a flat ribbon cable. The sensor PCB measures 28×32 mm and fits into the 3D printed case, constructed with 0.3 mm offsets on each side. It was printed with an Ultimaker S5 Pro. Tilt-Watch was designed to be as small as possible. It still provides the feeling of operating a regular smartwatch, although it is 5 mm thicker than the Apple Watch. Figure 3.4a shows all described components: The Apple Watch next to the Tilt-Watch case including the PCB, which is connected to the ESP32 inside the black box. Figure 3.4b shows the bottom side of Tilt-Watch, where one can find nine rangefinders.

3.2 Software Implementation

The following section describes the software implementation of Tilt-Watch. This is split into two parts: In the first section, we explain how the ESP32 records the sensor data and makes it available as a Bluetooth service. The second section explains how the data is used to calulate the inclination of the smartwatch.

3.2.1 Data Recording and Transfer

Sensor data is recorded by 12-bit ADCs

The ESP32 integrates a total of 18 channels of 12-bit analog-to-digital converter (ADC). An ADC converts an analog signal into a digital signal. As explained in Section 3.1.2 "How Tilt-Watch Measures Inclinaton", the current emitted by the rangefinders changes with the intensity of the reflected light. The ADCs of the ESP32 convert this varying current into a 12-bit digital number (0-4095), that then can be used in software. It is important to note that many of the pins of the ESP32 are assigned with several functions. Which function is currently used is determined in the program. Therefore, some of the ADC channels can only be used when the wifi driver has not started and others (GPIO0, GPIO34, GPIO35) cannot be used at all as ADCs on the ESP32-DevKitC.

Multisampling mitigates noise of ADCs

As per documentation [Espressif Systems, 2020], the ESP32 ADCs can be sensitive to noise. To counter this, the programm samples each of the nine ADCs multiple times and calculates the average for every sensor. This approach is called multisampling and is common to mitigate the effect of noise. We tested out several sample numbers and found that the function `readSensors`, responsible for sampling the ADCs, takes 10.54 ms for one sample, but recording 40 samples only doubles the runtime (21.1 ms).

The sensor data, then, is made available as a Bluetooth Low Energy (BLE) service. Using the low level Espressif IoT Development Framework (ESP-IDF) is considered difficult because of the big amount of states and events that have to be

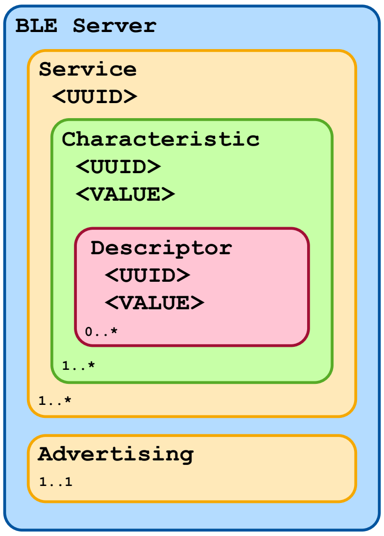

Figure 3.5: Bluetooth Low Energy (BLE) stack as implemented by the `ESP32 BLE Arduino` library. Tilt-Watch implements one BLE characteistic containing the values of all nine sensors.

handled [Kolban, 2020]. Therefore, we relied on the `ESP32 BLE Arduino`[6] library to make use of BLE on the ESP32. The library provides higher level classes and functions, to simplify using BLE.

All nine sensor values are advertised as one BLE characteristic

The BLE stack, also depicted in Figure 3.5, is structured as follows: A BLE server exposes one or more services. A service contains one or more characteristics and each of these characteristics may have zero or more descriptors. Service, characteristic and descriptor are represented by Universally Unique Identifier (UUID). The BLE server has to actively start advertising, such that it can be located by clients. The advertisement includes the UUID of the service provided by the server. We decided to implement one characteristic that includes the values of all nine sensors combined. This is possible, by mapping the 12-bit values to 8-bit values and then putting these nine 8-bit values in series. Publishing all values in one characteristic guarantees that the values were recorded at the same time and thereby prevents sychronization errors.

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[6] `https://github.com/nkolban/esp32-snippets` (Accessed: January 18, 2021)

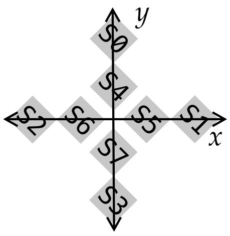
Additionally, we used the `TaskScheduler`[7] library that provides a lightweight implementation of task scheduling on Arduino or Espressif microcontrollers. In our program, the library is responsible for the periodic task execution. The task, which runs every 100 ms, contains the multisampling of the sensors and the update of the BLE characteristic value. At the end of the task, connected clients are notified that the value of the characteristic has changed.

TaskScheduler library implements periodic task execution

3.2.2 Calculating Inclination with Distance

A device that subscribes to the BLE characteristic is notified, when the value changes. As explained in the previous section, the characteristic contains the raw-value of all nine sensors. This approach allows all the computation to be executed on the device receiving the values, thus makes the approach more flexible.

The arrangement of the sensors (see Figure 3.6a) makes the calculation straight forward. For this, we first rotate the sensor array by 45 degrees clockwise, such that the sensors lie on the axes instead of pointing towards the corners of the smartwatch. This simplifies calculating a two-dimensional point based on $f_{rotated}$, because each sensor only influences one dimension of the point at a time.



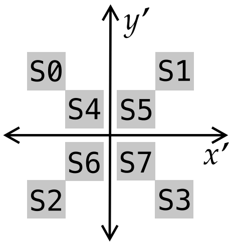
$f_{rotated} = (x, y)$

$$f_{rotated}(S_0, S_1, S_2, S_3, S_4, S_5, S_6, S_7) = \\ (S_1 + S_5 - S_2 - S_6, S_0 + S_4 - S_3 - S_7) = (x, y) \quad (3.1)$$

The calculated point has to be rotated back 45 degrees counter clockwise. This is done by $f_{corrected}$.

$$f_{corrected}(x, y) = (\frac{x}{\sqrt{2}} - \frac{y}{\sqrt{2}}, \frac{x}{\sqrt{2}} + \frac{y}{\sqrt{2}}) = (x', y') \quad (3.2)$$

Here, (x', y') represents both the two-dimensional direction and extent of the inclination of the smartwatch.



$f_{corrected} = (x', y')$

The center sensor S_8 is only considered when Tilt-Watch is tilted strongly. If an outer sensor reports maximum value,

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[7] `https://www.arduino.cc/reference/en/libraries/taskscheduler/` (Accessed: January 18, 2021)

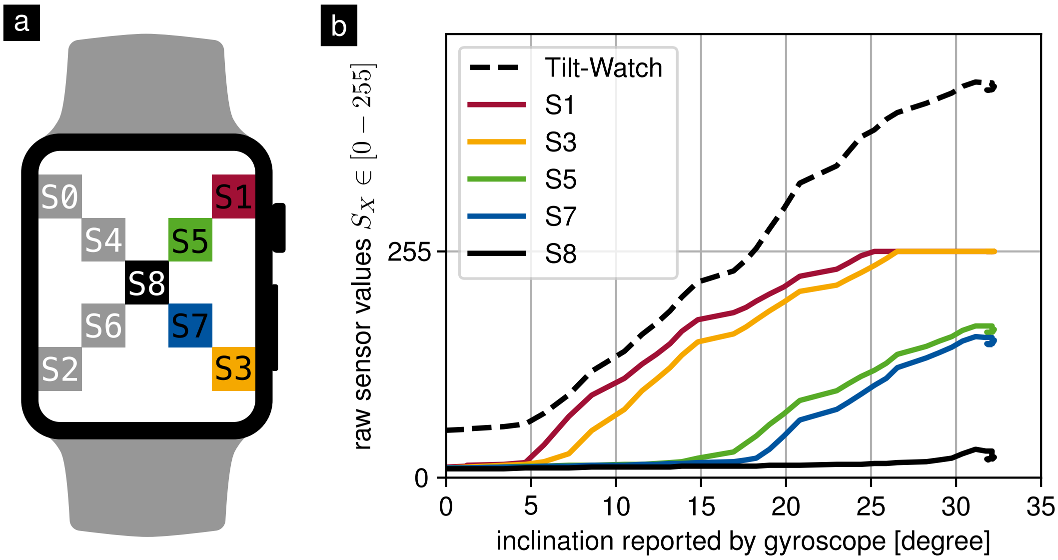


Figure 3.6: (a) Sensor arrangement of Tilt-Watch. (b) Raw sensor values as well as the calculated Tilt-Watch inclination in relation to the inclination measured by the gyroscope for example inclination towards the left side

the value of S_8 is substracted from the opposing outer sensor. This is because increasing values of the opposing inner and outer sensor would cancel out a increasing degree of inclination, because of the simple nature of Equation (3.1).

Figure 3.6b depicts how the values of the sensors change for one example inclination towards the left side. For this, we plotted the raw sensor values as well as the calculated Tilt-Watch inclination in relation to the inclination reported by the gyroscope. One can see that only using S1 and S3 would limit horizontal tilting to a maximum of 25 degrees, because at this point the sensors reach their maximum value of 255. The dashed line denotes the calculated inclination of Tilt-Watch and increases approximately linearly. Thus, we could simply divide the calculated Tilt-Watch value by a factor to cover the same range of values as reported by the gyroscope.

Chapter 4

Study: Maximum Degree of Inclination

In the previous chapter, we presented our final Tilt-Watch prototype and explained the implementation in detail. After initial experimentation with the prototype we conducted a user study to derive framework conditions for the novel interaction technique. The property we investigated in the study was the maximum degree of comfortable inclination, i.e. the range of values that users utilize for the interaction.

The following chapter presents the study design, explains in detail which tasks participants did and which information we recorded. The chapter concludes with the results of the anaylsis, along with a discussion on several things we learned from the study. Lastly, we present the limitations of the study.

4.1 Experimental Design

The participant has to tilt the watch in a specific direction to the maximum degree until it can no longer be moved in that direction. The direction is specified on the display of Tilt-Watch with an arrow. The participant has to hold the maximum inclination for one second, in order for it to register. After that, the arrow disappears and a new one is displayed after Tilt-Watch has returned to the resting position. To prevent the Apple Watch from going into sleep mode, the participant has to press a button after every ten trials.

4.2 Participants

We conducted the study with ten participants between the ages of 23 and 63 (mean: 34.4 years, SD: 15.24 years). Four participants were females, the other six males. Nine participants wore wristwatches on the left and one participant on the right arm. Only two participants stated that they wear smartwatches.

4.3 Apparatus

We used the Tilt-Watch prototype for this study. The detailed assembly of this is explained in the previous chapter. Besides the nine photo-reflective rangefinders the prototype contains an Apple Watch Series 2 (GPS, 42 mm). The Tilt-Watch prototype without the ESP32 weighs approximately 70 grams.

The display of the Apple Watch has a resolution of 312×390 pixels with a diagonal of 1.65 inches. Additionally, an iPhone X was used to record the Tilt-Watch data and monitor the study progress.

4.4 Study Procedure

In the beginning, the participant is welcomed and Tilt-Watch is introduced by the conductor. Participants were seated in front of a table.

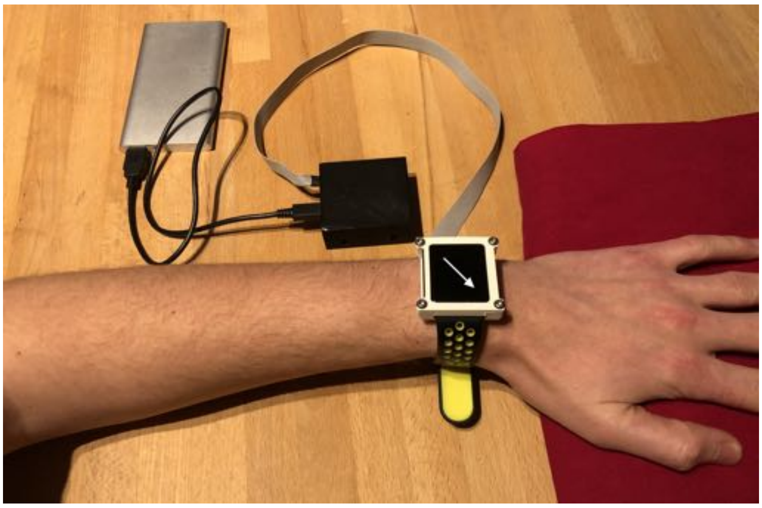


Figure 4.1: Setup for userstudy. The ESP32 inside the black box is connected to a power bank to supply power. The Apple Watch currently displays an arrow to the bottom right.

In the pre-experiment questionnaire, participants filled out demographic questions and also provided their wrist circumference (see Appendix A.1). Because of the ongoing COVID-19 pandemic, the study was designed in a way, such that the conductor could advise it from two meters away. Because of this, participants had to measure the circumference of their wrist on their own with the supplied measuring tape. After participants put on Tilt-Watch, they noted in which hole of the bracelet the buckle was inserted. With this, we could later determine how firm the watch was worn. In addition to the consent form and questionnaire, participants were also provided with a short usage guide on how to operate the Apple Watch (see Appendix B).

Participants measured their wrist circumference on their own

For the experiment, participants placed their hands on a small cushion such that the watchband could move freely. For the study, participants had to use their second hand to tilt in the direction, to which the arrow on the display pointed. This setup is depicted in Figure 4.1. Before we started recording the inclination data, participants did a trial run of the experiment, to try out the interaction. After that, the study started and participants had to tilt Tilt-Watch for 80 times consecutively.

Participants rested their arm on a cushion to enable free movement

Participants rated the ease of tilt per direction

After participants completed the experiment, they were asked to fill out a post-experiment questionnaire regarding their subjective rating of the different directions (see Appendix A.2). When participants had successfully completed the questionnaire, we close the study by asking "What do you think about the interaction?" and noted valuable input.

4.5 Measurements

Tilt-Watch sample was recorded every 100 ms and saved into a CSV file

During the study, we recorded both, data from the gyroscope and data from Tilt-Watch. The first measurement started, when the participant touched the "Start Study" button on the Apple Watch and stopped, when all 80 trials were finished. New samples were recorded approximately every 100 ms with the reception of the newest Tilt-Watch data via Bluetooth. The data was logged into a CSV file with an application on an iPhone, which was later transfered to a computer for the analysis.

We recorded 10 repetitions for each of the 8 directions

In summary, we recorded 10 repetitions for each of the 8 directions with 10 participants which results in 800 total trials. Depending on how fast participants reached the dwell-time, one trial could produce 10 to 50 samples in the log. Dwell-time describes the amount of time (in our case: 1 second) that the participant has to hold Tilt-Watch at the maximum comfortable inclination degree in order for it to register the input.

In addition to that, participants rated their agreement with the statement "It felt easy to tilt the watch in that direction" for every direction on a five-point Likert scale.

4.6 Results

Besides the maximum inclination, we also present an investigation on whether the firmness of the watchstrap influenced it and the ease of tilt for the different directions.

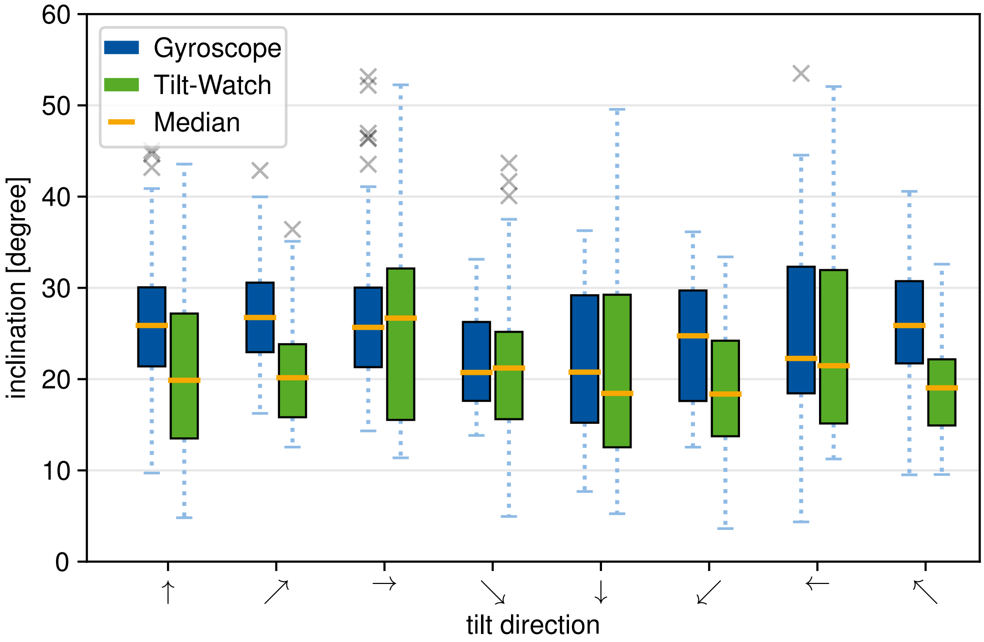


Figure 4.2: Average maximum inclination for all eight directions measured by gyroscope and Tilt-Watch. On average, participants tilted the watch to a maximum of 25.06 degrees but the inclination differs depending on the direction.

4.6.1 Maximum Inclination

The focus of the study was to investigate the maximum degree of comfortable inclination. On average, our participants tilted the watch to a maximum of 25.06 degrees (measured by gyroscope). Figure 4.2 depicts the distribution of the maximum inclination per direction. One can see that depending on the direction, participants tilted the smartwatch sometimes more and sometimes less. For every direction, the blue box represents data recorded by the gyroscope and the green box represents data recorded by Tilt-Watch. Also, the boxes in Figure 4.2 span more than 15 degrees for some directions. This means that the maximum inclination differed widely among the participants. While the average maximum inclination was between 20 and 30 degrees for most participants, one participant reached an average maximum inclination of 41 degrees.

On average, participants tilted the watch to 25 degrees

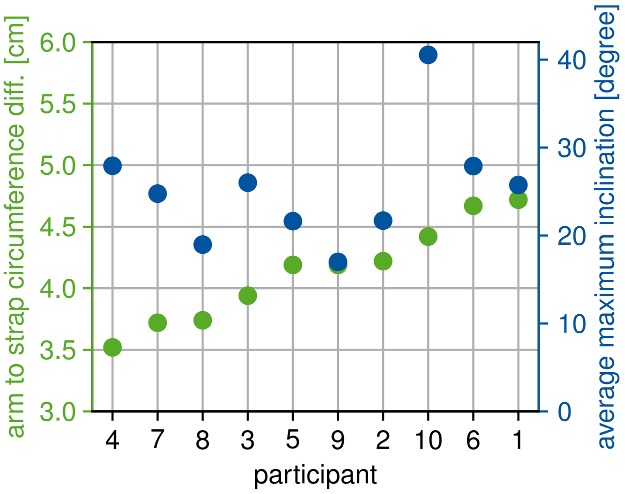


Figure 4.3: Watchstrap firmness (arm to strap circumference difference) and average maximum inclination per participant. Participants are ordered by watch strap firmness.

4.6.2 Does Firmness Matter?

We could not find firmness affecting the maximum inclination

We calulated the arm to strap circumference difference per participant to investigate if the firmness of the watch strap influenced the maximum inclination. Under tension, the difference in cirmumference ranges from 3.52 cm to 4.72 cm depending on the participants. Figure 4.3 shows the watch strap firmness and the average maximum inclination per participant. Participants are ordered ascending by watch strap firmness. In our study, we could not find an effect on the average maximum inclination.

4.6.3 Ease of Tilt

We also evaluated the ease of tilt in the eight directions on a five-point Likert scale. The results for this are depicted in Figure 4.4. The radar plot shows the mean and standard deviation of the rating per direction. A lower score (and with this close range to the outer circumference of the circle) indicates more agreement with the statement, thus a higher ease of tilt. Overall, the mean ranges from 1.9 (tilt-

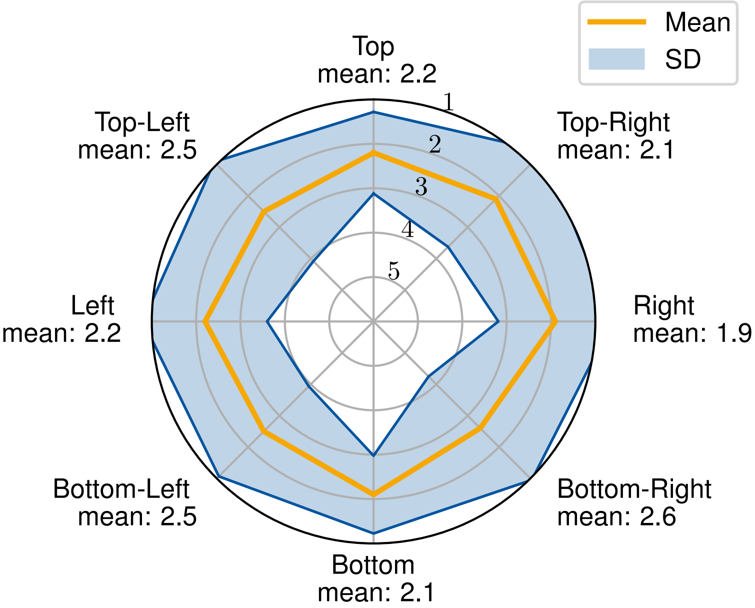


Figure 4.4: Ease of tilt for all eight directions (lower score = easier). Tilting to the right was rated the easiest. Participants preferred tilting over the sides rather than the corners.

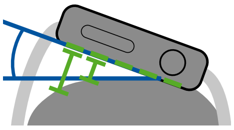
ing to the right) to 2.5 (tilting to the bottom left) depending on the direction. Additionally, the standard deviations for tilting over the sides of Tilt-Watch were all lower, than the standard deviations for tilting over the corners. This shows, participants preferred tilting over the sides, rather than the corners. Individual user feedback attests this. Participants noted that "tilting over the corner is wobbly" or "tilting to the diagonal sides feels strange".

Participants preferred tilting over the sides, rather than the corners

4.7 Discussion and Implications

Overall, Tilt-Watch was well-received by the participants. When looking at the requirements regarding the interaction design of Tilt-Watch, there are several things we learned from the study.

Haptic feedback can improve the interaction.
Several participants praised the haptic feedback of Tilt-Watch. This is despite the fact that we only used haptic feedback in addition to visual feedback to inform the user that the dwell-time has been reached. This singals that the sample has been taken and the user can release the smartwatch. In a future version of Tilt-Watch, we imagine haptic feedback dependant on the current inclination value.



Gyroscope measures inclination (blue), Tilt-Watch calculates inclination in relation to the arm (green)

Tilt-Watch does not measure inclination.
It is important, to note what exactly Tilt-Watch measures. Figure 4.2 shows data for both, the inclination measured by the gyroscope and the inclination calculated by Tilt-Watch. One can see, that the boxes do not line up perfectly. This is because both sensor types measure different physical properties. The gyroscope measures inclination in relation to the earth face. Tilt-Watch measures the distance towards the arm and thereby calculates the inclination in relation to the arm. This brings disadvantages and advantages. On the one hand, Tilt-Watch will produce slightly different data for the same physical inclination, because humans have arms in different shapes and differently pronounced wrist bones. On the other hand, it creates new opportunities. Since Tilt-Watch is independent of the inclination in relation to the earth face, the inclination value can be used for interaction no matter of the position or orientation of the arm. This can be helpfull during movement, when the inclination in relation to the earth face permanently changes.

Due to sensor bias, diagonal inclination was consistently lower

The two-dimensional inclination value is biased.
Another observation we made during the data analysis process is that the arrangement of the rangefinders influences the calculated inclination. Going back to Figure 4.2, we noticed, that while the boxes for vertical and horizontal inclination do match to some extent, the ones for diagonal inclination are consistently lower for Tilt-Watch. We suggest, that this is because of the sensor arrangement and the way we calculate the inclination. When tilting vertical or hotizontal, there are always two sensors measuring the inclination at the same time. When tilting diagonal, e.g. to the top left, there is only one sensor at every step, that influences the inclination reported by Tilt-Watch. Because our algorithm is the same for both diagonal and straight

inclinations, having one less sensor decreases the precision of the calculated inclination.

4.8 Limitations

Apple Watch turns off its display when tilting strongly

During the study, we found that using the Apple Watch in the prototype comes with caveats. Two participants found, that when tilting the watch strongly, it turns off its display. This is because the accelerometer of the Apple Watch is used to check if a user is currently looking at the smartwatch. The smartwatch concludes that after this positional change, the user cannot still be looking at the screen and thus the screen can be turned off. Unfortunately, this function cannot be disabled. The effect does not directly influence Tilt-Watch per se, because the sensors work independent of the Apple Watch, but it does limit the interaction for inclinations of high degree, because visual feedback cannot be provided. Also, the Apple Watch will turn off its display, if the display is not touched for 70 seconds. For the study, we solved this by displaying a button every 60 seconds.

One participant accidentally pressed a button on the Apple Watch

Prior to the study, we found that when tilting the smartwatch left or right, people grab Tilt-Watch on the sides, where the side button and the digital crown are positioned. Thereupon, we designed and printed a new case which protudes the buttons on the right side of the Apple Watch. Unfortunately, during the study, one participant mentioned that she had to adjust his grip while tilting, because she pressed the side button on the Apple Watch. The side button shows recently used applications, thus triggering it interrupts the study.

We could only test ten participants

Another limitation that has to be noted, is the small sample size of the study. Because of the COVID-19 pandemic it was only possible to do the study with ten participants, because it was subsequently forbidden to meet people from another household.

Chapter 5

Preliminary Investigation: Performance During Movement

In Section 3.1.1 "Sensor Selection", we explained that we decided against using an IMU to detect the inclination, in order to be more robust against movement. The following chapter will present a small excursus into the performance of Tilt-Watch during movement. For this, we will first present the task we completed to evaluate the performance and then discuss results and limitations.

To investigate the performance during movement we would have liked to conduct a study, similar to the study presented in the previous chapter. Unfortunately it was prohibited to meet people of another household at that time in the course of the preparation of this thesis, at which this investigation should take place. Thus, it was only possible to examine the performance during movement of myself, because nobody else was in possession of a Tilt-Watch prototype. Therefore, any results presented in this chapter must be taken with a grain of salt.

STANDING	Top	Right	Down	Left	**Mean**
Gyroscope	1.7	2.3	2.1	2.1	**2.1**
Tilt-Watch	2.1	2.7	2.6	1.9	**2.3**

MOVING	Top	Right	Down	Left	**Mean**
Gyroscope	3.3	4.1	5.2	3.8	**4.1**
Tilt-Watch	3.4	2.9	4.0	3.7	**3.5**

Table 5.1: Spreading per direction in degrees for STANDING and MOVING conditions. When MOVING, the datapoints of the gyroscope are more spread than the ones that are recorded by Tilt-Watch.

5.1 Measurements

We repeated the previous study with two movement conditions

For the investigation of performance during movement, the same tasks were repeated, that participants had done earlier while sitting. This time, the following two movement conditions were added. In the STANDING condition the 80 tilt trials were done standing still, holding both arms in front of the body. In the MOVING condition figures eight were walked inside. Walking in figure eight simulated splitting the cognitive load between walking and interacting with Tilt-Watch. Similar to the study investigating maximum inclination, we recorded data from the gyroscope and from Tilt-Watch.

To determine the performance during movement, we analyzed the average spread per direction. For this, we calculated the standard deviation of the points where the dwell-time was reached for every direction, respectively.

5.2 Results

Average spread per direction went up less for Tilt-Watch than for gyroscope

Table 5.1 lists the spreading for the four cardinal directions for both movement conditions. For STANDING, the average spreading reported by the gyroscope was 2.1 degrees and for Tilt-Watch 2.3 degrees. When MOVING, the average spread per direction went up to 4.1 degrees for the gyroscope and 3.5 for Tilt-Watch. So for the MOVING condition the average spread went up nearly 200% for the gyroscope, but only 152% for Tilt-Watch.

5.3 Discussion

We set out to improve on using an IMU to detect the inclination and decided to measure the distance towards the arm. We suggest, that the presented difference in spreading for the MOVING condition can be reasoned by the way Tilt-Watch works. The measurement is based on very local conditions. The distance towards the arm is measured, no matter in which orientation relative to the earth's surface Tilt-Watch is. Hence, the moving and turning of the arm during movement has no direct impact on the measurement.

Performance during movement has to be studied in the future

Because the data was only generated with one participant we do not suggest, that the results can be generalized. We propose that similar to when stationary, in motion, Tilt-Watch has different applications than the gyroscope. Thus, calculating the inclination with the distance towards the arm could be advantageous in some situation. In future user studies, one could also study the accuracy during movement of Tilt-Watch versus the gyroscope. Section 7.3.2 "Future User Studies" goes into detail on which user studies we plan on doing next.

Chapter 6

Tilt-Watch Interaction Design

Interaction design describes the process of creating a physical product and exploring the ways a user might interact with it [Preece et al., 2015]. The following chapter contains a detailed description of the interaction design we propose with Tilt-Watch and studied for this thesis. Also, we describe potential applications of Tilt-Watch and present demonstrator applications we implemented to explore the interaction.

6.1 Inclination-Based Smartwatch Input

Tilt-Watch detects two-dimensional inclination in relation to the forearm

Tilt-Watch is able to detect two-dimensional inclination in relation to the forearm. The inclination is manipulated with the opposite side hand. This means, Tilt-Watch enables two-dimensional continuous input, while still providing unrestricted visibility of the screen.

Figure 6.1a shows a visual representation of the two-dimensional value, representing the inclination of Tilt-Watch. In the picture, the prototype is tilted to the top right side. The length of the red line represents the extent of the inclination.

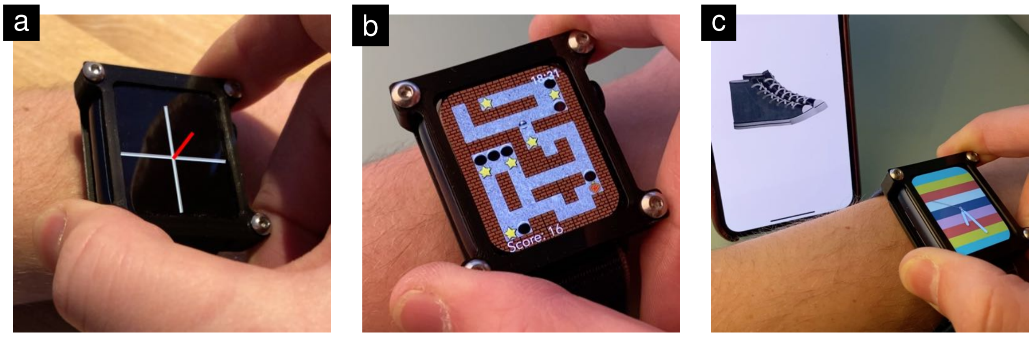


Figure 6.1: (a) Graph view of inclination to the top right. The length of the red line represents the extent of the inclination. (b) Balancing game on Tilt-Watch. The gravity of the game is changed by the inclination. (c) 3D viewer application running on iPhone. Tilting the smartwatch manipulates the viewing direction.

The interaction makes use of the gravity metaphor, but does not rely on gravity, because it measures the distance towards the arm and thereby the inclination in relation to the forearm. Weberg et al. [2001] explained the usage of a device's inclination as input, by comparing it to sliding a stick of butter in a hot pan. The following section provides more examples of the interaction.

6.2 Tilt-Watch Applications

To illustrate the potential of Tilt-Watch, we present three applications to explain the use-cases of the presented interaction technique. The applications are inspired by the ones described by Rekimoto [1996], who presented the first mobile-device prototype with inclination-based input. Rekimoto [1996] implemented one-dimensional menu selection tasks, a two-dimensional map browser as well as a three-dimensional object viewer.

One-Dimensional Direct Input

There are use-cases (e.g. scrolling), that require only a single degree of freedom. In this case, only one of the two dimensions is used and the other one is discarded. With this, the inclination of Tilt-Watch could be used to implement an alternative to existing scrolling solutions.

Two-Dimensional Direct Input

Navigation of planar content like a map requires two-dimensional panning. Tilt-Watch can enable the manipulation of the viewport by tilting the smartwatch, i.e. tilting the smartwatch to the top pans the viewport to the top. Users can vary the speed by decreasing or increasing the inclination. Based on this input technique, we implemented a two-dimensional balancing game where you have to navigate a marble through a maze (Figure 6.1b). With this, we were able to test a wide range of tilt-sequences and were able to experiment with two-dimensional direct input.

Two-Dimensional Indirect Input

With the aid of user feedback gathered during the study (see Section 4 "Study: Maximum Degree of Inclination"), we found that participants wanted to control more, than just onscreen content. One participant imagined controlling an two-dimensional industrial crane at a production site by tilting the smartwatch on his arm. To illustrate using Tilt-Watch as a remote controller we implemented an application, that displays a 3D model on an iPhone that can be controlled with Tilt-Watch (Figure 6.1c). Tilting the smartwatch directly manipulates the viewing direction of the object.

Chapter 7

Summary and Future Work

The last chapter concludes the thesis in three parts. First, the limitations are presented and discussed. After that, we give a summary and list the contributions of our findings. The last section describes the variety of future work that can build onto this thesis.

7.1 Limitations of Tilt-Watch

Direct sunlight disturbs the sensors

When investigating how Tilt-Watch performed during movement, we found that direct sunlight disturbs the rangefinders. In Section 3.1.2 "How Tilt-Watch Measures Inclinaton", we explained that the rangefinder measures the intensity of the reflected infrared light. To be precise, the QRE1113 from ON Semiconductor used in Tilt-Watch emits light with a peak wavelength of 940 nm. On the other hand, the spectrum of sunlight spans a range of 100 nm to about 1.000.000 nm. Thus, the photo-electric diode of the rangefinder cannot distinguish between infrared light emitted by its own LED or infrared light emitted by the sun. We expected this effect when exploring sensors but still decided to continue with infrared-based sensors. This was because they were already used in other research projects and based on our findings these sensors were the best fit for fast prototyping.

As explained in Section 4.8 "Limitations" the study could only be conducted with ten participants. Additionally, during the study we found that using the Apple Watch limits the range of inclination, where Tilt-Watch can provide feedback. This is because the display is turned off when the Apple Watch is tilted strongly. In the section we also explained that the button placement on the Apple Watch made one participant adjust his grip, in order to prevent accidental activation.

7.2 Summary and Contributions

Tilt-Watch enables two-dimensional continuous input

This thesis investigated a novel input technique for smartwatches that enables two-dimensional continuous input without occluding the screen. With Tilt-Watch we built a prototype containing nine rangefinders to measure the distance towards the arm. With these sensors, we calculate the inclination of the smartwatch originating from its resting position.

Inclination-based input can be precise and intuitive

Important work on inclination-based input on mobile devices was presented by Rekimoto [1996], according to which inclination-based input can be precise and expressive. Götzelmann and Vázquez [2015] investigated inclination-based input on smartwatches with the goal to improve keyboard input on smartwatches and found the interaction to be intuitive and fast to learn.

We found that on average, people tilt the smartwatch to 25 degrees

The presented implementation of inclination-based input on smartwatches has not been explored already. Therefore, we conducted an initial user study to explore to which degree people comfortably tilt smartwatches. We found that on average people tilted the smartwatch to 25 degrees and preferred tilting over the sides, rather than the corners. Also, the maximum comfortable inclination differed widely for different users, thus the algorithm computing the inclination has to be adapted to a specific user. This can be done by a calibration step or by a learning algorithm, which adapts the appropriate parameters automatically by monitoring the users use of this input modality. Feedback in the study concerning the input modality was generally positive and users imagined applications like skipping a song or manipulating the viewport of a map.

We implemented two demonstrator applications

Additionally, we implemented different applications that demonstrate the technical capabilities of Tilt-Watch. In the study, several people were reminded of the marble balancing game where you have to navigate a marble through a maze by turning two knobs that control the inclination of the platform. Therefore, we implemented a balancing game that is controlled by tilting the smartwatch on the arm. Also, we implemented a 3D viewer application that supports indirect input to manipulate the viewing direction by using Tilt-Watch as a remote controller. Both sample applications showed that inclination based input relativ to the forearm can be valuable to be incorporated in future smartwatches.

7.3 Future Work

This concluding section presents future work, divided into three categories. First, technical improvements to the Tilt-Watch protoype are presented. After this, we list a range of user studies we propose to deepen the understanding of the proposed interaction. Lastly, we present further interaction possibilities which we did not investigate for the thesis but found during working on it.

7.3.1 Improving the Prototype

Using VCSELs makes Tilt-Watch robust against sunlight

As explained earlier in Chapter 7.1 "Limitations of Tilt-Watch", Tilt-Watch breaks when direct sunlight shines onto the wrist. This limitation could be solved by using different sensor types. We think that vertical-cavity surface- emitting lasers are best suited for this application. These sensors are not based on measuring the intensity of the reflected light, but on the duration light beams travel towards and object and back to the sensor. Thus, these will not be influenced by sunlight.

Tilt-Watch body is very rectangular

Allthough Tilt-Watch was designed to be as small as possible, its body can still be improved. One study participant noted that Tilt-Watch is so much more angular than a regular Apple Watch, to a point where it was easier to use Tilt-Watch. When we asked participants to reason the ease of tilt, some mentioned that the corners of the prototype pressed into the skin, when tilting diagonally. This can be

attributed to the way, we designed the Tilt-Watch case to be printed. Future studies could investigate if the form factor influences the way people grab the smartwatch.

7.3.2 Future User Studies

After finishing the current prototype, we discussed which aspects of the interaction we wanted to study in detail. We found that before studying the inclination accuracy or the performance compared to other input modalities, we needed to understand the basis of the interaction: What is the inclination range we can expect users to use comfortably? This is why we decided to study the maximum degree of comfortable inclination first (see Chapter 4 "Study: Maximum Degree of Inclination").

Investigating inclination accuracy is the next step

We planned on investigating the inclination accuracy next. Rekimoto [1996] found that users were able to control the inclination of a handheld mobile device with an accuracy of only 2 degree, provided that visual feedback was displayed. The accuracy could also be determined in two ways: On the one hand, one could investigate only one-dimensional accuracy with selection tasks on vertical or horizontal lists. On the other hand, one could also evaluate accuracy in a two-dimensional selection task like a grid. In selection tasks like these, the independent variable is the number of targets. When there are more targets, the targets are smaller and thus more accuracy is needed.

Another factor that could be tested in the study is the effect of feedback on accuracy. Rekimoto [1996] already emphasized the importance of visual feedback for inclination accuracy. Today, haptic engines are built into every smartwatch by default, and it was shown that users can even distinguish different types of haptic stimuli on their wrist [Pasquero et al., 2011]. Including haptic feedback in addition to, or instead of visual feedback could improve the inclination accuracy.

The use of haptic feedback could be explored

In addition to the feedback type, movement is expected to have an effect on accuracy, too. In Chapter 5 "Preliminary Investigation: Performance During Movement", we presented a small excursus into the topic, but a future user study has to be conducted.

Performance during movement could be explored

Finally, we imagine comparing inclination-based input to other input modalities of smartwatches. To study this, users would do the same task with different input modalities: Touchscreen input, rotating bezel input, rotating crown input and inclination-based input.

Tilt-Watch should be tested against touchscreen input or rotating crown input

7.3.3 Further Interaction Possibilities

After spending more than six months on the topic and having built several prototypes, we still found new ideas that Tilt-Watch could enable even with the current prototype.

Tilt-Watch should be able to detect whether the whole smartwatch is hoisted away from the wrist. This is possible, when pinching the watchband and pressing it beneath the smartwatch with the thumb and the index finger. The prototype could detect this, when the five sensors in the center of Tilt-Watch first raised approximately the same rate and suddenly reach their maximum at a similar time. The outer four sensors could detect reflections from the watchband.

Until now only the absolute, two-dimensional inclination value was used for classification of movements. In addition to the absolute value, one could also take into account the gradient of consecutive values, i.e. the rotational speed.

Calculating the rotational speed could enable implementing brief tilt gestures

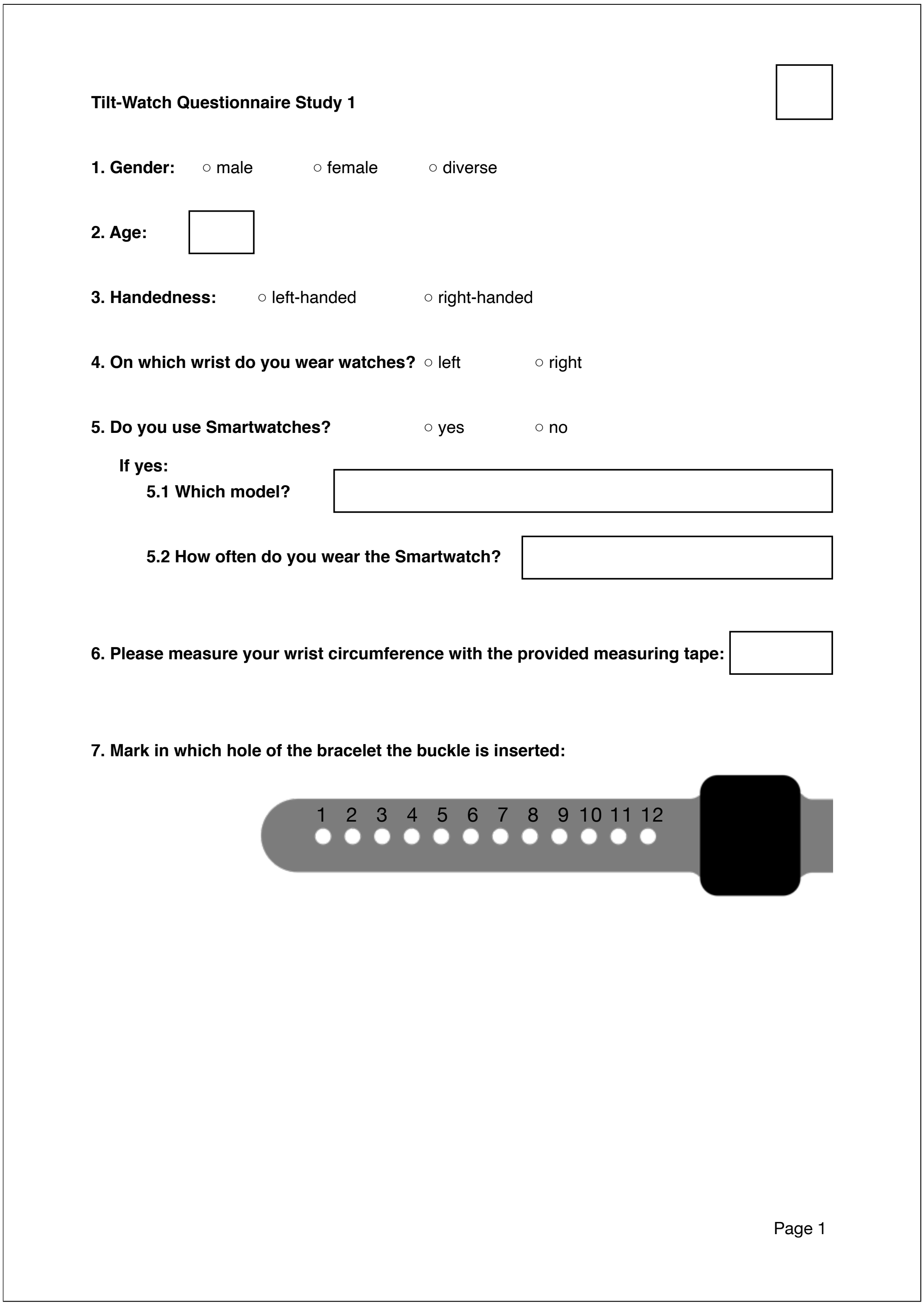
Because Tilt-Watch only publishes values every 100 ms, this should be calculated on the ESP32 itself, in order for it to be more precise. We imagine that calculating the rotational speed would make it easy to implement brief tilt gestures like flicking the watch and thereby tilting it to the right side and then immediately releasing it again. An interaction like this would take less than one second and could be implemented in addition to the current interaction.

New sensors built into smart devices constantly enable new interaction capabilities that current research does not cover. The technology incorporated in Tilt-Watch enables expressive input on smartwatches with the potential to be part of the interaction with smartwatches in the future.

Appendix A

User Study Questionaire

This appendix contains both pages of the user study questionnaire. Figure A.1 depicts the first page, which was administered before the experiment. Figure A.2 depicts the second page investigating the ease of tilt and was filled out by participants after the experiment.



Tilt-Watch Questionnaire Study 1

1. Gender: ○ male ○ female ○ diverse

2. Age: ☐

3. Handedness: ○ left-handed ○ right-handed

4. On which wrist do you wear watches? ○ left ○ right

5. Do you use Smartwatches? ○ yes ○ no

If yes:

5.1 Which model? ☐

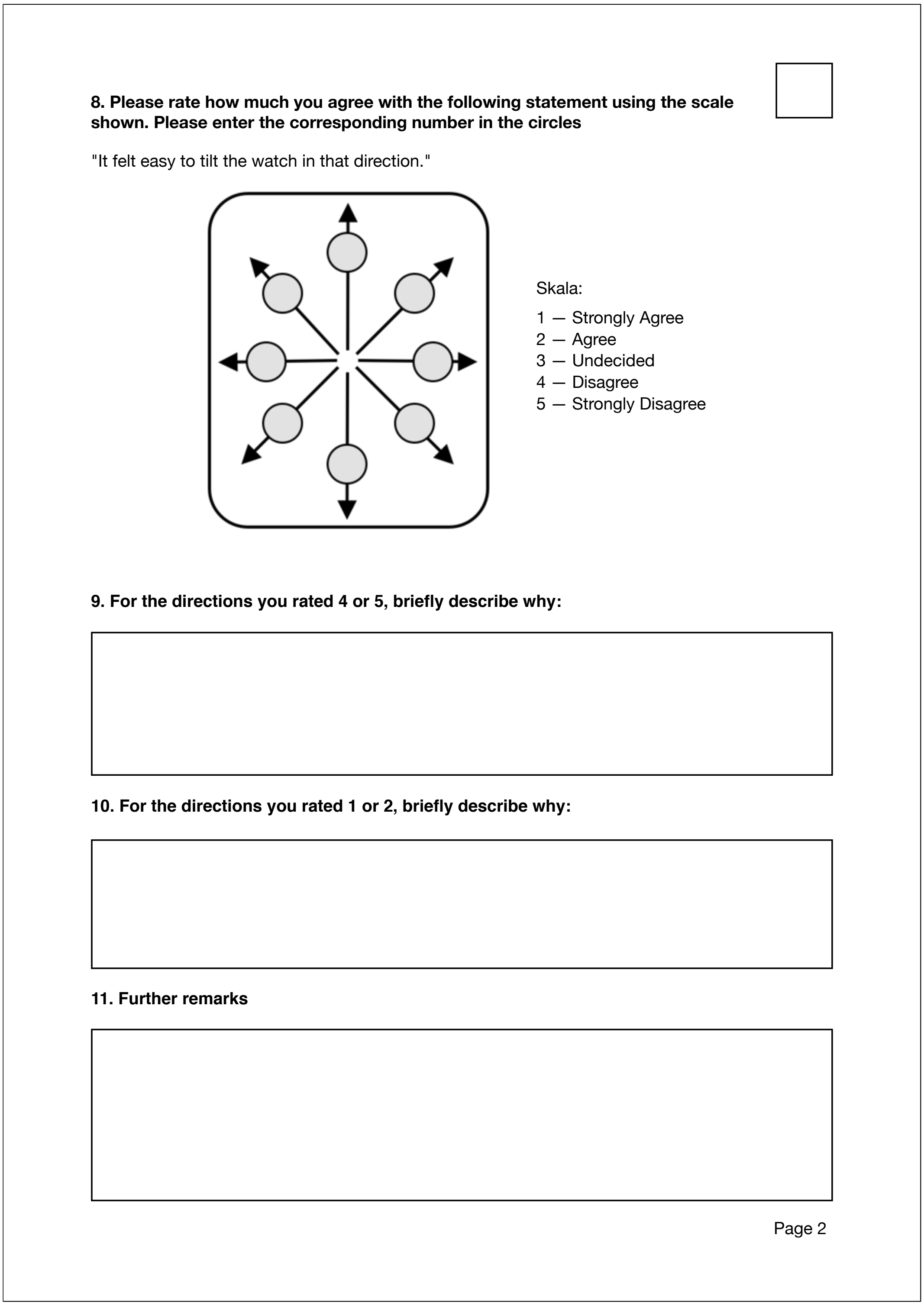
5.2 How often do you wear the Smartwatch? ☐

6. Please measure your wrist circumference with the provided measuring tape: ☐

7. Mark in which hole of the bracelet the buckle is inserted:

Page 1

Figure A.1: First page of the questionnaire answered before doing the experiment



8. Please rate how much you agree with the following statement using the scale shown. Please enter the corresponding number in the circles

"It felt easy to tilt the watch in that direction."

Skala:

1 — Strongly Agree
2 — Agree
3 — Undecided
4 — Disagree
5 — Strongly Disagree

9. For the directions you rated 4 or 5, briefly describe why:

10. For the directions you rated 1 or 2, briefly describe why:

11. Further remarks

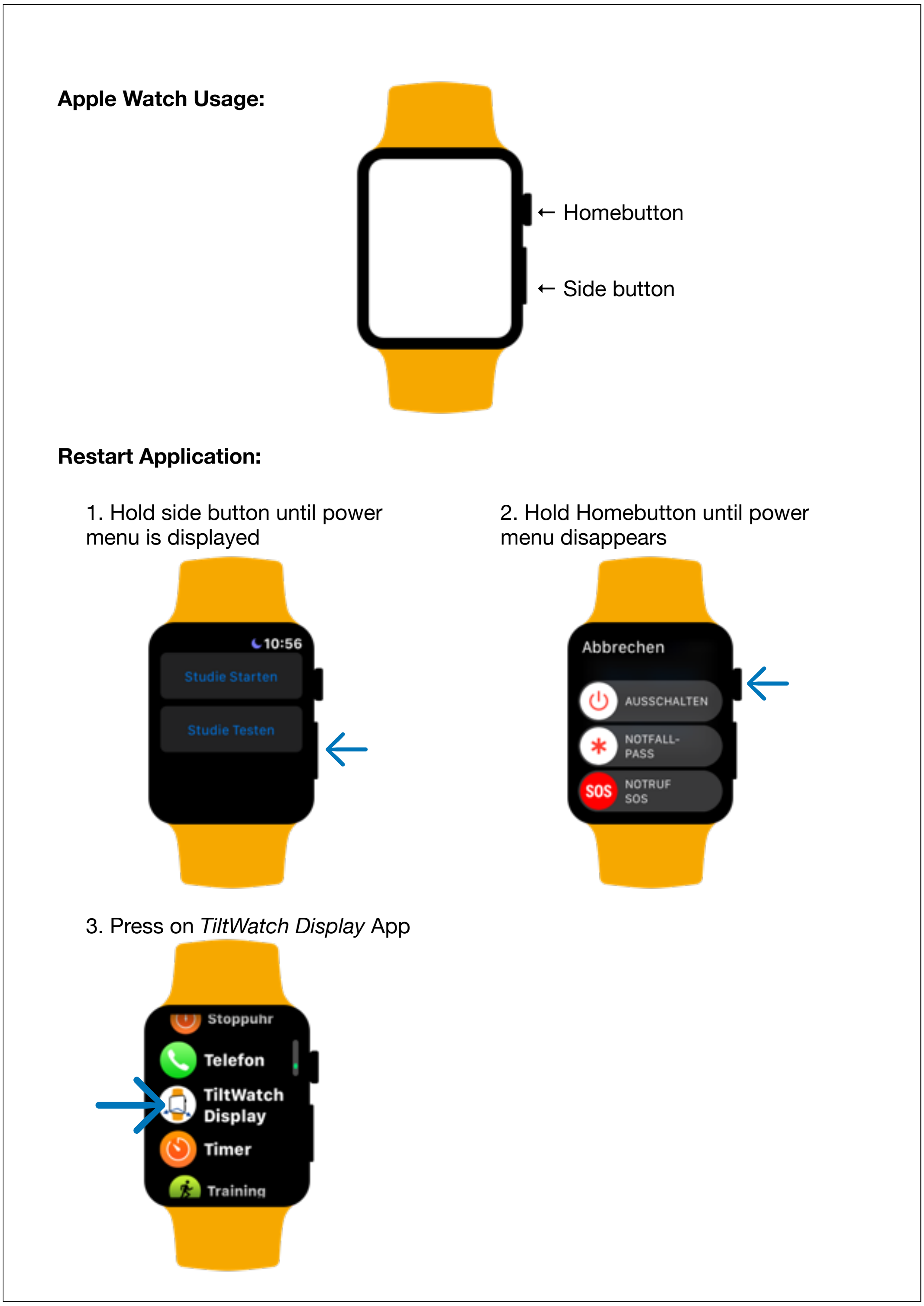
Page 2

Figure A.2: Second page of the questionnaire answered after doing the experiment

Appendix B

Apple Watch Usage Guide

This appendix contains the Apple Watch usage guide for the study. The page was printed out in order to ensure trouble-free operation despite COVID-19 safety distance and enabled the participants to operate the Apple Watch on their own.



Apple Watch Usage:

Restart Application:

1. Hold side button until power menu is displayed

2. Hold Homebutton until power menu disappears

3. Press on *TiltWatch Display* App

Figure B.1: Apple Watch usage guide for the study to ensure trouble-free operation despite COVID-19 safety distance

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Index

Bluetooth, 15

dwell-time, 28

ESP32, 16
experimental design, 25

fat finger problem, 6
force sensing resistor (FSR), 13

inclination-based smartwatch input, 39
interaction design, 39
intertial measurement unit (IMU), 11

Linux Watch, 12

performance during movement, 35
photo-reflective rangefinder, 14
Proof of concept, 16
Pull-up Resistor, 17

smartwatch, 1
study discussion, 31
study limitations, 33
study procedure, 26

Tilt-Watch, 39
Tilt-Watch applications, 40

ultrasonic distance sensor, 13

vertical-cavity surface-emitting laser (VCSEL), 14

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