

Master's Thesis

Enabling Independent Swimming for Blind and Visually Impaired Athletes

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Abstract

Blind and visually impaired (BVI) swimmers cannot independently detect the end of a swim lane, impacting their safety and training efficiency. As a result, BVI swimmers rely on a 'tapper', which limits their ability to train independently and increases the risk of injuries. This thesis investigates whether a transmitter-based technology can enable BVI swimmers to independently detect their turning point in a swimming pool.

Design requirements were used to evaluate three transmitter-based technologies; Radio frequency identification (RFID), ultrasound and Ultra-wideband (UWB). Based on range, accuracy and power consumption, RFID was excluded. Subsequently, after performing preliminary experiments and comparing concept designs, UWB was selected for further development.

A test setup was designed with the Pozyx UWB kit and its ranging performance was characterized on land using one and two anchors. After integration of the haptic motor and a waterproof enclosure, the test setup was validated in a swimming pool. These validation tests included static measurements at and above the water surface, as well as dynamic tests with a swimmer performing front crawl and breaststroke.

The results showed that the UWB system provided reliable ranging up to eight meters, with performance decreasing significantly beyond this distance. Furthermore, the system accuracy degraded when the wearable was partially or fully submerged or when the haptic vibrations led to multipath propagation. During the dynamic tests, false negatives occurred more frequently than false positives, particularly under non line of sight (NLOS) conditions, when the swimmer's head obstructed the UWB signal.

These results demonstrate the potential of Ultra-wideband as a detection method within an eight meter range, which is sufficient to trigger the feedback signal. However, for full lane coverage, additional anchors are required. This thesis presents a proof of concept and further development is required to miniaturize the design, calibrate the ranging system for consistent performance across different swimming pools and improve the feedback component.

Preface

This report concludes my master's degree in Mechanical Engineering and marks the end of my student time in Delft. I would like to express my gratitude to everyone who supported me throughout my thesis. First and foremost, I would like to thank my supervisors, Frans and Rienk, for their guidance and valuable feedback over the past nine months. Their critical questions challenged me to think more deeply and continuously improve my work.

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Contents

Abstract	1
Preface	2
1 Introduction	5
2 Design requirements	7
3 Selection of detection method	9
3.1 Comparison detection methods	9
3.2 Concept designs	10
3.3 Feedback signal	10
3.4 Selection of concept design	11
3.5 What is Ultra-wideband technology?	12
4 Development and testing of the UWB system on land	13
4.1 UWB system and initial test setup	13
4.1.1 Initial ranging measurements	13
4.1.2 Data acquisition and analysis	14
4.2 Ranging performance	14
4.2.1 Test environment	14
4.2.2 Single anchor measurements	15
4.2.3 Two anchor measurements	15
4.3 Haptic feedback integration	16
4.3.1 Effect of haptic feedback on ranging	16
4.3.2 Effect of wearable orientation	18
4.4 Development of the waterproof system	19
4.4.1 Final ranging measurements	19
4.5 Discussion of land measurements	20
5 System validation in a pool environment	22
5.1 Pool test with test setup above the water surface	22
5.1.1 Test setup at pool environment	22
5.1.2 Ranging results	22
5.2 Pool test with the test setup at water level	23
5.2.1 Results outside the trigger zone	24
5.2.2 Results inside the trigger zone	25
5.3 Pool test with a swimmer	25
5.4 Discussion of pool test results	26
6 Discussion	29
7 Conclusion	32
References	33
A Final versions of Arduino sketches and Python scripts	35
B One-anchor measurements performed at ECHO	51
C Two-anchor measurements performed at ECHO	52
D Two-anchor measurements performed at X, outside the trigger zone	54
E Two-anchor measurements performed at X, inside the trigger zone	56
F Components of the final test setup	58

G	Land-based benchmark measurements with the final test setup	59
H	Measurements performed in the pool	64
I	Measurements at water level in the pool, outside the trigger zone	67
J	Measurements at water level in the pool, inside the trigger zone	69

1 Introduction

Blind and visually impaired (BVI) athletes face numerous challenges in their daily lives due to limited access to visual information. In sport, these challenges are also present. As visual signals play an important role in perceptual motor skills such as orientation, timing and spatial awareness (Wenderoth & Weigelt, 2009), performance at the highest levels can be affected. Additionally, it may limit the athletes' independence. Independence is particularly crucial in sport, especially when it comes to consistent and effective training (Gibelli et al., 2023). For BVI swimmers, the most difficult aspects of swimming are recognizing where the end of the swim lane is and swimming without deviating from their intended swimming path. Both aspects are essential to keep BVI swimmers safe and unharmed during their training or competition.

Currently, the most used solution for recognizing the end of the swim lane is that each BVI swimmer has a 'tapper' at both ends of the swimming pool (Muehlbradt et al., 2017; Oommen et al., 2018). A tapper is a staff member who is responsible for tapping the BVI swimmer on the head or the back, to warn the swimmer about the end of the swim lane. This is done using a long cane with a ball (e.g. tennis or foam) attached to the end. This solution is far from ideal, given that the swimmer relies on another person at all times (Gibelli et al., 2023). For the front crawl and backstroke, the BVI swimmer is always tapped at the same distance from the poolside, around the three meter mark. The swimmer then has to decide whether they can complete a full swimming stroke before reaching the pool wall. For the breaststroke and butterfly stroke, this differs slightly. Because the swimmer's head is submerged for part of the stroke, the tapper has to estimate when to tap the swimmer. After the tap, the swimmer finishes the current stroke and then starts their turn.

Hence, the tapper-swimmer relationship has to be trained to perfection, since a tap which is given too early or too late can result in the swimmer either missing the pool wall or ending up very close to it. Nevertheless, such misjudgments almost never happen in practice, as the BVI swimmers generally end up in the right spot by the pool wall. It is the exception rather than the norm (R. Van den Haak, personal communication, September 28, 2026).

Another technique that is used by BVI swimmers to identify their turning point is counting the number of strokes (Veldhuizen, 2025). However, this requires the swimmer to be very consistent and stable in swimming to make this a reliable method. Moreover, the number of strokes differs per swim pace, which makes it more difficult to always be accurate (Veldhuizen, 2025).

Problem definition

The current state highlights the need for technology to enable blind and visually impaired swimmers to swim autonomously. As long as they are dependent on others while training, it limits the training efficiency of BVI swimmers and this may negatively affect their swimming potential. This limitation can particularly be seen during the turn. BVI swimmers tend to show slower performances on short course events with an increased number of turns, indicating time losses associated with turning (Wippich, 2024). This is in contrast to sighted swimmers, who benefit from more turns.

Besides that, BVI swimmers may touch the lane rope to confirm in which direction they are swimming, leading to an unusual swimming posture which again leads to time loss and can be perceived as disturbing by the BVI swimmer (Chien et al., 2018).

In addition, BVI swimmers are afraid of collisions with the lane rope or worse, the pool wall. These collisions can lead to serious physical injuries such as concussions, bruises, abrasions and hitting the heels against the pool edge while turning (Chien et al., 2018; Veldhuizen, 2025).

This solution gap can be divided into two parts. First, the technology or technique should include a detection component, which is able to detect the BVI swimmer or their position with respect to the pool wall. Once the swimmer or their position is detected, a feedback component should provide information back to the BVI swimmer, telling them that they have reached their turning point.

Based on the findings of the literature review of Hugo Stallenberg, this report will investigate three transmitter-based technologies and compare them against one another using parameters like accuracy and operability in the pool. Subsequently, extensive measurements are performed using the selected technology to further understand and evaluate its performance.

Based on the problem definition, this thesis pursues the following research goal:

Is a transmitter-based technology suitable to enable blind and visually impaired swimmers to independently detect their turning point in any swimming pool?

To help answer this question, several sub-questions are proposed:

- *Which transmitter-based technology has the greatest potential to enable blind and visually impaired swimmers to independently detect their turning point?*
- *How does the selected technology perform in ranging measurements conducted on land?*
- *How can this technology be developed into a waterproof and wearable design and validated through ranging measurements in a swimming pool?*

Focus group

This thesis has been conducted in collaboration with the Paralympic swimmers from TeamNL, specifically the blind and visually impaired swimmers. There are three sport classes for swimmers with vision impairment, namely S/SB11, S/SB12 and S/SB13 (Swimming, 2022). The prefixes S & SB stand for different kinds of swimming strokes, where the 'S' represents freestyle, butterfly and backstroke events and the 'SB' breaststroke events. In Table 1.1 the three classes are described.

S/SB11	S/SB12	S/SB13
Have a very low visual acuity and/or no light perception	Have a higher visual acuity than athletes competing in the S/SB11 sport class and/or a visual field of less than 5 degrees radius	Have the least severe vision impairment eligible for Paralympic sport. They have the highest visual acuity and/or a visual field of less than 20 degrees radius

Table 1.1: Sport classes for athletes with a vision impairment (Swimming, 2022)

This thesis focuses only on design criteria derived for the BVI Paralympic swimmers from TeamNL. As a result, the outcome may not be directly applicable to recreational or other BVI swimmers.

Report structure

Chapter 2 first presents the design requirements derived from the literature review. Chapter 3 elaborates on the selection of the detection method from the three transmitter-based technologies. Afterwards, Chapter 4 presents the results from the measurements conducted on land and discusses these results. In Chapter 5, the outcome of the measurements performed in the swimming pool are presented and discussed. Chapter 6 addresses the research goal and sub-questions, evaluates whether the design requirements have been fulfilled, and concludes with recommendations for future research. Finally, Chapter 7 presents the conclusions of this report.

2 Design requirements

Before selecting a detection technology, a set of design requirements was established. These requirements were derived from the literature review conducted by Hugo Stallenberg, which explored methods for enabling blind and visually impaired swimmers to recognize the end of the swim lane. In the literature review, the design requirements were further complemented with the input from the national coach of the Paralympic swim team of TeamNL, Bram Dekker.

Table 2.1 lists the design requirements, which were ranked by importance by the author. DR-01 is the most crucial design requirement and therefore is listed first. Then, DR-02 till DR-06 are regarded as the second most important set of requirements. Lastly, DR-07 till DR-11 are deemed the least important from this list.

Table 2.1: Design requirements: ranked by importance (ranked by author)

Design requirement	Description
DR-01	The design must enable the BVI swimmer to train independently in a lane, without the presence of other swimmers or relying on external assistance. This also includes the weight and size of the design: it must be transportable independently by the BVI swimmer.
DR-02	The design must be reliable and ensure the safety of the BVI swimmer by enabling timely recognition of the pool wall while swimming, preventing a collision with the wall under normal training conditions.
DR-03	The design must withstand water movement along the body of the BVI swimmer without hindering the BVI swimmer while swimming.
DR-04	The design must operate for at least 2.5 hours continuously.
DR-05	The design should be usable as much as possible in combination with standard training material, such as snorkels (including front-mounted snorkels), kickboards, pull buoys, zoomers, and equipment dragged behind the swimmer.
DR-06	The design must operate without requiring a power socket.
DR-07	The costs of the design should be kept as low as possible.
DR-08	The design must function regardless of the body position of the BVI swimmer (e.g. during different kinds of swimming strokes).
DR-09	The design should be as suitable as possible for BVI swimmers of all genders, races, and ages.
DR-10	The design must be easy to use for the BVI swimmer.
DR-11	The features of the design must be comfortable for the BVI swimmer.

Additionally, in Table 2.2, the technical design requirements are presented. These technical requirements defined the pool and water conditions, under which the system must operate.

Together, these two sets of design requirements formed the basis against which the three technologies in Chapter 3 were evaluated, and later guided the design decisions made during testing and development of the design in Chapter 4 and Chapter 5.

Table 2.2: Technical design requirements

Technical design requirement	Description
TDR-01	The design must be suitable for a 4- to 10-lane swimming pool, with a swim lane width of 2.5 meters per lane.
TDR-02	The design must be suitable for a long course swimming pool, with a length of 50.000–50.030 meters.
TDR-03	The design must be suitable for a short course swimming pool, with a length of 25.000–25.020 meters.
TDR-04	The design must be suitable for a swimming pool depth of 1.4–2.5 meters.
TDR-05	The design must operate in a water temperature of 25–28 degrees Celsius.
TDR-06	The design must operate in water with a salt concentration of 3 grams of salt per liter.
TDR-07	The design must operate under the strictest water quality requirements (in accordance with Article 15.16 of the " <i>Besluit activiteiten leefomgeving</i> ") (Overheid.nl, 2025).

3 Selection of detection method

The upcoming chapter discusses three transmitter-based technologies, one of which is selected for further development in this thesis. In Section 3.1, the three technologies are compared against each other based on several design requirements from Chapter 2. Subsequently, Section 3.2 presents the concept designs for ultrasound and Ultra-wideband. The feedback component of these concept designs is then discussed in Section 3.3. In Section 3.4, one of the concept designs is selected based on its performance and limitations. Finally, Section 3.5 describes Ultra-wideband technology and what types of noise can affect its measurements.

3.1 Comparison detection methods

To determine which detection method should be selected for further development, three options were explored: Radio frequency identification (RFID), ultrasound and Ultra-wideband (UWB).

Radio frequency identification uses radio waves to enable wireless communication between the RFID reader and the RFID tag, which is attached to an object or person. When the reader emits a radio signal via its antenna and the tag is in range, the tag responds by transmitting its stored data. Then, the object can be identified and tracked without requiring a direct line of sight (LoS). As the radio waves are strongly attenuated by water, which reduces signal transmission, both the reader and the tag need to remain above the water surface (Domdouzis et al., 2007; Roberts, 2006).

Ultrasound sensing operates by emitting high-frequency sound waves and measuring the time it takes for the echoes to return after reflecting off an object or a person. The distance between the sensor and object is calculated by multiplying the speed of sound with the time it took for the sound wave to return, known as the time of flight (ToF). Since the speed of sound differs significantly between air and water, because of the different densities and acoustic properties, there are two kinds of ultrasound sensors: underwater sensors and air-based sensors. This means that an air-based sensor typically will not work underwater and vice versa (Qiu et al., 2022).

Ultra-wideband is a wireless positioning technology that works by transmitting short radio pulses across a wide frequency spectrum between the two UWB radio transceivers. By measuring the time of flight of these pulses, the distance between the two devices can be determined with centimeter-level accuracy. These systems typically consist of a tag and one or more anchors, whereby the measured distances are used to determine the tag's position. However, the radio pulses cannot propagate through water as water attenuates the signal. This means that both the tag and the anchor need to remain above the water surface (Alarifi et al., 2016; Pozyx, 2026).

Parameter comparison of detection methods

The three technologies were further investigated to determine the most suitable option for this thesis. As presented in Table 3.1, the technologies were assigned a score for each parameter. This could either be low, medium or high, depending on how well the technology was expected to operate. Each parameter could be linked to one or more (technical) design requirements from Chapter 2.

First, the accuracy could be linked to DR-02. To ensure the reliability and safety of the BVI swimmer, the system had to be accurate and warn the BVI swimmer on time. Secondly, the power consumption was relatable to DR-04, as low power consumption would facilitate a longer operating time and thus help achieve the minimum operating time of 2.5 hours. Thirdly, the cost of the design was directly addressed in the requirements as DR-07. Lastly, the range represented TDR-01 till TDR-03, as these requirements concerned the pool dimensions. The greater the range of the design, the easier it would be to cover the entire swim lane. Because RFID scored poor for accuracy and power consumption and the range is expected to not cover an entire swim lane, this thesis continued with ultrasound and Ultra-wideband technologies.

Table 3.1: Parameter comparison between RFID, ultrasound and UWB

	RFID	Ultrasound	UWB
Accuracy	Low	Medium	High
Power consumption	High	Medium	Low
Cost	Medium	Low	Low
Range	Medium	High	High

3.2 Concept designs

For both detection methods, several concept designs were invented. These were concepts that illustrated the working principle of the design and what it would look like. First, the concept designs for ultrasound will be described, followed by the concept designs which integrated Ultra-wideband.

Ultrasound

The first concept design based on ultrasound applied an underwater ultrasonic sensor. As this sensor specifically was designed for underwater applications, it was relatively easy to implement this design in the swimming pool. The sensor was placed on the pool wall and below the water surface. It emitted ultrasonic waves, which propagated through the water and reflected off the swimmer's body. Subsequently, the sensor received the reflected waves and calculated the distance of the swimmer based on the measured time of flight. Because this ultrasonic sensor was designed for underwater applications, the sound waves only travelled through water and thus the sensor was expected to provide reliable detections in the pool environment.

Another concept had the ultrasonic sensor mounted on the swimmer's head. As this sensor remained above the water surface for a large part of each swimming stroke, an air-based ultrasonic sensor was considered appropriate. It sent the ultrasonic waves towards the pool wall in front of the swimmer, where they would be reflected off and travelled back to the sensor. Based on the ToF of the reflected waves, the distance to the pool wall could be calculated.

However, two major challenges arose with the second concept, where the ultrasonic sensor was located on the swimmer's head. First, the sensor was expected to not always be aimed at the correct pool wall. Because the emitted ultrasonic waves had to reflect off the pool wall whose distance was being measured, it was important that the sensor was directed towards the pool wall in front of the swimmer. However, as a swimmer will have to breathe, this will lead to head rotations while swimming and therefore the ultrasonic sensor will be rotated as well. This could affect the measured distance as the measured distance is no longer the actual distance to the pool wall in front of the swimmer.

Secondly, this design operated with an air-based ultrasonic sensor, which would not be reliable when (slightly) immersed. This was likely to happen while swimming, as the sensor would be exposed to water splashes which could interfere with the ultrasonic waves. As a result, the reliability and accuracy could be reduced.

Ultra-wideband

The concept ideas which implemented Ultra-wideband technology required the tag and the anchor to remain above the water surface to maintain their connection, as this system communicated via electromagnetic waves which are strongly attenuated by water. Therefore, the concept ideas aimed to minimize the time spend underwater by either the tag or the anchor.

This led to the first concept design, where multiple tags were distributed around the swim cap of the swimmer. This would ensure that for every moment during a swimming stroke, at least one tag remained above the water surface. By doing so, a reliable connection between the tag and the anchor could be established along the entire length of the swim lane.

The second concept idea integrated a single tag into the swim cap. It was decided to position the tag at the occipital region of the head. This location was expected to provide a steady connection during the front crawl, the breaststroke and the butterfly stroke, as the occipital region remained above the water surface for most of the stroke cycle (Gibelli et al., 2023).

The third concept idea included two tags integrated into the swim cap. The first tag was mounted at the occipital region, as previously mentioned, while another tag was positioned at the forehead of the swimmer. It was discovered that these two regions combined had the least percentage of immersion across different swimming strokes and were therefore selected (Gibelli et al., 2023). Consequently, it was predicted that the tags would remain above the water surface for a longer period in time and improve the reliability of the connection.

Lastly, each design also included the anchor placement. This was identical for all three concept designs. Two anchors were used and they were placed on opposite sides of the swim lane on the poolside.

3.3 Feedback signal

Besides the detection method, the feedback component had to be taken into account. Without a feedback signal, the first two design requirements from Chapter 2 could never be achieved, as the BVI swimmer would need to receive a feedback signal to train independently and to avoid collisions with the pool wall.

For the concept designs using ultrasound, this proved to be quite a challenge. The first concept had the sensor positioned at the pool wall. Since the distance calculations were performed by this sensor, the feedback signal had to originate from the pool wall as well. This introduced a similar problem to that of the detection method, as a communication link was required between the ultrasonic sensor and the BVI swimmer to provide feedback. For the second concept idea, with the sensor positioned on the swimmer's head, it was slightly less complicated. The sensor could transmit a signal instantly to the feedback component, allowing for the feedback signal to be applied. The connection between these two components could be established by wires, which would be located on the swimmer's head.

To incorporate the feedback component in the UWB concept designs was less complex. The UWB tag was already located on the swimmer's head. From this tag a signal could be sent to the feedback component, enabling feedback to be provided to the BVI swimmer. Similar to the head-mounted ultrasound design, the connection between the two components could be established using wires, as both components were located on the swimmer's head.

3.4 Selection of concept design

In order to select one of the two detection methods, preliminary tests were conducted. These were performed with simple experimental test setups for both UWB and ultrasound. These tests were not formally recorded, as they were only used to investigate the working principle and assess the performance of both methods. The measured performance was utilized to determine the reliability of each method and whether that method could ensure the safety of the BVI swimmer, thereby satisfying DR-02.

Both the UWB tag and the ultrasonic sensor were connected to a microcontroller, the Arduino Uno. The Arduino Uno was connected to a laptop, which provided power to the detection systems. To operate both systems, Arduino code was necessary, which was written in a 'sketch'. These sketches were uploaded to the Arduino Uno. The sketches used were written with the help of Claude AI, as well as all the future sketches for this thesis (Anthropic, 2026).

Performance

The underwater ultrasonic sensor demonstrated good measurement accuracy. It produced consistent readings. Variations in the mean distance were minor and the bias was negligible. It should be noted that, since this ultrasonic sensor was made for underwater purposes, these tests were conducted in a small water tank at home. Due to the small distances, the measured distances were limited. This slightly reduced the representativeness of the tests. Next up was the UWB system. This performed well, establishing a high accuracy with minimal variations and a small bias. The test setup was arranged at home, where the distances between the tag and the anchor ranged from two to four meters.

Overall, the two detection methods demonstrated comparable performance during these preliminary tests. Because no notable differences in performance were observed, these tests could not help decide which detection method was more promising. Therefore, the technology selection was based on the limitations of the concept designs.

Limitations

The major limitation of the first ultrasound concept design was that the feedback signal had to be sent from the pool wall. This would require an additional communication link between the pool wall and the BVI swimmer, effectively proposing a similar problem as the original detection problem. Therefore, this design was excluded. The second ultrasound concept design, where the ultrasonic sensor was positioned on the swimmer's head, was expected to be inconsistent due to the head rotations and the frequent immersions while swimming, which reduced the reliability of the measurements. As a result, this concept did not meet the safety requirements for the BVI swimmer and failed to satisfy the second design requirement. Therefore, it was also excluded.

Reconsideration of the tag placement on the swim cap for the UWB concept designs, showed that multiple tags around the swim cap were excessive. Given the high signal update rate from the tag, it was considered acceptable if the tag occasionally lost connection due to submersion while swimming. As a result, only a single tag in the swim cap was deemed sufficient. This would greatly reduce the complexity of the design. Therefore, it had the potential to satisfy the design requirements.

In conclusion, Ultra-wideband was selected for further development based on the comparison of the limitations of the different concept designs. The design consisted of a single tag, which would be placed at the occipital region on the swim cap. Besides the tag, a battery and a feedback component were integrated into the swim

cap. Implementing a battery in the design would satisfy the sixth design requirement by eliminating the need for a power socket. Furthermore, the fourth design requirement regarding the operating time, could be achieved by selecting a suitable battery. Finally, the design included two anchors, positioned on the poolside on opposite sides of the swim lane.

3.5 What is Ultra-wideband technology?

Before describing the implementation of Ultra-wideband as the detection method, it is useful to provide background information about UWB and how this technology operates (Minew, 2025; Murata Manufacturing Co., Ltd., 2023). It originated in the 1960s, where UWB was primarily developed for military radars. In the early 2000s, it was first declassified and made available for civilian use as well. It typically operates within the frequency spectrum of 3.1 to 10.6 GHz. Next to that, it transmits very short radio pulses of approximately 2 ns over a wide channel bandwidth of 500 MHz. This results in highly accurate ranging and positioning. This is unlike Bluetooth or Wi-Fi for example, as these systems continuously transmit on a smaller frequency range. Due to the low power consumption of UWB, it can coexist alongside other wireless technologies with minimal interference.

As mentioned previously, there are multiple ranging methods when using UWB. All methods determine the distance between the tag and the anchor by measuring the Time of Flight and multiplying it with the speed of light. The difference between these methods lies in what physical quantities they measure and what infrastructure they require. The different methods are:

- **Time Difference of Arrival (TDoA):** Calculates the tag's position by using the time difference between the signals from different anchors. It needs three or four anchors for 2D and 3D positioning .
- **Two-Way Ranging (TWR):** Measures the total round-trip time it takes to travel between the tag and the anchor. By using TWR, the need for clock synchronization of both devices is eliminated.
- **Phase Difference of Arrival (PDoA):** Phase differences across several anchors are measured to determine the distance and the direction of the signal.
- **Angle of Arrival (AoA):** With the use of multiple antennas, the angle of the arriving signal is measured. This can enable 2D and 3D positioning.

When designing a test setup that utilizes one of these ranging techniques, signal noise is inevitable. This noise can either originate from within the UWB transceivers or from external environmental sources. However, internal noise, such as thermal noise, contributes only minimally to the overall noise level and will therefore not be discussed any further in this report.

Regarding the environmental noise, the phenomenon called multipath propagation influences the performance of the ranging technique (Gharehpetian & Karami, 2023). This occurs when the UWB signal is reflected, scattered or absorbed by surfaces and objects, such as walls or floors. Reflection and scattering causes additional signal paths between the tag and the anchor. These additional signals become a delayed copy of the original signal, which travel a longer path. The ranging system is designed to detect the first arriving pulse, as this corresponds to the direct path between tag and anchor. Therefore, the effect on ranging accuracy depends on whether line of sight (LOS) is maintained.

When the reflected path is only slightly longer than the direct path, the two pulses overlap. This occurs in LOS conditions, when the direct path is detectable. The receiver may interpret the combined signal as a single pulse that arrived sometime between the direct signal and the reflected signal. In this way, the reading can produce a (positive) bias. Secondly, in non line of sight (NLOS) conditions, the direct path is blocked by an obstacle. This results in the receiver locking onto the strongest available reflected path instead. Although this reflected path might arrive as the stronger signal, it travelled a greater distance than the direct path. Accordingly, this effect can produce a (positive) bias as well.

While the bias induced by multipath interference is typically positive due to the longer path of reflected signals, destructive multipath interference between direct and reflected pulses can cause the pulses to cancel each other out and may result in a negative bias.

4 Development and testing of the UWB system on land

The following chapter describes the iterative development of the UWB system and presents the results obtained during each phase of testing. In Section 4.1, the initial test setup is explained and the updates to the hardware and software are discussed. Next, in Section 4.2, the results of the measurements performed at ECHO TU Delft with one and two anchors are presented. Section 4.3 describes the implementation of the haptic motor and shows the results of the accompanying measurements at X TU Delft. Then, in Section 4.4, the waterproof and portable test setup is shown, which is required for pool testing. Finally, Section 4.5 provides a discussion about the obtained test results on land.

4.1 UWB system and initial test setup

For this thesis, the Creator One kit from Pozyx had been used (Pozyx, [2026](#)). This kit uses the Two-Way Ranging technique and it contained four developer tags and four creator anchors, earlier described as radio transceivers. The first test setup included a developer tag, a creator anchor and the Arduino Uno. For the remainder of this report, the developer tag plus the Arduino Uno will be called the 'wearable', as this would be the main part that the BVI swimmer would have to wear. See Figure 4.1.



Figure 4.1: The wearable; including the developer tag (top) and the Arduino Uno (bottom)

4.1.1 Initial ranging measurements

The initial measurements focused on understanding how the UWB system functioned and how to develop the necessary Arduino sketches. This was achieved through an iterative experimental approach, which included clarification for both the software and the hardware setup (Wynn et al., [2007](#)). The final versions of the Arduino sketches can be found in Appendix A.

Initially, the test setup was placed on the ground, with distances of two to three meters between the wearable and the anchor. The output from the ranging measurements could be read in the Arduino IDE. However, this test setup of the UWB system introduced inaccuracies. These occurred due to the placement of the wearable and the anchor on the ground, which led to multipath reflections that interfered with the UWB signal. As a result, the anchor was elevated fifteen to twenty centimeters from the ground, which resolved the interference and this was used during future measurements.

The UWB system processed every signal as an output, which led to high variations. Amongst the raw UWB signals were extreme outliers or even failed readings. To make sure that every reading was plausibly correct, a median filter was applied. This is a filter that took a number of readings and then the median value was reported as the actual reading. Therefore, this number of readings had to be an odd number. Such a filter is commonly used in UWB systems to improve ranging performance. The Pozyx kit itself also employs several

algorithms and filters, however, this is not publicly published (Pozyx, [n.d.](#)). Two window sizes were compared against one another, one of five samples and one of three samples. The median filter of five samples greatly reduced the variations, but also decreased the update frequency considerably. Whereas the filter of three samples also significantly reduced the variations, but kept the update frequency higher. Therefore, the median filter of three samples was selected, as this provided a sufficient balance between measurement reliability and update frequency.

Ranging measurements were conducted at several distances up to a maximum of three meters. During each measurement the initial couple of readings were inaccurate, with biases up to 500 mm. These readings were discarded by flushing them and so the ranging process would start after a brief warm-up period.

4.1.2 Data acquisition and analysis

To be able to perform an analysis of the measurements, the data was logged to a CSV file using Python scripts developed in Spyder. An additional advantage was that the ranging process could be initiated directly from Spyder, without requiring the developer tag to be detached from the Arduino Uno when a sketch had to be modified between test runs. The final versions of these Python scripts can be found in Appendix A.

At the same time, a second Python script was created that could extract descriptive statistics, like the mean distance and the standard deviation. The final versions of these files can be found in Appendix A. The metrics will be explained later in this report, along with the accompanying tables. Similar to the Arduino sketches, the Python scripts were constructed with the assistance of Claude AI (Anthropic, [2026](#)).

4.2 Ranging performance

After getting acquainted with the UWB system, measurements were conducted with test setups including two anchors. The Arduino sketch and Spyder files received an update, in order to be able to measure the distance to two anchors. The working principle was similar to the test setup with a single anchor, so no drastic changes were required to let the system operate with two anchors.

4.2.1 Test environment

The initial trials including two anchors were still done at home. However, this proved to be a challenge. The main issues that arose were the multipath reflections from objects and these same objects also hindered the line of sight between the wearable and anchors. Because of these two factors, the measurements had to be done at TU Delft.

The next phase of testing was performed in a classroom in ECHO. The space that was required was available, although there were obstacles like tables and chairs. It was made sure that the line of sight between the anchors and the wearable was not blocked by any of it, to ensure a stable connection. In this setting, the test results were logged for the first time this thesis.

As previously mentioned, statistical values could be extracted from the CSV files. From these values, tables were created to show and compare different test runs. Each table contained a list of metrics in the left column. Most of the measured values were expressed in millimeters (mm). Except for the success and outlier rates, therefore percentages (%) were used and the variance was expressed in squared millimeters (mm²). Below is an explanation per metric:

- Successful (%): the number of successful readings as a percentage of the total number of readings
- Mean dist (mm): the mean distance of all readings per test run
- Mean error (mm): the mean error per test run, also reported as bias
- MAE (mm): mean absolute error, the average size of the errors per test run
- Var (mm²): variance, shows how far the readings are spread out from their average value (uses squared units)
- Std dev (mm): standard deviation, also quantifies the amount of variation in each test run (uses original units)
- Min (mm): minimum, the lowest reading
- Max (mm): maximum, the highest reading
- Outliers (%): the number of readings outside the acceptable range (± 150 mm from the set distance)

4.2.2 Single anchor measurements

The distance between the wearable and the anchor was set between three and eight meters. Per distance, ten test runs were completed to get sufficient data per distance. Per test run, 200 readings were executed. The results are shown in Appendix B. Up to seven meters, all test runs performed consistently. All readings were successful, meaning none of the signals failed ranging. The bias from the mean distance was negligible, as this was 70 mm or less in all of the test runs. The standard deviation and variance showed consistently low values across all test runs. Moreover, only seven outliers were measured in the runs going up to six meters. In Table 4.1, this can be seen for the anchor placement at six meters.

When the anchor was at seven meters away from the wearable, only the outlier rate for three test runs displayed percentages outside the acceptable range. The other results were comparable with the measurements up to six meters.

Table 4.1: UWB ranging results with one anchor positioned 6 m from the wearable

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	6002.9	5973.8	6005.1	6018.8	6037.1	6025.1	6000.6	5970.5	5997.6	5961.5
Mean error:	-14.1	-43.2	-11.9	1.8	20.1	8.1	-16.4	-46.5	-19.4	-55.5
MAE:	42.5	45.5	22.3	16.5	28.2	22.9	27.9	54.8	28.8	59.6
Var:	2397.1	1167.1	844.7	624.0	1064.9	1024.2	825.4	2283.0	922.7	1437.0
Std dev:	49.0	34.2	29.1	25.0	32.6	32.0	28.7	47.8	30.4	37.9
Min:	5914.0	5876.0	5923.0	5951.0	5961.0	5951.0	5933.0	5876.0	5923.0	5886.0
Max:	6110.0	6054.0	6063.0	6110.0	6110.0	6110.0	6063.0	6063.0	6091.0	6091.0
Outliers:	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)

Subsequently, the results for the distance of eight meters are visible in Table 4.2. Compared to the previous results, these showed less accurate measurements. The mean distance was, for most of the runs, within a 100 mm bias from the actual distance. Nonetheless, for half of the runs, either the standard deviation or the outlier rate was high. A standard deviation of around 30 to 40 mm was desired. Additionally, the outlier rate should stay under 10%. This also could be seen in the minimum and maximum metrics, as they reported divergent numbers.

Table 4.2: UWB ranging results with one anchor positioned 8 m from the wearable

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	8031.4	8041.7	7988.9	7996.3	7957.4	8130.3	7956.8	7931.1	7920.1	7920.8
Mean error:	18.4	28.7	-24.1	-16.7	-55.6	117.3	-56.2	-81.9	-92.9	-92.2
MAE:	129.4	48.5	37.0	36.1	58.3	128.6	103.2	82.6	94.0	95.3
Var:	42807.7	4674.5	1719.9	1715.7	1323.9	18616.2	11643.5	1303.3	1608.1	2411.7
Std dev:	206.9	68.4	41.5	41.4	36.4	136.4	107.9	36.1	40.1	49.1
Min:	7807.0	7901.0	7802.0	7891.0	7854.0	7905.0	7793.0	7830.0	7812.0	7774.0
Max:	8811.0	8492.0	8093.0	8116.0	8065.0	8956.0	8421.0	8037.0	8074.0	8112.0
Outliers:	34 (17.0%)	5 (2.5%)	1 (0.5%)	0 (0.0%)	1 (0.5%)	41 (20.5%)	31 (15.5%)	5 (2.5%)	17 (8.5%)	20 (10.0%)

4.2.3 Two anchor measurements

The results of the measurements with the test setup with two anchors are displayed in Appendix C. As visible in the tables in Appendix C, the results included several symmetrical and asymmetrical anchor placements. For the distances of three and five meters, the system performed similar to results in the previous section with a single anchor. In Table 4.3, it is shown that this was different at distances of seven meters. The mean distance for anchor B concerned a bias of minus 200 mm. Consequently, the outlier rate was almost 100% each run, as most readings were outside the acceptable range. For anchor A, the ten test runs delivered reliable metric values.

This phenomenon was also observed in the tables with asymmetrical distances in Appendix C.

Table 4.3: UWB ranging results with anchors A and B positioned 7 m from the wearable

<i>Anchor A</i>	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	6986.0	6986.8	7007.2	6994.3	6995.2	7005.9	7000.7	6952.8	6961.9	6966.4
Mean error:	-29.0	-28.2	-7.8	-20.7	-19.8	-9.1	-14.3	-62.2	-53.1	-48.6
MAE:	34.2	31.9	25.4	27.0	30.1	27.5	24.3	63.4	53.9	51.5
Var:	826.3	772.3	1054.6	519.4	756.4	1079.2	819.1	912.8	728.9	1252.3
Std dev:	28.7	27.8	32.5	22.8	27.5	32.9	28.6	30.2	27.0	35.4
Min:	6944.0	6907.0	6930.0	6949.0	6949.0	6949.0	6912.0	6893.0	6893.0	6893.0
Max:	7080.0	7048.0	7062.0	7062.0	7080.0	7118.0	7080.0	7029.0	7043.0	7066.0
Outliers:	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
<i>Anchor B</i>	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	6800.0	6786.0	6786.2	6777.5	6787.4	6815.3	6821.8	6819.8	6809.4	6803.9
Mean error:	-215.0	-229.0	-228.8	-237.5	-227.6	-199.7	-193.2	-195.2	-205.6	-211.1
MAE:	215.0	229.0	228.8	237.5	228.9	199.7	193.2	195.2	205.6	211.1
Var:	1004.7	696.2	594.9	510.8	1443.9	550.5	819.1	662.8	628.8	705.7
Std dev:	31.7	26.4	24.4	22.6	38.0	23.5	23.1	25.7	25.1	26.6
Min:	6729.0	6729.0	6729.0	6729.0	6729.0	6757.0	6757.0	6747.0	6757.0	6757.0
Max:	6898.0	6860.0	6832.0	6851.0	7080.0	6907.0	6898.0	6888.0	6860.0	6860.0
Outliers:	194 (97.0%)	200 (100%)	200 (100%)	200 (100%)	198 (99.0%)	199 (99.5%)	198 (99.0%)	197 (98.5%)	200 (100%)	200 (100%)

4.3 Haptic feedback integration

The next stage of testing was performed at X TU Delft, as the sports halls have plenty of space and no obstacles, which was relevant for multipath propagation. Additionally, the test setup changed. A breakout board with a small vibration motor was added. This haptic motor represented the feedback component of the test setup. Due to the integration of the haptic motor with the test setup, it had to be checked whether the Pozyx tag and the motor breakout board could run simultaneously via the Arduino Uno. After a small experiment, it was evident that these two devices were compatible over I2C (Docs, 2025).

Next, a trigger zone was defined. As long as the wearable was inside the trigger zone, the haptic motor vibrated. This trigger zone could be positioned at any distance from the pool wall and configured at any desired width. When the wearable was inside the trigger zone, the readings became more variable and included random outliers due to the vibrations. To prevent this effect, a short delay was added after the vibrations, to pause the ranging while the motor vibrated.

As additional components were added to the test setup, the test runs took longer to complete. Before the haptic motor was included, a test run with two anchors took 12.4 seconds. Eventually, this increased up to 20 seconds. How much it exactly increased depended on two factors. Firstly, the distance to the anchors, since larger distances meant slightly longer test times. Secondly, the placement of the trigger zone. If the wearable was outside the trigger zone, the haptic motor did not vibrate and thus there was no extra delay. Subsequently, with an increased test duration, the update frequencies decreased, as the number of readings remained consistent in each test run. The update frequency is the inverse of a time period, meaning if the time increased, the frequency had to decrease.

All measurements at X TU Delft were performed with a test setup with two anchors and included 200 readings per test run. Between the measurements, two factors could be changed. The distance to each anchor from the wearable and where the trigger zone was defined. The outcome of these measurements can be found in Appendix D and Appendix E.

4.3.1 Effect of haptic feedback on ranging

For the findings in Appendix D, the trigger zone was implemented from 3000 to 3500 mm. The wearable was positioned outside this trigger zone, so no vibrations occurred during these test runs.

In Table 4.4, the results are presented where the distances to anchor A and anchor B were two and eight meters, respectively. The results show that every run had a 100% success rating. A bias of 70 to 80 mm appeared when the anchor was eight meters away from the wearable. The variance and standard deviation were well within the acceptable range. Additionally, the number of detected outliers was limited, especially when including the other tables from Appendix D. Only three of the 24 runs reported more than 10% as outliers. The length of the test runs was 12.4 seconds, resulting in an update frequency of 16.1 Hz.

Table 4.4: UWB ranging results with anchor A at 2 m and anchor B at 8 m from the wearable, with the wearable outside the trigger zone (3000–3500 mm)

<i>Anchor A</i>	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	1952.4	1961.1	2025.2
Mean error:	-47.6	-38.9	25.2
MAE:	50.9	44.0	33.2
Var:	1196.7	1562.6	867.7
Std dev:	34.6	39.5	29.5
Min / Max:	1872.0 / 2046.0	1872.0 / 2046.0	1947.0 / 2083.0
Outliers:	0 (0.0%)	0 (0.0%)	0 (0.0%)
<i>Anchor B</i>	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	7931.2	7919.8	7930.2
Mean error:	-68.8	-80.2	-69.8
MAE:	69.8	80.2	70.0
Var:	1118.5	1192.5	1005.1
Std dev:	33.4	34.5	31.7
Min / Max:	7849.0 / 8023.0	7812.0 / 7994.0	7835.0 / 8023.0
Outliers:	4 (2.0%)	14 (7.0%)	3 (1.5%)

For the results in Appendix E, the trigger zone was defined around the measured distance to the nearest anchor. For example, when the nearest anchor was located at three meters from the wearable, the trigger zone extended from 2750 to 3250 mm. By doing so, it could be determined how much the ranging process was affected if the haptic motor vibrated for a longer period in time. Accordingly, two new metrics were introduced:

- False pos: false positives; a result that shows that a reading is inside the trigger zone, although it was outside (false alarm).
- False neg: false negatives; a result that shows that a reading is outside the trigger zone, although it was inside (missed detection)

Table 4.5 displays the test runs in two scenarios. The left side of Table 4.5 shows the test setup with anchor A at three meters and anchor B at seven meters, while on the right side the distances of the anchors have switched. For both cases the trigger zone was defined between 2750 and 3250 mm. This meant that, on the left side of Table 4.5, anchor A triggered the haptic motor, whereas on the right side anchor B activated the haptic motor.

When the distance was three meters to an anchor, the mean distance contained a bias of 125 to 150 mm. This was when the wearable was inside the trigger zone with respect to the corresponding anchor. Due to this bias, the outlier rate was higher than before. Many of the readings lay further away than 150 mm, compared to the actual distance, resulting in high outlier rates. The other measured data showed similar results as before, all within the tolerable range. The length of the test runs was 15.5 seconds, resulting in an update frequency of 12.9 Hz. Two new statistical values shown in Table 4.5 are the false positive and false negative rates. These two rates only applied to the results inside the trigger zone, because it indicated if the haptic motor incorrectly vibrated. As visible in Table 4.5, there were never any false positives or false negatives.

Table 4.5: UWB ranging results with anchor A at 3 m & 7 m and anchor B at 7 m & 3 m from the wearable, with the wearable inside the trigger zone (2750–3250 mm)

<i>Anchor A</i>	Run 1	Run 2	Run 3	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	3128.6	3132.1	3128.9	7037.7	7027.3	7038.4
Mean error:	128.6	132.1	128.9	37.7	27.3	38.4
MAE:	129.4	134.5	130.2	46.4	40.3	45.4
Var:	1563.5	1861.3	1625.8	1641.6	1822.9	1456.0
Std dev:	39.5	43.1	40.3	40.5	42.7	38.2
Min / Max:	2949.0 / 3231.0	2930.0 / 3212.0	2949.0 / 3235.0	6888.0 / 7132.0	6855.0 / 7127.0	6874.0 / 7118.0
Outliers:	49 (24.5%)	67 (33.5%)	77 (38.5%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
False pos	0 (0.0%)	0 (0.0%)	0 (0.0%)	-	-	-
False neg	0 (0.0%)	0 (0.0%)	0 (0.0%)	-	-	-
<i>Anchor B</i>	Run 1	Run 2	Run 3	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	7023.0	7028.8	7072.0	3147.2	3142.5	3151.9
Mean error:	23.0	28.8	72.0	147.2	142.5	151.9
MAE:	36.1	43.5	75.4	148.0	142.5	151.9
Var:	1654.3	1875.0	1833.9	1979.0	1228.2	1384.4
Std dev:	40.7	43.3	42.8	44.5	35.0	37.2
Min / Max:	6837.0 / 7085.0	6879.0 / 7118.0	6912.0 / 7184.0	2954.0 / 3249.0	3019.0 / 3221.0	3034.0 / 3249.0
Outliers:	3 (1.5%)	0 (0.0%)	4 (2.0%)	111 (55.5%)	93 (46.5%)	136 (68.0%)
False pos	-	-	-	0 (0.0%)	0 (0.0%)	0 (0.0%)
False neg	-	-	-	0 (0.0%)	0 (0.0%)	0 (0.0%)

4.3.2 Effect of wearable orientation

Table 4.6 displays the results for the test setup where anchor A was placed at three meters and anchor B at seven meters from the wearable. The trigger zone was established between 2750 and 3250 mm. The duration of the test runs was 20 seconds, resulting in an update frequency of 10 Hz.

Table 4.6: UWB ranging results for three wearable orientations with anchor A at 3 m and anchor B at 7 m from the wearable and with the wearable inside the trigger zone (2750–3250 mm)

<i>Anchor A</i>	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	3223.5	3231.3	3145.7	3141.9	3235.1	3231.9
Mean error:	223.5	231.3	145.7	141.9	235.1	231.9
MAE:	223.5	231.3	145.7	141.9	235.1	231.9
Var:	1661.2	1364.5	1104.7	1722.2	6715.7	8250.8
Std dev:	40.8	36.9	33.2	41.5	81.9	90.8
Min / Max:	3085.0 / 3301.0	3085.0 / 3305.0	3048.0 / 3226.0	3010.0 / 3263.0	3052.0 / 3352.0	3090.0 / 3352.0
Outliers:	187 (93.5%)	192 (96.0%)	88 (44.0%)	87 (43.5%)	161 (80.5%)	134 (67.0%)
False pos	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
False neg	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
<i>Anchor B</i>	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	7087.1	7085.1	7082.8	7079.9	7175.5	7149.9
Mean error:	87.1	85.1	82.8	79.9	175.5	149.9
MAE:	89.9	86.6	85.4	83.0	176.7	152.6
Var:	1835.7	1541.2	2002.6	1286.8	22572.0	8546.0
Std dev:	42.8	39.3	44.8	35.9	150.2	92.4
Min / Max:	6907.0 / 7174.0	6954.0 / 7193.0	6935.0 / 7193.0	6898.0 / 7155.0	6968.0 / 8815.0	6949.0 / 7343.0
Outliers:	17 (8.5%)	6 (3.0%)	15 (7.5%)	3 (1.5%)	123 (61.5%)	119 (59.5%)
False pos	-	-	-	-	-	-
False neg	-	-	-	-	-	-

There are six runs shown in Table 4.6, which can be grouped according to how the wearable was positioned during the measurements. For the first two runs, the side of the wearable containing the UWB chip was directed to anchor A. The third and fourth run had the UWB chip in the middle (perpendicular to the test setup) and for the last two runs the UWB chip was aimed at anchor B. These different positions of the wearable were tested to understand if this had an effect on the measurement accuracy.

Based on Table 4.6, it could be concluded that run five and six were less accurate than the first four runs. Especially the standard deviations stood out in run five and six, as these were at least twice the size of the

other measured standard deviations. For anchor A, the outlier rate was similar to the first two runs. The mean distance had a bias of 100 to 200 mm, with the wearable inside the trigger zone. This bias could lead to an outlier rate which was higher than 10%. Additionally, the outlier rate for anchor B was considerably higher than the other four runs. However, there was no haptic feedback from the haptic motor as interference.

4.4 Development of the waterproof system

The final test phase on land included the same test setup that would be used for the measurements in the swimming pool. Up to now, the wearable (the Pozyx tag plus the Arduino Uno) was connected to the haptic motor and this was all powered via a laptop. Besides, the laptop was used to start and to log the ranging measurements. However, in a pool this would not be possible, because the test setup had to be waterproof and portable. Therefore, three extra components were added to the hardware setup.

First, a battery was required, as this made the test setup portable. This battery had to deliver 5 V and enough energy capacity to the Arduino Uno. Thus, the Li-Po battery, a lithium ion battery, was selected. This battery had an energy capacity of 2200 mAh. As the nominal voltage was only 3.7 V, the Lipo Rider Plus was added to acquire the 5 V output. In addition, a SD card was necessary to log the data from the measurements. Hence, the microSD card breakout board+ was selected to accomplish this task. All added components were connected to the Arduino Uno via jumper wires.

The whole test setup is shown in Figure 4.2. Next to that, a list of components is presented in Appendix F.

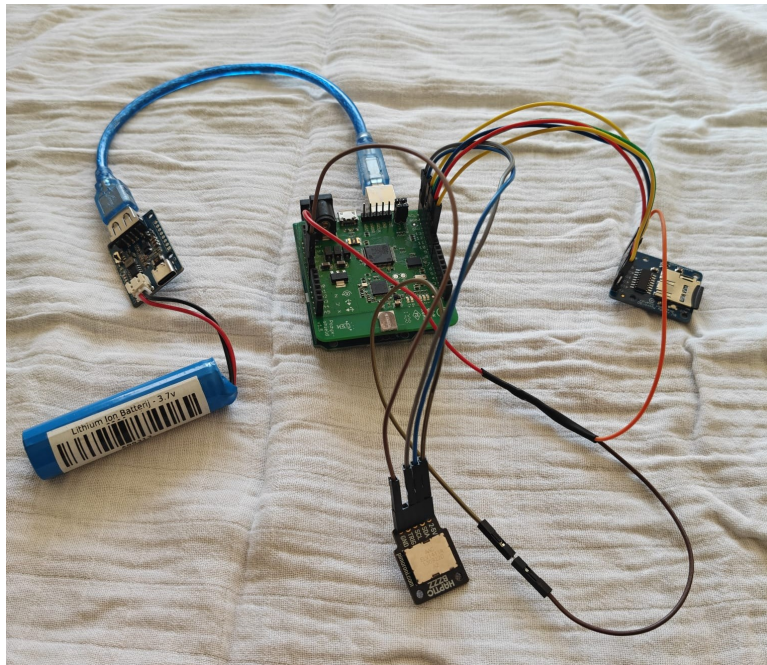


Figure 4.2: The test setup used for the final land-based and pool measurements

4.4.1 Final ranging measurements

Adding the Li-Po battery and the microSD card breakout board concluded the test setup. Before the tests in a swimming pool could be performed, a series of measurements was conducted at X TU Delft. After updating the Arduino sketch, the ranging measurements were performed. The results of the measurements can be found in Appendix G. These results served as a baseline against which the pool measurements in Chapter 5 will be compared. Two additional measurements were conducted, which involved a single anchor at distances of nine and ten meters.

The outcome of these measurements were comparable to the previously obtained results. Only the length of the test runs changed, because of the integration of the microSD module. Therefore, the test duration increased for an extra two to three seconds. This resulted in a test duration of 14.6 seconds with the wearable outside the trigger zone and approximately 23 seconds when inside the trigger zone. The latter scenario had an update frequency around 8.5 Hz.

4.5 Discussion of land measurements

The results from Section 4.2 were mainly used to better understand the UWB ranging system. Nonetheless, a few aspects were remarkable. When the distance between the wearable and the anchor was a maximum of seven meters, the small amount of noise that was present could arise as internal noise. However, at a distance of eight meters, the measurements became less accurate. It showed an increase in the standard deviation and a notable bias in the mean distance occurred. The acceptable range for the standard deviation was up to 50 mm, whereas values above 50 mm indicated inadequate measurement consistency. It could be that the signal was not consistently locking onto any path: it was switching between the direct path and reflected paths, resulting in the large variations in the measurements.

Furthermore, a measurement could exhibit an acceptable standard deviation, but still show a large negative bias of up to 200 mm. As mentioned in Chapter 3, a positive bias was to be expected. This negative bias may suggest that the path detection threshold was triggering on a strong multipath reflection that arrived slightly before the direct signal. The obstacles in the classroom at ECHO may be the reason that the ranging system sometimes locked onto a reflected signal. As the distance between the anchor(s) and the wearable increased, it became more likely a reflected signal could be interpreted as the direct signal.

Effect of haptic feedback

When the haptic motor was integrated into the test setup in Section 4.3, the mean distance to the nearest anchor showed a systematic bias of 100 to 200 mm. Yet, this only applied when the wearable was inside the trigger zone. Outside the trigger zone, the outcome of the measurements was similar to the previously obtained results from Section 4.2. The observed bias can have emerged due to vibrations of the haptic motor, which may result in multipath interference. At small distances of only three or five meters, a stronger reflected signal can be detected instead of the direct signal. Because this reflected signal took a longer path to reach the wearable, it resulted in an overestimated distance and thus in a positive bias. The increase in the outlier rates mainly existed because of this bias. If the ranging system was calibrated to compensate for the offset, the outlier rate would be expected to decrease below the maximum acceptable threshold of 10%.

Considering the results investigating the orientation of the wearable in Appendix E, a pattern can be observed. When the wearable was aimed towards the furthest anchor, the readings were the least reliable. The test setup with the UWB chip positioned in the middle performed the best, as this resulted in the most consistent readings. Yet, when the UWB chip was oriented towards the nearest anchor, the measurements showed similar results. Therefore, the wearable may be oriented towards the nearest anchor without affecting the performance during the measurements.

Comparing the results from the measurements from ECHO with the results from X TU Delft, the test results improved a lot for the distances of seven and eight meters. Particularly the standard deviation was more consistent throughout the test runs. However, the bias in the mean distance still was present at these distances. The examined improvements can be attributed to the change in test environment between the two locations. Several obstacles were present in the classroom at ECHO, while the sports hall at X was completely empty. These obstacles in ECHO may have influenced the multipath propagation, whereas the open test environment at X likely led to fewer multipath reflections.

Comparison with final land tests

With the last test runs on land from Section 4.4, some previous discussion points can be confirmed. First, the measurements at distances of seven and eight meters had become consistent, which was in contrast with previous conducted measurements at these distances. The standard deviation had improved to well within the acceptable range for both distances. However, a bias was still observed.

The two additional measurements at nine and ten meters resulted in poor performance, with standard deviations well outside the tolerable range. It appears that the reliability decreases at distances beyond eight meters. This suggests that this UWB system can be used up to a maximum of eight meters.

This maximum operating range would contradict the second and third technical design requirements, which state that the design must be suitable for both short and long course swimming pools. However, BVI swimmers are currently tapped at approximately three meters from the pool wall, meaning that the effective UWB ranging range of eight meters should be sufficient (R. Van den Haak, personal communication, September 28, 2026).

Offset calibration

The bias in the mean distances at the distances of seven meters or more, can be attributed to multipath reflections. At these distances, the UWB system was more likely to lock onto a reflected signal during a test

run, as larger distances increased the potential for reflections from surrounding objects or surfaces. A bias of 100 to 200 mm is not necessarily a problem, because the UWB ranging performance is very dependent on the environment in which the system is used. Once the UWB system is placed in its desired environment, the UWB system can be calibrated by updating the Arduino sketch to compensate for the offset. However, this requires the bias to be consistent in direction, meaning it should consistently be a positive or a negative bias. This condition was not consistently achieved throughout the measurement results.

Update frequency trade-off

Lastly, the trade-off between adding new hardware to the test setup and a decrease in update frequency of the ranging system should be considered. At the start of testing, when the test setup only included two anchors and the wearable, the update frequency was 16.1 Hz. After adding four additional components, the final test setup had an update frequency of 8.5 Hz. The frequency was almost reduced by 50% due to the additional components. For now this frequency is sufficient, yet it should be monitored during further development. If the update frequency decreases too much, the UWB system could not provide feedback quickly enough to ensure the safety of the BVI swimmer and would thereby fail to meet the second design requirement.

5 System validation in a pool environment

Having validated ranging performance and designing a waterproof test setup on land, the system was taken to a swimming pool to evaluate performance in the target environment. This chapter will first analyze the measurements performed with the test setup above the water surface in Section 5.1. Then, Section 5.2 describes the updates made to position the test setup directly on the water surface, along with the resulting measurements. Next, in Section 5.3, the results from the measurements conducted with a swimmer are presented. Finally, the results of the pool measurements will be discussed in Section 5.4.

5.1 Pool test with test setup above the water surface

The test setup presented in Chapter 4 was subsequently tested in swimming pools in Delft. Measurements were conducted at two locations; Zwembad Kerkpolder and Sportfondsenbad Delft. Next to the test setup from Section 4.4, two new Arduino sketches were developed to apply in the pool. The first sketch only controlled the haptic motor and the second sketch only controlled the microSD module. These two sketches can be found in Appendix A. Together with the original Arduino sketch, which controlled all components, these three sketches could be utilized to determine whether a specific component caused problems during a measurement.

5.1.1 Test setup at pool environment

For the first set of measurements, the test setup consisted of a single anchor, with the distance to the wearable varying from three to ten meters. The test setup was placed inside a zip bag to prevent water from affecting the components. This zip bag was placed onto a kickboard to keep the test setup above the water surface. Due to the uncertainty in positioning the wearable in the pool, the actual distance was not always an exact whole meter. It could deviate by 100 mm less or more than the intended distance. Therefore, the mean error and MAE could be smaller or larger than expected. Also, the outlier rate was often significantly higher when the distance in the Spyder files was not adjusted to this bias.

5.1.2 Ranging results

In Table 5.1, the results are presented for a distance of six meters between the anchor to the wearable. All three runs were successful, with zero outliers. The standard deviations were within the tolerable range, as it was around 30 mm. The other measurements up to a distance of nine meters from Appendix H showed similar results, with minimal standard deviations and only a couple of outliers, where none of the runs reported above the 10% outliers. The duration of the test runs outside the trigger zone was 8.2 seconds, resulting in an update frequency of 24.4 Hz, whereas the duration for the measurements at four meters was inside the trigger zone and resulted in a test duration of 10.4 seconds with an update frequency of 19.3 Hz.

Table 5.1: UWB ranging results for the pool test at a distance of 6 m from the anchor, with the wearable outside the trigger zone (3750–4250 mm)

	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	6077.6	6091.3	6081.2
Mean error:	-22.4	-8.7	-18.8
MAE:	30.4	26.4	28.1
Var:	901.2	1311.2	834.0
Std dev:	30.0	36.2	28.9
Min / Max:	5975.0 / 6152.0	5998.0 / 6213.0	5988.0 / 6157.0
Outliers:	0 (0.0%)	0 (0.0%)	0 (0.0%)

In Table 5.2 shows that the first two test runs with the wearable at a distance of ten meters from the anchor exhibited inconsistent results. The mean distance was 600 to 700 mm off the actual distance, which resulted

in outlier rates above 60%. Subsequently, the standard deviation was 17 times higher than in the third test run, which was inside the acceptable range.

Table 5.2: UWB ranging results for the pool test at a distance of 10 m from the anchor, with the wearable outside the trigger zone (3750–4250 mm)

	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	10740.9	10593.5	9990.8
Mean error:	740.9	593.5	-9.2
MAE:	753.4	608.1	29.1
Var:	416967.3	387697.8	1235.6
Std dev:	645.7	622.7	35.2
Min / Max:	9880.0 / 12909.0	9871.0 / 12844.0	9894.0 / 10072.0
Outliers:	151 (75.5%)	123 (61.5%)	0 (0.0%)

To better understand how the test setup with the wearable inside the trigger zone would operate in a pool environment, additional measurements were conducted. The test setup was positioned more towards the middle of the swim lane, to better simulate a real scenario. However, it still was placed on the kickboard to make sure the electronics stayed clear above the water.

The outcome of such a measurement is presented in Table 5.3 and was comparable to the other results in Appendix H. Here, the distance between the wearable and the anchor was ten meters and the trigger zone was defined from 9750 to 10250 mm. The duration of the test runs was 10.3 seconds, resulting in an update frequency of 19.4 Hz. All readings were successful and the standard deviation was around 35 mm, which was within the acceptable range. The outlier rate was 0% for each test run, while the alert rate was 100%, which was expected due to the placement inside the trigger zone. The alert rate is a new metric that represents the number of readings flagged as an alert by the ranging system in a test run. It was added because, during a test run in the pool, the haptic motor was too far away from the researcher to confirm whether it was vibrating when expected, i.e., when it was inside the trigger zone.

Table 5.3: UWB ranging results for the pool test at a distance of 10 m from the anchor, with the wearable inside the trigger zone (9750–10250 mm)

	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	10087.1	10099.1	10115.2
Mean error:	-12.9	-0.9	15.2
MAE:	29.8	27.2	30.4
Var:	1240.4	1295.9	1188.4
Std dev:	35.2	36.0	34.5
Min / Max:	10007.0 / 10194.0	9988.0 / 10227.0	10016.0 / 10208.0
Outliers:	0 (0.0%)	0 (0.0%)	0 (0.0%)
Alerts	200 (100.0%)	200 (100.0%)	200 (100.0%)
False pos	0 (0.0%)	0 (0.0%)	0 (0.0%)
False neg	0 (0.0%)	0 (0.0%)	0 (0.0%)

5.2 Pool test with the test setup at water level

The previous section showed very consistent results, with the test setup above the water surface. Hence, it was decided to remove the kickboard and position the electronics in two zip bags on the water surface. This placement more accurately simulated how the test setup would operate when worn by a swimmer. The main difference with the test setup from Section 5.1 was the height of the UWB chip above the water. When placed on the kickboard, the whole test setup was ten to twenty centimeters above the water, whereas now everything was positioned directly at the water surface and sometimes slightly below it.

Next to the modification in height, a few updates were made to the Arduino sketches. Up to this point, only one vibration type had been used for the haptic motor, namely the 'Sharp tick 1'. However, the Adafruit library offers 123 different vibration types, called waveforms (Texas Instruments, 2014, p.13). The objective was to establish a waveform that would be reliably noticeable by the swimmer while swimming. Subsequently, different waveforms were informally tested and three were selected as most promising due to their intensity.

In the sketches, the waveforms were called 'tick_effect'. See Table 5.4 for a short description per waveform. These waveforms were ranked from least to most intense, thus from tick_effect 24 to tick_effect 56.

Table 5.4: Three waveforms selected from the Adafruit library (Texas Instruments, 2014)

Tick_effect 24	Sharp tick 1 (100%)
Tick_effect 34	Short double sharp tick 1 (100%)
Tick_effect 56	Pulsing sharp 1 (100%)

The implementation of these new waveforms also required adjustments to the delay after the vibrations. Because every waveform was unique, a specific delay was required to maintain a smooth and consistent ranging process. The number of readings that had to be flushed during the warm-up period increased from 55 to 80 due to these adjustments. By doing so, it was ensured that no extreme deviations were recorded at the start of the ranging process.

Finally, test runs were restarted using the Arduino Uno's reset button rather than power cycling the battery, because power cycling risked interfering with the microSD module and then a test run would not start at all.

According to the results of the benchmark tests from Section 4.4, the following measurements should consist of two anchors. However, this proved to be difficult to achieve at both swimming pools due to the size of the pool. The 25 m side was too long for accurate measurements, while the short side included starting blocks, which made executing the measurements more challenging. Therefore, all the measurements at the swimming pools only included a single anchor instead of two anchors.

From this point onward, all the measurements were conducted using the three different waveforms.

5.2.1 Results outside the trigger zone

Investigating the tables in Appendix I, where the wearable was positioned outside the trigger zone, the results for a distance of four meters were consistent. For one test run, the outlier rate was above the 10%, yet it reported a low standard deviation which made it an acceptable result. When the distance between the wearable and the anchor was six meters, three test runs showed standard deviations around the 300 mm. Additionally, their measured maximum value was almost one meter higher than the other six test runs. As a result, the outlier rate reported high percentages ranging from 23.5% to 82.5%. Of these three runs, two implemented the tick_effect at 56 and one the tick_effect at 34.

In Table 5.5, the test run using tick_effect 34 is shown at a distance of six meters. The third test run was already discussed, with a mean distance of nearly 400 mm larger than the other runs. The first and second run demonstrated the expected successful results obtained under the same operating conditions. Here, the duration of the test runs was 8.3 seconds, resulting in an update frequency of 24.1 Hz.

Table 5.5: UWB ranging results for the pool test at a distance of 6 m from the anchor, with the wearable outside the trigger zone (3000–3500 mm) and tick_effect 34

	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	5949.7	6123.2	6459.7
Mean error:	-50.3	123.2	459.7
MAE:	54.4	123.2	501.5
Var:	1462.4	1059.0	125065.8
Std dev:	38.2	32.5	353.6
Min / Max:	5858.0 / 6096.0	6035.0 / 6237.0	5825.0 / 6893.0
Outliers:	0 (0.0%)	34 (17.0%)	165 (82.5%)

Table 5.6 presents the outcome for the measurements conducted at a distance of eight meters, with tick_effect 56. In the first two runs, the mean distance had a large bias of more than 500 mm and the outlier rate exceeded 10%. Furthermore, the standard deviation was outside the acceptable range for all three test runs. Comparable behavior was seen in one of the test runs using tick_effect at 34 at eight meters. Besides, the percentages of successful readings dropped considerably, as only the third run approached a 100% success rate. When a ranging attempt failed, the error code presented was 'FAIL,0x12', which corresponded to a ranging timeout. This indicated that the Pozyx tag did not receive a response from the anchor in time.

Furthermore, several other results presented in Appendix I showed large standard deviations ranging between 300 and 1200 mm. However these test runs also included several extreme outliers between the 12 and 13 m, which contributed to the increased standard deviation.

Table 5.6: UWB ranging results for the pool test at a distance of 8 m from the anchor, with the wearable outside the trigger zone (3000–3500 mm) and tick_effect 56

	Run 1	Run 2	Run 3
Successful:	119 (59.5%)	158 (79.0%)	196 (98.0%)
Mean dist:	9314.6	8513.0	7992.8
Mean error:	1314.6	513.0	-7.2
MAE:	1377.0	616.9	162.6
Var:	4020196.6	802171.5	260388.9
Std dev:	2005.0	895.6	510.3
Min / Max:	7821.0 / 14067.0	7751.0 / 11047.0	7797.0 / 12712.0
Outliers:	47 (39.5%)	117 (74.1%)	27 (13.8%)

5.2.2 Results inside the trigger zone

For the next set of measurements, the trigger zone was defined around the wearable. By doing so, the haptic motor vibrated continuously during each test run, allowing the effect of these vibrations to be determined. From Appendix J, the results for a distance of eight meters showed a marked deterioration in performance. This was not observed at distances of four and six meters, where the results remained consistent and thus similar to the results from Section 5.2.1.

The outcome for a distance of eight meters is presented in Table 5.7. Here, the trigger zone was defined from 7750 to 8250 mm, using tick_effect 24. All three runs did have a 100% success rate, however the standard deviations were well above 100 mm. The alert rate for the third run was only 11%, resulting in only 22 alerts out of the 200 signals. Moreover, this was in combination with an outlier rate of 89%.

Table 5.7: UWB ranging results for the pool test at a distance of 8 m from the anchor, with the wearable inside the trigger zone (7750–8250 mm) and tick_effect 24

	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	8098.9	8141.5	8615.5
Mean error:	98.9	141.5	615.5
MAE:	108.4	152.3	619.5
Var:	16736.3	291300.2	77955.6
Std dev:	129.4	539.7	279.2
Min / Max:	7910.0 / 8557.0	7901.0 / 12220.0	7933.0 / 9359.0
Outliers:	37 (18.5%)	9 (4.5%)	178 (89.0%)
Alerts	177 (88.5%)	192 (96.0%)	22 (11.0%)
False pos	0 (0.0%)	0 (0.0%)	0 (0.0%)
False neg	0 (0.0%)	0 (0.0%)	0 (0.0%)

The duration of the test runs was different for each waveform. For tick_effect 24 it was 9.3 seconds, resulting in an update frequency of 21.5 Hz. Yet, for tick_effect 34 it was 10.3 seconds, resulting in an update frequency of 19.4 Hz. Lastly, for tick_effect 56 it was 12.2 seconds, resulting in an update frequency of 16.4 Hz. In Appendix J, the results for tick_effect 56 at a distance of eight meters are not presented due to time constraints during testing in the swimming pool.

5.3 Pool test with a swimmer

The final phase of testing included a swimmer carrying the wearable while swimming. The wearable was located at the back of the neck, where it floated on the water. Furthermore, as with all measurements at the pool, a single anchor was used. The number of readings was set to 2000, which equaled a test duration of 84.7 seconds. This resulted in an update frequency of 23.6 Hz. The trigger zone was defined between 4000 and 5000 mm. The measurements were conducted with two different swimming strokes, the front crawl and the breaststroke. Additionally, the swimmer started at the side of the swim lane where the anchor was positioned and swam for eight meters, before turning around and swimming back towards it. No further instructions were given to the swimmer.

In Table 5.8, the results for the two test runs are shown. First of all, the success rate for both runs was slightly above 90%, meaning almost 200 readings failed during the measurements. Although the swimmer only swam

for eight meters, the maximum value for both runs reported distances well above fifteen meters. For the first run, the swimmer swam the distance of eight meters five times in a row, whereas for the second run, the distance was only covered four times. Due to additional meters covered in the first run, the number of alerts was 1.5 percentage points higher. Yet, the false positives and false negatives were comparable between the two test runs. The number of false negatives was consistently greater than the number of false positives. A metric from the CSV files that was not included in Table 5.8 indicated whether the haptic motor had fired or not. Because the burst interval of the waveform was set at 500 ms, the haptic motor activated every half second. During the front crawl, the motor fired three times while the swimmer remained in the trigger zone for an average of 1.3 seconds. During the breaststroke, the motor activated four or five times, with the swimmer in the trigger zone for 2.2 seconds on average. The difference between the two swim strokes can be attributed to the slower swimming speed during breaststroke.

Table 5.8: UWB ranging results for the pool test with a swimmer, where the trigger zone was defined from 4000–5000 mm and with tick_effect 24

	Run 1: Front crawl	Run 2: Breaststroke
Successful:	1813 (90.6%)	1836 (91.8%)
Min / Max:	259.0 / 15756.0	123.0 / 16895.0
Alerts	143 (7.8%)	114 (6.3%)
False pos	3 (1.8%)	2 (1.4%)
False neg	22 (13.1%)	25 (17.8%)

5.4 Discussion of pool test results

The results presented in Section 5.1 were consistent with the results from the measurements performed on land. From the 36 measurements that were conducted with the test setup on the kickboard, only three runs produced inaccurate outcomes. When investigating the results of the measurements performed at a distance of ten meters, two runs had substantial variation in the results, including large standard deviations of up to 600 mm and outlier rates above 60%. In contrast, the three test runs visible in Table 5.3 showed consistent results and good accuracy. This contrast indicates that the ranging process easily can be affected by multipath interference, which can become worse at greater distances between the anchor and the wearable.

There was one test run at eight meters in Section 5.2, with the wearable inside the trigger zone, which reported an exceptional large standard deviation of more than 500 mm. However, the outlier rate was only 2.0%. Those four outliers were so far off the actual distance, that it enlarged the standard deviation. Although the standard deviation was so much larger due to the extreme outliers, these test runs will still be deemed as good enough, also for future measurements. A filter could be implemented, which ignores all readings above a certain threshold, as these readings only apply for 2% of the total amount. The remaining readings can still be sufficient to fulfill the intended task, providing the swimmer with a correctly timed feedback signal.

Because the kickboard was used to elevate the wearable above the pool water, the outcome of the measurements was comparable to the results from Section 4.4. The anchor and the wearable were positioned ten to twenty centimeters above the water surface, which significantly reduced the effect of multipath interference. This will be addressed more extensively in 'Testing with the test setup at the water surface'.

Testing with the test setup at the water surface

The next step was to position the test setup directly on the water surface, leading to the results in Section 5.2. When the wearable was located outside the trigger zone, the results became more inconsistent. A test run with the distance between the anchor and the wearable at four meters, reported an outlier rate of 35% due to the large bias of the measurement. This could have happened if either the wearable locks onto a reflected path instead of the direct path or if the placement of the wearable was slightly off from the desired distance. In both cases, this led to the UWB signal traveling a longer path, resulting in an overestimated distance.

Increasingly more measurements presented poor results at six and eight meters. It is possible that for longer distances, the chance increases that the system will lock onto a reflected signal. Due to the longer distances to the anchor, there was also more water movement and splashes that could disturb the UWB signal.

Furthermore, the previously made observation of a standard deviation outside the acceptable range due to a couple of extreme outliers, was also seen in three test runs with the wearable at eight meters. This could happen a few times because of the unpredictability of the pool environment. It may be caused by a reading that represented a reflected signal which travelled a longer path, but was perceived as the strongest signal.

When the wearable was positioned at the water surface and within the trigger zone, a similar distance-dependent unpredictability was observed, confirming that this trend did not only occur in measurements outside the trigger zone.

The performed measurements illustrate the sensitivity of the UWB system. The test runs at four meters with tick_effect 56 and within the trigger zone, showed poor results. Whereas the measurements with tick_effect 56 but outside the trigger zone, showed reliable results at this distance. This suggests that the addition of the haptic motor may have negatively affected the measurements. Nevertheless, when comparing the results with and without the haptic vibrations at six meters, the opposite appeared to occur. The test runs with the activated haptic motor, showed more promising results than without it. This variability demonstrates the potential sensitivity of the UWB system to multipath interference. While the measurements can be consistent and reliable, a next test run under similar conditions can suddenly produce poor results.

In conclusion, the measurements from Section 5.2, where the wearable was positioned at water level, showed that the UWB system has potential to operate well at shorter distances. The readings during a measurement were generally consistent and accurate. Yet, an individual test run occasionally showed a substantially poorer performance, with standard deviations ten times or more than expected and the presence of extreme outliers. This may occur due to multipath interference caused by reflections from the surrounding pool water, leading to the ranging system locking onto a reflected signal.

However, the measurements got increasingly unreliable from a distance of eight meters and beyond. The difference in performance between Section 5.1 and Section 5.2 can possibly be explained by the height difference of the wearable above the water surface. In Section 5.1, the wearable was ten to twenty centimeters above the water surface. Although it was a small distance, it may have allowed the UWB signal to propagate from the wearable to the anchor with less interference from the pool environment. A similar observation was made in Section 4.1, where the anchor was elevated to roughly the same height above the ground.

Dynamic tests with a swimmer

Examining the tests conducted with a swimmer provided further insight into the presence of false positives and false negatives in the measurements. Since this was the first test conducted with a moving wearable, the performance of the UWB system could be evaluated in these new circumstances.

With the results from Section 5.3, the rates for false positives and false negatives can be evaluated in combination with the alert rate. These metrics are important to inspect the performance of the UWB system, as these detect when the swimmer is in the trigger zone and should receive the feedback signal. Receiving the feedback too early or too late or receiving it not at all, can lead to an increased risk of physical injuries to the swimmer.

The false positive rates for both test runs were under 2%, which is acceptable. However, the rates of the false negatives were well above 13%. When the swimmer started by the anchor and swam away from it, the system operated in a clear LOS condition. Yet, if the swimmer swam towards the anchor, the head of the swimmer was in front of the wearable, leading to an NLOS condition. The UWB signal was blocked by the swimmer's head, pushing the already marginal system beyond its reliable operating range. Consequently, readings either failed or locked onto a reflected path as a result of multipath interference, resulting in a high number of false negatives.

This could be observed in the CSV files. If the swimmer swam away from the anchor, only two readings were false positives and six readings were false negatives. However, when the swimmer swam towards the anchor, three readings were false positives and 41 readings were false negatives. This high number of false negatives introduced too much uncertainty in the system. Therefore, this test setup can be considered as a proof of concept, especially under LOS conditions. Notably, the vibration frequency during the trigger zones was not affected by the occurrence of false positives or false negatives. The haptic motor was activated at the same frequency, once every 500 ms, as under circumstances with very few false positives or false negatives. This observation is important, as maintaining a reliable connection is crucial for blind and visually impaired swimmers to receive the feedback signal. If this interval were to decrease to 250 ms, the high number of false negatives may result in a decrease in the vibration frequency.

Furthermore, the trend observed in the stationary tests, where the measurements became less reliable at distances of eight meters and beyond, was also discovered in these dynamic tests. Informal measurements showed that the ranging ability considerably reduced when exceeding eight meters, reporting almost always a failed reading or a reading with a bias. However, as this was observed by the researcher himself, from a file without an external reference of what the actual distance was, it cannot be validated whether this trend was actually occurring during the moving tests.

Impact of the pool environment

Throughout the different test sessions at the pool, it occurred that the measurements increasingly reported more failed readings. This could also occur when repeating a previously performed measurement, with the results showing less reliable findings than before. This could happen due to the unpredictable environment in the swimming pool, in comparison to the tests on land that did not experience this trend. The water surface can reflect UWB signals, as the surface is always disturbed by the movement of water. This increases the possibility that the wearable suffers from multipath interference, leading to readings where the direct signal overlaps with reflected signals and combining into one reflected signal. Then, the UWB system can incorrectly estimate the distance between the wearable and the anchor, resulting in a bias. Additionally, water can strongly attenuate radio signals like UWB, which can result in the direct signal being absorbed and causing the wearable to lock onto reflected signals.

Furthermore, the wearable was placed inside one or two zip bags during the pool measurements. However, this solution did not guarantee waterproofness. During the final stationary tests, the electronics of the test setup would create little holes in the zip bags. It could happen that some water entered the zip bags and slightly wet the electronics. This could affect the working mechanism of the test setup and its accuracy during ranging. In addition, the test setup was placed outside the zip bags in between measurements, to retrieve the data from the SD card. It is possible that the high humidity in the swimming pool slowly affected the components, especially given the total number of hours tested in the pool. The influence of the moisture resulting from the humidity and leakages may explain the increase in the number of failed readings throughout the pool tests. The UWB system was already less stable at longer distances, which made it more prone to influences in the pool environment. Therefore, even relatively small effects from the environment could have pushed the system below its threshold, resulting in failed readings.

Limitations of the haptic motor

Finally, the feedback component of the test setup was not discussed in this chapter, as it was not tested during the dynamic measurements. The haptic motor was included in the measurements and was activated when the wearable was inside the trigger zone. It was only during the investigation of the three different waveforms in Section 5.2 that it became evident that the haptic motor could not produce a strong enough vibration which could be felt while swimming. Besides the vibration strength, the positioning of the haptic motor proved to be a challenge as well. Since all the components were connected via jumper wires, it was difficult to maintain firm contact between the haptic motor and the swimmer's head.

6 Discussion

To answer the first sub-question, three transmitter-based technologies were considered to select the most suitable option: Radio frequency identification (RFID), ultrasound and Ultra-wideband (UWB). These technologies were compared based on their parameters, after which RFID was excluded. Next, several concept designs were created for both ultrasound and UWB. After evaluating the performance and limitations for both technologies, UWB was selected for further development.

Extensive testing was then conducted, both on land and in the pool environment, to establish the performance of the UWB ranging system. The measurements performed on land showed that the UWB system functioned consistently up to approximately eight meters between the wearable and each anchor. Beyond this distance, the results became unreliable due to multipath propagation. Additionally, the orientation of the wearable influenced accuracy, with the least reliable readings occurring when it was aimed towards the furthest anchor. Finally, the difference in results between measurements at ECHO and X demonstrated that the UWB system was dependent on its environment, where multipath interference from obstacles could lead to a bias in the results.

When the measurements were conducted at the swimming pool, the same trend in the maximum operating range of the UWB system was observed. Furthermore, the UWB system's sensitivity to the environment was demonstrated, as the height of the wearable above the water surface proved to be influential on the performance. The dynamic tests with a swimmer revealed that false negatives occurred substantially more often than false positives, particularly in NLOS conditions when the swimmer's head obstructed the UWB signal. The increasing number of failed readings was potentially attributable to moisture affecting the components. In addition, it may have been influenced by the unpredictable pool environment, such as water movement disturbing the UWB signal.

In conclusion, this thesis has demonstrated the potential of a transmitter-based technology, namely Ultra-wideband, as the basis for a proof of concept design that enables blind and visually impaired swimmers to independently detect their turning point. In its current form, the technology cannot cover an entire swim lane. However, with a reliable ranging distance of approximately eight meters, the BVI swimmer can still be reliably detected and can receive the feedback signal. Furthermore, since the observed biases were found to be dependent on the specific test environment, calibration of the UWB system would be required. Further development is therefore necessary to accomplish a compact and mobile design.

While the above discussion addressed the research goal and sub-questions, which were related to the detection method, the complete design also comprises a feedback component. However, this fell outside the scope of this discussion. Table 6.1 presents the (technical) design requirements for the complete design and whether they have been fulfilled.

Table 6.1: Overview of fulfillment of the design requirements

Design requirement	Fulfilled?
DR-01	No. Currently, the design does not incorporate a functioning feedback component, and without a feedback signal, the BVI swimmer cannot train independently.
DR-02	No. Although the design is promising, it currently does not ensure the safety of the BVI swimmer as the UWB system is not reliable under all conditions.
DR-03	No. The design withstands the water movement, however its large size and the use of zip bags both hinder the BVI swimmer.
DR-04	Yes. The chosen battery is expected to power the design for a minimum of 2.5 hours.
DR-05	Not tested. Further iterations are necessary to determine whether the design is compatible with training material. Nonetheless, the current design remains relatively difficult to handle due to its size.
DR-06	Yes. The Li-Po battery removes the need for a power socket.
DR-07	Yes. The cost of this design was kept as low as possible, totaling €85.34. However, as the Pozyx Creator One kit was provided by De Haagse Hogeschool, it did not add to this cost. The kit normally costs €1050.

Continued on next page

Table 6.1 – continued from previous page

Design requirement	Fulfilled?
DR-08	Not tested. If the design is positioned at the occipital region, it is expected to function regardless of the body position of the BVI swimmer.
DR-09	Not tested. Future research should take this into account, as testing only included one swimmer.
DR-10	Not tested. Future research should take this into account, as testing only included one swimmer.
DR-11	Yes. Although this design is relatively large, it is still comfortable for the BVI swimmer. Future iterations should nonetheless aim to improve this.
TDR-01	Yes. The design functions regardless of the width of the swimming pool or lanes.
TDR-02	Yes. Although the design cannot detect the BVI swimmer over an entire lane length, it generally can detect the swimmer at distances of up to eight meters, which is sufficient to trigger the feedback signal.
TDR-03	Yes. Although the design cannot detect the BVI swimmer over an entire lane length, it generally can detect the swimmer at distances of up to eight meters, which is sufficient to trigger the feedback signal.
TDR-04	Yes. The design functions regardless of the depth of the swimming pool, as it remains above the water surface.
TDR-05	Not tested. Once the design is made compact and waterproof, this requirement should be considered.
TDR-06	Not tested. Once the design is made compact and waterproof, this requirement should be considered.
TDR-07	Not tested. Once the design is made compact and waterproof, this requirement should be considered.

Recommendations for future development

A distinct outcome from the pool measurements was the pool coverage of the UWB system. This outcome indicated that the UWB system was reasonably reliable up to a distance of approximately eight meters. Therefore, the second and third technical design requirement from Chapter 2 can only be satisfied under one condition. This UWB system will not be able to detect the BVI swimmer over the entire length of the lane. However, this is not required since the BVI swimmer only has to be notified about the end of the swim lane. The feedback signal can be sent at a distance less than eight meters, so it can be suitable for swimming pools as stated in TDR-02 and TDR-03.

Another solution could be to increase the number of anchors per swim lane. This report only conducted pool tests with a single anchor, although the measurements in Chapter 4 included two anchors. Two anchors still would not be enough to cover the entire swim lane, but perhaps it is possible to increase the number of anchors even more. A difficulty with a test setup that uses more than two anchors can be the placement of the additional anchors. The first two anchors can be placed at the end of the swim lane, allowing a straightforward ranging process as the BVI swimmer swims directly towards the anchor. However, the additional anchors need to be positioned somewhere along the swim lane, making the ranging process more complex.

The test setup could withstand the conditions of the pool environment for a certain amount of time, yet this test setup with zip bags was not a very sustainable solution. The number of failed readings increased throughout the testing phase, potentially due to the moisture affecting the components. Because a failed reading cannot result in a feedback signal, the BVI swimmer would not receive any. Therefore, DR-01 and DR-02 were not met because of the reliability required. Furthermore, the test setup used in the tests with the swimmer, did not meet DR-03. This requirement states that the design must not hinder the swimmer while swimming. While the test setup functioned adequately, it hindered the swimmer's breathing by making it more difficult to turn the head sideways.

The test setup used in this thesis was therefore considered a proof of concept rather than a finished design which would be ready to use. To accomplish the first three design requirements, the components should be integrated into a design that is waterproof. Additionally, the components should be miniaturized to fit in a compact design that is comfortable for the BVI swimmer, as stated in DR-11. A more compact design may also reduce the extent to which it hinders the swimmer while swimming. In the current test setup, the components were selected because of their specifications and ease of use, while the size was not deemed important as it was used for a proof of concept. When developing a waterproof design, the technical design requirements about the pool water conditions, TDR-05 to TDR-07, should be taken into account.

Following the development of a smaller and waterproof design, its position on the swimmer's head is crucial for the ranging process. As mentioned in Chapter 3, different regions of the head remained above the water surface during different swimming strokes (Gibelli et al., 2023). For the front crawl, the most suitable position is the occipital region, because the design would always remain above the water surface. This was also observed during the tests with a swimmer. During the breaststroke and butterfly stroke, the swimmer's head is expected to be completely submerged in each stroke, so a short signal loss is unavoidable. The design could be positioned at the occipital region as well, as this region experiences the least immersion. Lastly, the design can be positioned on the swimmer's forehead while performing the back stroke. This test setup was not tested during this thesis and thus can not be confirmed.

The proposed design positions on the swimmer's head are expected to satisfy the eighth design requirement, as they allow the UWB system to function regardless of the body position of the BVI swimmer during different swimming strokes. Besides further investigating different design positions on the swimmer's head, future research should examine the effect of positioning the design at exactly the occipital region. With the test setup used in this report, it was positioned in the neck rather than at the occipital region. Because of this placement, the wearable was closer to the water surface than it would be at the occipital region, which could have increased multipath interference from the reflections off the water. Additionally, positioning the wearable at the occipital region may improve the chance of an LOS condition, as the swimmer's head is less likely to obstruct the UWB signal.

The haptic motor used in this report did not provide sufficient vibration intensity to be perceived by the swimmer. It was mainly selected for its ease of integration into the UWB system. With the test setup inside the two zip bags, the vibrations of the haptic motor were difficult to notice, even when it was pressed firmly against the skin. During the dynamic tests, the haptic motor could not be pressed firmly against the swimmer's head, as the components were connected via jumper wires. These wires were too fragile to allow the components to be pressed against the head. Therefore, the swimmer did not feel any of the vibrations during the measurements, indicating that a different haptic motor and mounting method would be required. Without a functioning feedback component, the first two design requirements cannot be satisfied. The test setup cannot enable the BVI swimmer to train independently, since there is no feedback indicating when the end of the swim lane is approaching. Consequently, the safety of the BVI swimmer cannot be ensured.

Another feedback signal which can be used is bone conduction feedback. For this thesis, it was too difficult to integrate a bone conduction headphone into the ranging system. Most bone conduction earphones available on the market operate via Bluetooth with their own internal battery and cannot be directly controlled from the Arduino Uno. Additionally, the Bluetooth signal was expected to be unreliable in the pool environment. Therefore, a bone conduction earphone had to be opened and the internal wires to the transducer elements had to be desoldered. Then, the transducer elements could be soldered to new wires and connected to the Arduino Uno. However, as indicated by the literature review of Hugo Stallenberg, this is the most promising feedback method.

During this thesis, several assumptions were made, including that the BVI swimmer swims alone in the swim lane and follows a straight path towards the pool wall. These assumptions were established to simplify the design challenge. Future work should therefore evaluate this design under more realistic conditions, such as scenarios with multiple swimmers per swim lane.

More broadly, this thesis represents an initial proof of concept rather than a ready-to-use design. To develop a design that can be practically used by BVI swimmers, the findings in the thesis will have to be implemented in both the hardware and the software, with particular attention to system calibration and the limitations of the feedback component.

7 Conclusion

This thesis investigated whether a transmitter-based technology could enable blind and visually impaired swimmers to independently detect their turning point in a swimming pool. Out of three options, Ultra-wideband was selected as the most promising technology. RFID was excluded because of its low accuracy and high power consumption. Ultrasound was ruled out after several concept designs for both UWB and ultrasound were developed and their performance and limitations were assessed. The ultrasound concepts were considered less feasible for two reasons. First, the sensor mounted on the pool wall required an additional communication link to deliver the feedback signal. Second, the head-mounted sensor's accuracy was unreliable due to the head rotations while swimming. The findings of this report focused solely on UWB technology, as all the measurements were performed using this technology.

During the tests in the swimming pool, the test setup showed good performance at distances of up to approximately eight meters between the wearable and the anchor. However, not every test run demonstrated reliable results. This mainly occurred when the test setup was positioned at water level, where multipath interference from the water surface could disturb the UWB signal.

The implementation of the trigger zone functioned well and could easily be adjusted through the Arduino sketch. Additionally, the haptic motor vibrated when the test setup was located inside the trigger zone, demonstrating the working principle of the feedback mechanism.

Although the feedback mechanism was successfully demonstrated, the haptic motor itself was not suitable for this application. The tests with the swimmer showed that the vibrations produced by the haptic motor were too weak to notice while swimming. It was selected because it was easy to integrate into the test setup. However, a more powerful motor should be used for future iterations.

The position of the wearable during the dynamic tests was not ideal. The test setup used in this report positioned the wearable at the back of the swimmer's neck, just above the water surface. This led to noisy measurements caused by multipath reflections from the water as well as the swimmer's head obstructing the UWB signal. Therefore, the wearable should be positioned at the occipital region on the swimmer's head. This places the wearable ten to twenty centimeters above the water surface and is expected to result in less multipath interference. Additionally, this elevation may improve the chance of an LOS condition between the anchor and the wearable, reducing the number of false negatives when the swimmer approaches the anchor.

The proposed test setup in this report was designed to increase the independence of BVI swimmers. It included both a detection method and a feedback component, so that a tapper would no longer be needed. Although the feedback component was not successfully implemented, the detection method demonstrated its feasibility, despite the previously mentioned limitations. The literature review, conducted by Hugo Stallenberg, did not identify any published results about the ranging performance of UWB systems in a pool environment. While UWB was already widely used in land-based settings, very little was known about how this technology would operate near or at the water surface. The measurements in this report demonstrated how submersion, reflections from the water and the placement of the wearable and the anchor affect ranging performance, yet reliable results could still be achieved up to approximately eight meters in the pool environment. Therefore, to the best of the author's knowledge, the measurements and results presented in this report represent a novel contribution to the field.

Beyond its primary application, the proposed UWB ranging system may also be relevant to other applications. For instance, sighted swimmers could benefit from this system. They could rely on the UWB ranging system to measure the distance to the pool wall and receive a feedback signal once this distance drops below a certain threshold. This would allow the swimmers to focus more on their technique, without tracking when the end of the swim lane is approaching.

Furthermore, as the detection component operates independently from the feedback component, it could be used to track an athlete's position during training sessions. Each athlete would have to attach the wearable to their sportswear, for example to a helmet. Then, their position can be tracked given that enough anchors are placed around the pool, sports hall, or sports field. More broadly, the obtained results suggest that the underlying detection method could be relevant beyond swimming to other environments where reflective surfaces or NLOS conditions can affect positioning. This can occur in water sports, like rowing or sailing, or indoor sports where reflections from walls or floors may affect the signal quality.

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A Final versions of Arduino sketches and Python scripts

This appendix exhibits the final versions of the Arduino sketches and the Python scripts in Spyder.

```
1  #include <Pozyx.h>
2  #include <Pozyx_definitions.h>
3  #include <Wire.h>
4  #include <Adafruit_DRV2605.h>
5
6  Adafruit_DRV2605 drv;
7
8  #define ANCHOR_ID 0x696c
9  #define ZONE_FAR 5000
10 #define ZONE_NEAR 4000
11 #define HAPTIC_ENABLED true // set false to test ranging noise baseline
12 #define SAMPLES 3
13
14 // --- Haptic burst settings ---
15 const uint8_t TICK_EFFECT = 24; // Sharp tick 1 (100%)
16 //const uint8_t TICK_EFFECT = 34; // Short double sharp tick 1 (100%)
17 //const uint8_t TICK_EFFECT = 56; // Pulsing sharp 1 (100%)
18 const unsigned long BURST_INTERVAL = 250; // ms between bursts - 250ms for 24 &
    500ms for 34 & 56
19
20 unsigned long lastBurstTime = 0;
21
22 void fireBurst() {
23     drv.setWaveform(0, TICK_EFFECT);
24     drv.setWaveform(1, 0);
25     drv.go();
26     delay(60); // delay=60ms for 24 & delay=110ms for 34 & delay=160ms for 56
27 }
28
29 void setup() {
30     delay(2000);
31     Serial.begin(115200);
32     while (!Serial);
33     delay(500);
34
35     // --- Init Pozyx ---
36     Serial.println(F("Waiting for Pozyx shield..."));
37     while (Pozyx.begin(false, MODE_POLLING) == POZYX_FAILURE) {
38         Serial.println(F("Shield not found, retrying..."));
39         delay(1000);
40     }
41     Serial.println(F("Pozyx connected!"));
42
43     // --- Init DRV2605L ---
44     if (!drv.begin()) {
45         Serial.println(F("DRV2605L not found ãĀĤ check wiring!"));
46         while (1);
47     }
48     drv.selectLibrary(6);
49     drv.setMode(DRV2605_MODE_INTTRIG);
50     Serial.println(F("DRV2605L ready!"));
51
52     // --- Warmup ---
53     Serial.println(F("Warming up..."));
54     for (int i = 0; i < 80; i++) {
55         device_range_t range;
56         Pozyx.doRanging(ANCHOR_ID, &range);
```

```

57 }
58 Serial.println(F("Ready."));
59 Serial.println(F("Starting ranging..."));
60 }
61
62 long measureMedian(uint16_t anchorID) {
63     long readings[SAMPLES];
64     int successful = 0;
65
66     for (int i = 0; i < SAMPLES; i++) {
67         device_range_t range;
68         if (Pozyx.doRanging(anchorID, &range) == POZYX_SUCCESS) {
69             readings[successful++] = range.distance;
70         }
71     }
72
73     if (successful == 0) return -1;
74
75     for (int i = 0; i < successful - 1; i++)
76         for (int j = i + 1; j < successful; j++)
77             if (readings[j] < readings[i]) {
78                 long tmp = readings[i];
79                 readings[i] = readings[j];
80                 readings[j] = tmp;
81             }
82
83     return readings[successful / 2];
84 }
85
86 void loop() {
87     long dist = measureMedian(ANCHOR_ID);
88
89     if (dist != -1) {
90         bool inZone = (dist <= ZONE_FAR && dist >= ZONE_NEAR);
91
92         // --- Serial log ---
93         Serial.print(millis());
94         Serial.print(F(", "));
95         Serial.print(dist);
96         Serial.print(inZone ? F(", ALERT") : F(", OK"));
97         Serial.println();
98
99         // --- Haptic feedback ---
100     if (inZone && HAPTIC_ENABLED) {
101         unsigned long now = millis();
102         if (now - lastBurstTime >= BURST_INTERVAL) {
103             fireBurst();
104             lastBurstTime = now;
105         }
106     }
107
108     } else {
109         Serial.println(F("Ranging failed"));
110     }
111 }

```

Code Listing A.1: Arduino sketch used for ranging with 1 anchor, including the haptic motor

```

1  #include <Pozyx.h>
2  #include <Pozyx_definitions.h>
3  #include <Wire.h>
4  #include <Adafruit_DRV2605.h>
5
6  Adafruit_DRV2605 drv;
7
8  // --- Anchor IDs ---
9  #define ANCHOR_A  0x696c
10 #define ANCHOR_B  0x6e02
11 // --- Zone thresholds
12 #define ZONE_FAR   3250
13 #define ZONE_NEAR  2750
14 #define HAPTIC_ENABLED true // set false to test ranging noise baseline
15 #define SAMPLES    3
16
17 // --- Haptic burst settings ---
18 const uint8_t TICK_EFFECT = 24; // Sharp tick 1 (100%)
19 const unsigned long BURST_INTERVAL = 250; // ms between bursts
20
21 unsigned long lastBurstTime = 0;
22
23 void fireBurst() {
24     drv.setWaveform(0, TICK_EFFECT);
25     drv.setWaveform(1, 0);
26     drv.go();
27     delay(30);
28 }
29
30 void setup() {
31     delay(2000);
32     Serial.begin(115200);
33     while (!Serial);
34     delay(500);
35
36     // --- Init Pozyx ---
37     Serial.println(F("Waiting for Pozyx shield..."));
38     while (Pozyx.begin(false, MODE_POLLING) == POZYX_FAILURE) {
39         Serial.println(F("Shield not found, retrying..."));
40         delay(1000);
41     }
42     Serial.println(F("Pozyx connected!"));
43
44     // --- Init DRV2605L ---
45     if (!drv.begin()) {
46         Serial.println(F("DRV2605L not found âĀĤ check wiring!"));
47         while (1);
48     }
49     drv.selectLibrary(6);
50     drv.setMode(DRV2605_MODE_INTTRIG);
51     Serial.println(F("DRV2605L ready!"));
52
53     // --- Warmup both anchors ---
54     Serial.println(F("Warming up..."));
55     for (int i = 0; i < 30; i++) {
56         device_range_t range;
57         Pozyx.doRanging(ANCHOR_A, &range);
58         Pozyx.doRanging(ANCHOR_B, &range);
59     }
60     Serial.println(F("Ready."));
61     Serial.println(F("Starting ranging..."));
62 }
63
64 long measureMedian(uint16_t anchorID) {
65     long readings[SAMPLES];
66     int successful = 0;

```

```

67
68 for (int i = 0; i < SAMPLES; i++) {
69     device_range_t range;
70     if (Pozyx.doRanging(anchorID, &range) == POZYX_SUCCESS) {
71         readings[successful++] = range.distance;
72     }
73 }
74
75 if (successful == 0) return -1;
76
77 // Bubble sort
78 for (int i = 0; i < successful - 1; i++)
79     for (int j = i + 1; j < successful; j++)
80         if (readings[j] < readings[i]) {
81             long tmp = readings[i];
82             readings[i] = readings[j];
83             readings[j] = tmp;
84         }
85
86 return readings[successful / 2];
87 }
88
89 void loop() {
90     long distA = measureMedian(ANCHOR_A);
91     long distB = measureMedian(ANCHOR_B);
92
93     bool inZoneA = (distA != -1) && (distA >= ZONE_NEAR && distA <= ZONE_FAR);
94     bool inZoneB = (distB != -1) && (distB >= ZONE_NEAR && distB <= ZONE_FAR);
95     bool alert = inZoneA || inZoneB;
96
97     // --- Serial log ---
98     Serial.print(millis());
99     Serial.print(F(", "));
100
101     if (distA != -1) Serial.print(distA);
102     else Serial.print(F("FAIL"));
103     Serial.print(F(", "));
104     Serial.print(inZoneA ? F("ALERT") : F("OK"));
105
106     Serial.print(F(", "));
107
108     if (distB != -1) Serial.print(distB);
109     else Serial.print(F("FAIL"));
110     Serial.print(F(", "));
111     Serial.print(inZoneB ? F("ALERT") : F("OK"));
112
113     Serial.println();
114
115     // --- Haptic feedback ---
116     if (alert && HAPTIC_ENABLED) {
117         unsigned long now = millis();
118         if (now - lastBurstTime >= BURST_INTERVAL) {
119             fireBurst();
120             lastBurstTime = now;
121         }
122     }
123 }

```

Code Listing A.2: Arduino sketch used for ranging with 2 anchors, including the haptic motor

```

1  #include <Pozyx.h>
2  #include <Pozyx_definitions.h>
3  #include <Wire.h>
4  #include <SPI.h>
5  #include <SD.h>
6  #include <EEPROM.h>
7
8  #define ANCHOR_ID 0x696c
9  #define TEST_DISTANCE_M 5
10 #define ZONE_FAR 3500
11 #define ZONE_NEAR 3000
12 #define SAMPLES 3
13
14 #define SD_CS_PIN 10
15 #define EEPROM_ADDR 0
16
17 #define NUM_READINGS 200 // stop after this many logged rows
18
19 File logFile;
20 char filename[13]; // 8.3 format, e.g. "TEST007.CSV"
21
22 void setup() {
23     delay(2000);
24     Serial.begin(115200);
25     delay(500);
26
27     Serial.println(F("Waiting for Pozyx shield..."));
28     while (Pozyx.begin(false, MODE_POLLING) == POZYX_FAILURE) {
29         Serial.println(F("Shield not found, retrying..."));
30         delay(1000);
31     }
32     Serial.println(F("Pozyx connected!"));
33
34     // --- Init SD ---
35     Serial.println(F("Initializing SD card..."));
36     int sdAttempts = 0;
37     while (!SD.begin(SD_CS_PIN)) {
38         Serial.println(F("SD init failed, retrying..."));
39         delay(500);
40         sdAttempts++;
41         if (sdAttempts > 10) {
42             Serial.println(F("SD init failed!. Halting."));
43             while (1) delay(1000);
44         }
45     }
46
47     // --- unique filename via per-distance EEPROM counter ---
48     byte testNum = EEPROM.read(TEST_DISTANCE_M);
49     if (testNum == 255) testNum = 0;
50     sprintf(filename, "%dM%03d.CSV", TEST_DISTANCE_M, testNum);
51     EEPROM.write(TEST_DISTANCE_M, testNum + 1);
52
53     logFile = SD.open(filename, FILE_WRITE);
54     if (!logFile) {
55         Serial.println(F("Failed to open log file!"));
56         while (1) delay(1000);
57     }
58     logFile.println("millis,distance_mm,zone");
59     logFile.flush();
60
61     Serial.print(F("Logging to: "));
62     Serial.println(filename);
63
64     // flush warmup readings
65     Serial.println(F("Warming up..."));
66     for (int i = 0; i < 55; i++) {

```

```

67     device_range_t range;
68     Pozyx.doRanging(ANCHOR_ID, &range);
69 }
70 Serial.println(F("Ready."));
71 Serial.println(F("Starting ranging..."));
72 }
73
74 long measureMedian(uint16_t anchorID) {
75     long readings[SAMPLES];
76     int successful = 0;
77
78     for (int i = 0; i < SAMPLES; i++) {
79         device_range_t range;
80         if (Pozyx.doRanging(anchorID, &range) == POZYX_SUCCESS) {
81             readings[successful++] = range.distance;
82         }
83     }
84
85     if (successful == 0) return -1;
86
87     for (int i = 0; i < successful - 1; i++)
88         for (int j = i + 1; j < successful; j++)
89             if (readings[j] < readings[i]) {
90                 long tmp = readings[i];
91                 readings[i] = readings[j];
92                 readings[j] = tmp;
93             }
94
95     return readings[successful / 2];
96 }
97
98 int count = 0;
99
100 void loop() {
101     if (count >= NUM_READINGS) {
102         logFile.close();
103         Serial.println(F("Done logging. File closed."));
104         while (1) delay(1000); // stop here; power-cycle for a new test
105     }
106
107     long dist = measureMedian(ANCHOR_ID);
108
109     if (dist != -1) {
110         unsigned long t = millis();
111         const char* zone = (dist <= ZONE_FAR && dist >= ZONE_NEAR) ? "ALERT" : "OK";
112
113         // Serial (optional, useful when you DO have a laptop for debugging)
114         Serial.print(t); Serial.print(F(", ")); Serial.print(dist);
115         Serial.print(F(", ")); Serial.println(zone);
116
117         // SD log
118         logFile.print(t); logFile.print(F(", "));
119         logFile.print(dist); logFile.print(F(", "));
120         logFile.println(zone);
121         logFile.flush(); // ensures data survives a sudden power loss
122
123         count++;
124     } else {
125         Serial.println(F("Ranging failed"));
126     }
127 }

```

Code Listing A.3: Arduino sketch used for ranging with 1 anchor, including the microSD module

```

1  #include <Pozyx.h>
2  #include <Pozyx_definitions.h>
3  #include <Wire.h>
4  #include <SPI.h>
5  #include <SD.h>
6  #include <EEPROM.h>
7  #include <Adafruit_DRV2605.h>
8
9  Adafruit_DRV2605 drv;
10
11 #define ANCHOR_ID 0x696c
12 #define TEST_DISTANCE_M 4
13 #define ZONE_FAR 3000
14 #define ZONE_NEAR 3500
15 #define HAPTIC_ENABLED true // set false to test ranging noise baseline
16 #define SAMPLES 3
17
18 // --- SD settings ---
19 #define SD_CS_PIN 10
20 #define EEPROM_ADDR 0
21 #define NUM_READINGS 200 // stop logging after this
22
23 File logFile;
24 char filename[13]; // 8.3 format, e.g. "TEST007.CSV"
25 int count = 0;
26
27 // --- Haptic burst settings ---
28 const uint8_t TICK_EFFECT = 24; // Sharp tick 1 (100%)
29 //const uint8_t TICK_EFFECT = 34; // Short double sharp tick 1 (100%)
30 //const uint8_t TICK_EFFECT = 56; // Pulsing sharp 1 (100%)
31 const unsigned long BURST_INTERVAL = 250; // ms between bursts - 250ms for 24 &
    500ms for 34 & 56
32
33 unsigned long lastBurstTime = 0;
34
35 void fireBurst() {
36     drv.setWaveform(0, TICK_EFFECT);
37     drv.setWaveform(1, 0);
38     drv.go();
39     delay(60); // delay=60ms for 24 & delay=110ms for 34 & delay=160ms for 56
40 }
41
42 void setup() {
43     delay(2000);
44     Serial.begin(115200);
45     delay(500);
46
47     // --- Init Pozyx ---
48     Serial.println(F("Waiting for Pozyx shield..."));
49     while (Pozyx.begin(false, MODE_POLLING) == POZYX_FAILURE) {
50         Serial.println(F("Shield not found, retrying..."));
51         delay(1000);
52     }
53     Serial.println(F("Pozyx connected!"));
54
55     // --- Init DRV2605L ---
56     if (!drv.begin()) {
57         Serial.println(F("DRV2605L not found âĀĤ check wiring!"));
58         while (1);
59     }
60     drv.selectLibrary(6);
61     drv.setMode(DRV2605_MODE_INTTRIG);
62     Serial.println(F("DRV2605L ready!"));
63
64     Serial.println(F("Initializing SD card..."));
65     int sdAttempts = 0;

```

```

66 while (!SD.begin(SD_CS_PIN)) {
67     Serial.println(F("SD init failed, retrying..."));
68     delay(500);
69     sdAttempts++;
70     if (sdAttempts > 10) {
71         Serial.println(F("SD init failed!. Halting.));
72         while (1) delay(1000);
73     }
74 }
75
76 // --- unique filename via per-distance EEPROM counter ---
77 byte testNum = EEPROM.read(TEST_DISTANCE_M);
78 if (testNum == 255) testNum = 0;
79 sprintf(filename, "SW%dM%03d.CSV", TEST_DISTANCE_M, testNum);
80 EEPROM.write(TEST_DISTANCE_M, testNum + 1);
81
82 logFile = SD.open(filename, FILE_WRITE);
83 if (!logFile) {
84     Serial.println(F("Failed to open log file!"));
85     while (1) delay(1000);
86 }
87 logFile.println("millis,distance_mm,zone,ranging_status,error_code,haptic_fired");
88 logFile.flush();
89
90 Serial.print(F("Logging to: "));
91 Serial.println(filename);
92
93 // --- Warmup ---
94 Serial.println(F("Warming up..."));
95 for (int i = 0; i < 80; i++) {
96     device_range_t range;
97     Pozyx.doRanging(ANCHOR_ID, &range);
98 }
99 Serial.println(F("Ready.));
100 Serial.println(F("Starting ranging...));
101 }
102
103 long measureMedian(uint16_t anchorID, bool *rangingFailed) {
104     long readings[SAMPLES];
105     int successful = 0;
106     *rangingFailed = false;
107
108     for (int i = 0; i < SAMPLES; i++) {
109         device_range_t range;
110         if (Pozyx.doRanging(anchorID, &range) == POZYX_SUCCESS) {
111             readings[successful++] = range.distance;
112         }
113     }
114
115     if (successful == 0) {
116         *rangingFailed = true;
117         return -1;
118     }
119
120     for (int i = 0; i < successful - 1; i++)
121         for (int j = i + 1; j < successful; j++)
122             if (readings[j] < readings[i]) {
123                 long tmp = readings[i];
124                 readings[i] = readings[j];
125                 readings[j] = tmp;
126             }
127
128     return readings[successful / 2];
129 }
130
131 void logRow(unsigned long t, long dist, const char* zoneStr, const char* statusStr,

```

```

    const String &errCodeStr, int hapticFired) {
132 // Serial
133 Serial.print(t); Serial.print(F(", "));
134 if (dist >= 0) Serial.print(dist);
135 Serial.print(F(", "));
136 Serial.print(zoneStr); Serial.print(F(", "));
137 Serial.print(statusStr); Serial.print(F(", "));
138 Serial.print(errCodeStr); Serial.print(F(", "));
139 Serial.println(hapticFired);
140
141 // SD
142 logFile.print(t); logFile.print(F(", "));
143 if (dist >= 0) logFile.print(dist);
144 logFile.print(F(", "));
145 logFile.print(zoneStr); logFile.print(F(", "));
146 logFile.print(statusStr); logFile.print(F(", "));
147 logFile.print(errCodeStr); logFile.print(F(", "));
148 logFile.println(hapticFired);
149 logFile.flush();
150 }
151
152 void loop() {
153     if (count >= NUM_READINGS) {
154         logFile.close();
155         Serial.println(F("Done logging. File closed."));
156         while (1) delay(1000);
157     }
158
159     bool rangingFailed = false;
160     unsigned long t = millis();
161     long dist = measureMedian(ANCHOR_ID, &rangingFailed);
162
163     if (!rangingFailed) {
164         bool inZone = (dist <= ZONE_FAR && dist >= ZONE_NEAR);
165         const char* zoneStr = inZone ? "ALERT" : "OK";
166         int hapticFired = 0;
167
168         if (inZone && HAPTIC_ENABLED) {
169             unsigned long now = millis();
170             if (now - lastBurstTime >= BURST_INTERVAL) {
171                 fireBurst();
172                 lastBurstTime = now;
173                 hapticFired = 1;
174             }
175         }
176
177         logRow(t, dist, zoneStr, "OK", "", hapticFired);
178
179     } else {
180         uint8_t errorCode = 0;
181         int status = Pozyx.getErrorCode(&errorCode);
182         String errCodeStr = "0x";
183         if (status == POZYX_SUCCESS) {
184             if (errorCode < 16) errCodeStr += "0";
185             errCodeStr += String(errorCode, HEX);
186         } else {
187             errCodeStr = "N/A";
188         }
189
190         logRow(t, -1, "N/A", "FAIL", errCodeStr, 0);
191     }
192
193     count++;
194 }

```

Code Listing A.4: Arduino sketch used for ranging with 1 anchor, including both the haptic and the microSD module

```

1 import serial
2 import datetime
3 import time
4
5 PORT          = "COM11"
6 BAUD          = 115200
7 NUM_READINGS  = 100
8 DISTANCE      = 3110
9
10 with serial.Serial(PORT, BAUD) as ser:
11     print("Waiting for Arduino to boot...")
12     time.sleep(2)
13     ser.reset_input_buffer()
14
15     filename = f"test_{datetime.date.today()}_{DISTANCE}.csv"
16
17     with open(filename, "w") as f:
18         f.write("timestamp,millis,distance_mm,zone\n")
19
20         print(f"Logging to: {filename}")
21         print("Waiting for ranging to start...")
22
23         while True:
24             try:
25                 line = ser.readline().decode("utf-8").strip()
26             except UnicodeDecodeError:
27                 continue
28             if "starting ranging" in line.lower():
29                 print("Ranging started, logging...")
30                 break
31
32         count = 0
33         skip_msgs = ["retrying", "waiting", "starting", "pozyx connected",
34                     "warming", "ready", "drv2605"]
35
36         while count < NUM_READINGS:
37             try:
38                 line = ser.readline().decode("utf-8").strip()
39             except UnicodeDecodeError:
40                 print("SYSTEM: decode error, skipping")
41                 continue
42             if not line:
43                 continue
44             if any(m in line.lower() for m in skip_msgs):
45                 print(f"SYSTEM: {line}")
46                 continue
47             parts = line.split(",")
48             if len(parts) != 3:
49                 print(f"SYSTEM (bad format): {line}")
50                 continue
51
52             millis, distance, zone = parts
53             timestamp = datetime.datetime.now().isoformat()
54             print(f"[{count+1}/{NUM_READINGS}] [{millis}] {distance}mm âĖŠ {zone}")
55             f.write(f"{timestamp},{millis},{distance},{zone}\n")
56             f.flush()
57             count += 1
58
59     print(f"\nDone! Saved to {filename}")

```

Code Listing A.5: Python script used for data logging with 1 anchor

```

1 import pandas as pd
2
3 FILENAME = r"Zwembad test\extra OW&OWT\OWT7M013.csv"
4 TRUE_DIST = 7100
5 MAX_ERROR = 150
6 ZONE_NEAR = 6750
7 ZONE_FAR = 7250
8
9 df = pd.read_csv(FILENAME, dtype=str)
10 total = len(df)
11
12 #failed = df["distance_mm"] == "FAILED"           #zonder SD
13 failed = df["ranging_status"] == "FAIL"          #met SD
14 good = df[~failed].copy()
15 readings = good["distance_mm"].astype(float)
16 alerts = good["zone"] == "ALERT"
17
18 error = readings - TRUE_DIST
19 abs_error = error.abs()
20 outliers = readings[abs_error > MAX_ERROR]
21
22 in_zone = (readings >= ZONE_NEAR) & (readings <= ZONE_FAR)
23 false_positives = alerts & ~in_zone
24 false_negatives = ~alerts & in_zone
25
26 print(f"\n--- {FILENAME} (ground truth: {TRUE_DIST} mm) ---")
27 print(f"Total readings: {total}")
28 print(f"Successful: {len(good)} ({len(good)/total*100:.1f}%)")
29 print(f"Mean distance: {readings.mean():.1f} mm")
30 print(f"Mean error: {error.mean():.1f} mm")
31 print(f"MAE: {abs_error.mean():.1f} mm")
32 print(f"Variance: {readings.var():.1f}")
33 print(f"Std deviation: {readings.std():.1f} mm")
34 print(f"Min / Max: {readings.min():.1f} / {readings.max():.1f} mm")
35 print(f"Outliers: {len(outliers)} ({len(outliers)/len(good)*100:.1f}%)")
36 print(f"Alerts triggered: {alerts.sum()} ({alerts.sum()/len(good)*100:.1f}%)")
37 print(f"False positives: {false_positives.sum()} ({false_positives.sum()/len(good)*100:.1f}%)")
38 print(f"False negatives: {false_negatives.sum()} ({false_negatives.sum()/len(good)*100:.1f}%)")

```

Code Listing A.6: Python script used for data evaluation for the test setup with 1 anchor

```

1  import serial
2  import datetime
3  import time
4
5  port          = "COM12"
6  baud          = 115200
7  num_readings = 200
8
9  with serial.Serial(port, baud) as ser:
10     print("Waiting for Arduino to boot...")
11     time.sleep(2)
12     ser.reset_input_buffer()
13
14     distance_a = 3          # 0x696c
15     distance_b = 3          # 0x6e02
16     filename = f"test_{datetime.date.today()}_A{distance_a}_B{distance_b}.csv"
17
18     with open(filename, "w") as f:
19         f.write("timestamp,millis,anchor_a_mm,anchor_b_mm\n")
20
21         print("Waiting for ranging to start...")
22         while True:
23             try:
24                 line = ser.readline().decode("utf-8").strip()
25             except UnicodeDecodeError:
26                 continue
27             if "ready" in line.lower():
28                 print("Ranging started, beginning log...")
29                 break
30
31         print(f"Logging {num_readings} readings...")
32         count = 0
33         while count < num_readings:
34             try:
35                 line = ser.readline().decode("utf-8").strip()
36             except UnicodeDecodeError:
37                 print("SYSTEM: decode error, skipping line")
38                 continue
39
40             if not line:
41                 continue
42
43             timestamp = datetime.datetime.now().isoformat()
44
45             skip_messages = ["retrying", "waiting", "starting", "pozyx connected", "
warming", "ready"]
46             if any(msg in line.lower() for msg in skip_messages):
47                 print(f"SYSTEM: {line}")
48                 continue
49
50             parts = line.split(",")
51             if len(parts) != 3:
52                 print(f"SYSTEM: {line}")
53                 continue
54
55             millis, distA, distB = parts
56             distA = "FAILED" if distA in ["-1", "4294967295"] else distA
57             distB = "FAILED" if distB in ["-1", "4294967295"] else distB
58
59             print(f"[{count+1}/{num_readings}] {timestamp}: [{millis}] {distA} {distB}
        ")
60             f.write(f"{timestamp},{millis},{distA},{distB}\n")
61             f.flush()
62             count += 1
63

```

```
print(f"\nDone! Saved to {filename}")
```

Code Listing A.7: Python script used for data logging with 2 anchors

```

1 import pandas as pd
2
3 FILENAME = r"Static_57_trigzone\swim_2026-06-11_7055.csv"
4 TRUE_DIST_A = 7000
5 TRUE_DIST_B = 5000
6 MAX_ERROR = 150
7 ZONE_NEAR = 4750
8 ZONE_FAR = 5250
9
10 df = pd.read_csv(FILENAME, dtype=str)
11 total = len(df)
12
13 # --- Per-anchor filtering ---
14 def anchor_stats(df, anchor_col, true_dist, anchor_label):
15     failed = df[anchor_col] == "FAIL"
16     good = df[~failed].copy()
17     readings = good[anchor_col].astype(float)
18
19     error = readings - true_dist
20     abs_error = error.abs()
21     outliers = readings[abs_error > MAX_ERROR]
22
23     in_zone = (readings >= ZONE_NEAR) & (readings <= ZONE_FAR)
24     alerts = good["alert"] == "ALERT"
25     false_positives = alerts & ~in_zone
26     false_negatives = ~alerts & in_zone
27
28     print(f"\n --- Anchor {anchor_label} (ground truth: {true_dist} mm) ---")
29     print(f" Successful readings: {len(good)} ({len(good)/total*100:.1f}%)")
30     print(f" Mean distance: {readings.mean():.1f} mm")
31     print(f" Mean error: {error.mean():.1f} mm")
32     print(f" MAE: {abs_error.mean():.1f} mm")
33     print(f" Variance: {readings.var():.1f}")
34     print(f" Std deviation: {readings.std():.1f} mm")
35     print(f" Min / Max: {readings.min():.1f} / {readings.max():.1f} mm")
36     print(f" Outliers: {len(outliers)} ({len(outliers)/len(good)*100:.1f}%)")
37     print(f" False positives: {false_positives.sum()} ({false_positives.sum()/len(good)*100:.1f}%)")
38     print(f" False negatives: {false_negatives.sum()} ({false_negatives.sum()/len(good)*100:.1f}%)")
39
40 # --- Overall stats ---
41 failed_either = (df["anchor_a_mm"] == "FAIL") & (df["anchor_b_mm"] == "FAIL")
42 good_overall = df[~failed_either]
43 alerts_total = (good_overall["alert"] == "ALERT").sum()
44
45 print(f"\n=== {FILENAME} ===")
46 print(f"Total readings: {total}")
47 print(f"Both anchors FAIL: {failed_either.sum()} ({failed_either.sum()/total*100:.1f}%)")
48 print(f"Alerts triggered: {alerts_total} ({alerts_total/len(good_overall)*100:.1f}%)")
49 print(f"Anchor A active: {(good_overall['closest_anchor']=='A').sum()} times")
50 print(f"Anchor B active: {(good_overall['closest_anchor']=='B').sum()} times")
51
52 anchor_stats(df, "anchor_a_mm", TRUE_DIST_A, "A")
53 anchor_stats(df, "anchor_b_mm", TRUE_DIST_B, "B")

```

Code Listing A.8: Python script used for data evaluation for the test setup with 2 anchors

```

1 import pandas as pd
2
3 FILENAME = r"Setup tests @X\75M000.csv"
4 TRUE_DIST_A = 7000
5 TRUE_DIST_B = 5000
6 MAX_ERROR = 150
7 ZONE_NEAR = 4750
8 ZONE_FAR = 5250
9
10 df = pd.read_csv(FILENAME, dtype=str)
11 total = len(df)
12
13 # --- Per-anchor filtering ---
14 def anchor_stats(df, dist_col, status_col, zone_col, true_dist, anchor_label):
15     #failed = df[dist_col] == "FAILED" #zonder SD
16     failed = df[status_col] == "FAIL" #met SD
17     good = df[~failed].copy()
18     readings = good[dist_col].astype(float)
19     alerts = good[zone_col] == "ALERT"
20
21     error = readings - true_dist
22     abs_error = error.abs()
23     outliers = readings[abs_error > MAX_ERROR]
24
25     in_zone = (readings >= ZONE_NEAR) & (readings <= ZONE_FAR)
26     false_positives = alerts & ~in_zone
27     false_negatives = ~alerts & in_zone
28
29     print(f"\n --- Anchor {anchor_label} (ground truth: {true_dist} mm) ---")
30     print(f" Successful readings: {len(good)} ({len(good)/total*100:.1f}%)")
31     print(f" Mean distance: {readings.mean():.1f} mm")
32     print(f" Mean error: {error.mean():.1f} mm")
33     print(f" MAE: {abs_error.mean():.1f} mm")
34     print(f" Variance: {readings.var():.1f}")
35     print(f" Std deviation: {readings.std():.1f} mm")
36     print(f" Min / Max: {readings.min():.1f} / {readings.max():.1f} mm")
37     print(f" Outliers: {len(outliers)} ({len(outliers)/total*100:.1f}%)")
38     print(f" Alerts triggered: {alerts.sum()} ({alerts.sum()/len(good)*100:.1f}%)")
39     print(f" False positives: {false_positives.sum()} ({false_positives.sum()/len(good)*100:.1f}%)")
40     print(f" False negatives: {false_negatives.sum()} ({false_negatives.sum()/len(good)*100:.1f}%)")
41
42 # --- Overall stats ---
43 failed_either = (df["statusA"] == "FAIL") & (df["statusB"] == "FAIL")
44 good_overall = df[~failed_either].copy()
45
46 # no single "alert" column anymore - a row counts as an alert if either
47 # anchor's own zone flag says ALERT
48 alert_overall = (good_overall["zoneA"] == "ALERT") | (good_overall["zoneB"] == "ALERT")
49 alerts_total = alert_overall.sum()
50
51 # "closest_anchor" isn't logged directly either - derive it per row from
52 # whichever anchor reports the smaller successful distance
53 distA = pd.to_numeric(good_overall["distA_mm"], errors="coerce")
54 distB = pd.to_numeric(good_overall["distB_mm"], errors="coerce")
55 closest_anchor = pd.Series(index=good_overall.index, dtype=object)
56 closest_anchor[distA.notna() & distB.isna()] = "A"
57 closest_anchor[distB.notna() & distA.isna()] = "B"
58 both_valid = distA.notna() & distB.notna()
59 closest_anchor[both_valid & (distA <= distB)] = "A"
60 closest_anchor[both_valid & (distB < distA)] = "B"
61
62 print(f"\n=== {FILENAME} ===")

```

```

63 print(f"Total readings:      {total}")
64 print(f"Both anchors FAIL: {failed_either.sum()} ({failed_either.sum()/total*100:.1f
    }%)")
65 print(f"Alerts triggered:   {alerts_total} ({alerts_total/len(good_overall)*100:.1f}%)
    ")
66 print(f"Anchor A active:    {(closest_anchor=='A').sum()} times")
67 print(f"Anchor B active:    {(closest_anchor=='B').sum()} times")
68
69 anchor_stats(df, "distA_mm", "statusA", "zoneA", TRUE_DIST_A, "A")
70 anchor_stats(df, "distB_mm", "statusB", "zoneB", TRUE_DIST_B, "B")

```

Code Listing A.9: Python script used for data evaluation for the test setup with 2 anchors in the pool environment

B One-anchor measurements performed at ECHO

This appendix shows the measurements conducted at ECHO TU Delft. The test setup included the wearable and a single anchor. Measurements were performed for distances of three to eight meters.

Table B.1: UWB ranging results with one anchor positioned 3 m from the wearable

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	3043.9	3008.0	3051.0	2994.6	2990.5	2988.4	2990.8	2999.2	2998.5	3004.2
Mean error:	8.9	-27.0	16.0	-40.5	-44.5	-46.6	-44.2	-35.8	-36.5	-30.8
MAE:	17.3	30.4	23.1	42.4	45.7	47.2	44.9	36.9	38.0	33.4
Var:	442.6	661.9	729.1	868.2	661.1	698.3	693.2	572.4	679.2	648.8
Std dev:	21.0	25.7	27.0	29.5	25.7	26.4	26.3	23.9	26.1	25.5
Min:	3005.0	2963.0	3001.0	2930.0	2926.0	2930.0	2926.0	2963.0	2930.0	2963.0
Max:	3118.0	3076.0	3113.0	3066.0	3076.0	3038.0	3066.0	3066.0	3066.0	3076.0
Outliers:	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)

Table B.2: UWB ranging results with one anchor positioned 4 m from the wearable

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	4019.0	4053.8	4056.4	3956.0	3930.5	4101.5	4088.0	4086.0	4084.2	4077.1
Mean error:	-7.0	27.8	30.4	-70.0	-95.5	75.5	62.0	60.0	58.2	51.1
MAE:	20.1	32.1	32.6	70.0	95.5	75.6	62.3	60.0	58.3	51.6
Var:	600.5	982.7	831.4	666.4	593.7	1083.9	985.5	1240.3	991.6	1020.1
Std dev:	24.5	31.3	28.8	25.8	24.4	32.9	31.4	35.2	31.5	31.9
Min:	3956.0	3984.0	3994.0	3881.0	3872.0	4022.0	3994.0	4022.0	4022.0	3994.0
Max:	4087.0	4162.0	4171.0	4022.0	3984.0	4200.0	4200.0	4190.0	4237.0	4171.0
Outliers:	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	1 (0.5%)	1 (0.5%)	1 (0.5%)	1 (0.5%)	0 1 (0.5%)	0 (0.0%)

Table B.3: UWB ranging results with one anchor positioned 5 m from the wearable

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	5031.8	5030.0	5021.8	5011.6	5019.9	5014.9	5012.4	5008.9	4988.0	5033.5
Mean error:	10.8	9.0	0.8	-9.4	-1.1	-6.1	-8.6	-12.2	-33.0	12.5
MAE:	22.5	21.8	20.6	25.5	18.3	21.5	17.8	19.5	34.1	55.7
Var:	774.1	674.2	600.3	876.1	455.4	663.4	423.8	423.2	489.2	4009.0
Std dev:	27.8	26.0	24.5	29.6	21.3	25.8	20.6	20.6	22.1	63.3
Min:	4968.0	4939.0	4968.0	4939.0	4968.0	4939.0	4968.0	4939.0	4930.0	4930.0
Max:	5108.0	5108.0	5098.0	5108.0	5070.0	5108.0	5070.0	5070.0	5033.0	5173.0
Outliers:	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	2 (1.0%)

Table B.4: UWB ranging results with one anchor positioned 7 m from the wearable

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	7132.8	6973.3	7041.4	7017.4	7036.1	7120.3	7069.1	6973.7	7132.8	7104.5
Mean error:	117.8	-41.7	26.4	2.4	21.1	105.3	54.1	-41.3	117.8	89.5
MAE:	117.8	55.5	35.1	24.7	32.1	105.3	54.3	44.0	117.8	89.5
Var:	979.9	2297.5	1032.8	891.9	1436.1	2009.5	793.7	989.6	948.3	1137.1
Std dev:	31.3	47.9	32.1	29.9	37.9	44.8	28.2	31.5	30.8	33.7
Min:	7080.0	6888.0	6963.0	6930.0	6968.0	7015.0	7005.0	6912.0	7052.0	7015.0
Max:	7193.0	7179.0	7113.0	7080.0	7165.0	7268.0	7155.0	7062.0	7231.0	7202.0
Outliers:	18 (9.0%)	1 (0.5%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	18 (9.0%)	0 (0.0%)	0 (0.0%)	17 (8.5%)	3 (1.5%)

C Two-anchor measurements performed at ECHO

This appendix presents the measurements conducted at ECHO TU Delft. The test setup included the wearable and two anchors. Measurements were performed for distances of three to seven meters, varying in distance to both anchors.

Table C.1: UWB ranging results with anchors A and B positioned at 3 m from the wearable

<i>Anchor A</i>	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	3046.0	3048.9	3046.8	3055.8	3062.2	3056.7	3069.8	3052.4	3059.7	3059.7
Mean error:	11.0	13.9	11.8	20.8	27.2	21.7	34.8	17.4	24.7	24.7
MAE:	29.1	21.8	25.1	28.2	34.4	31.7	40.1	27.1	34.1	33.7
Var:	1838.1	583.7	951.7	982.8	1176.0	1199.2	1151.2	1056.1	1073.2	1057.8
Std dev:	42.9	24.2	30.8	31.3	34.3	34.6	33.9	32.5	32.8	32.5
Min:	2818.0	2991.0	2954.0	2991.0	2991.0	2991.0	2991.0	2991.0	2991.0	2954.0
Max:	3160.0	3123.0	3123.0	3160.0	3123.0	3123.0	3160.0	3123.0	3123.0	3123.0
Outliers:	2 (1.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)

<i>Anchor B</i>	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	3012.1	3016.2	3014.8	3007.4	3013.3	3010.9	3020.4	3013.6	3019.8	3015.4
Mean error:	-22.9	-18.8	-20.2	-27.6	-21.7	-24.1	-14.6	-21.4	-15.2	-19.6
MAE:	28.4	42.5	26.6	34.0	29.1	28.3	22.1	26.5	23.9	28.9
Var:	670.9	5010.4	652.9	896.3	654.5	468.8	492.4	475.3	618.8	783.2
Std dev:	25.9	70.8	25.6	29.9	25.6	21.7	22.2	21.8	24.9	28.0
Min:	2949.0	2940.0	2949.0	2940.0	2968.0	2968.0	2949.0	2968.0	2949.0	2949.0
Max:	3080.0	3446.0	3080.0	3080.0	3080.0	3080.0	3080.0	3080.0	3080.0	3104.0
Outliers:	0 (0.0%)	5 (2.5%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)

Table C.2: UWB ranging results with anchors A and B positioned at 5 m from the wearable

<i>Anchor A</i>	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	5066.3	5052.5	5062.9	5074.9	5061.1	5069.4	5062.3	5070.8	5070.9	5071.2
Mean error:	45.3	31.5	41.9	53.9	40.1	48.4	41.3	49.8	49.9	50.2
MAE:	45.6	34.4	44.9	56.1	44.4	51.3	45.1	52.2	51.7	52.5
Var:	459.6	711.2	1290.1	1065.2	1257.7	1366.8	1225.8	1221.5	1170.6	695.2
Std dev:	21.4	26.7	35.9	32.6	35.5	37.0	35.0	34.9	34.2	33.7
Min:	5005.0	4986.0	5014.0	4986.0	4986.0	4986.0	4986.0	4986.0	5014.0	4986.0
Max:	5126.0	5150.0	5150.0	5112.0	5112.0	5150.0	5150.0	5150.0	5150.0	5150.0
Outliers:	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)

<i>Anchor B</i>	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	4989.0	4990.2	4998.4	5004.9	4982.2	4961.9	4962.0	4954.9	4964.5	4959.7
Mean error:	-32.0	-30.8	-22.6	-16.1	-38.8	-59.1	-59.0	-66.1	-56.5	-61.3
MAE:	32.9	34.5	31.4	35.9	42.4	59.7	59.1	66.1	56.9	61.3
Var:	431.0	640.2	914.5	3427.6	914.5	759.6	665.6	742.8	1132.6	526.4
Std dev:	20.8	25.3	30.2	58.5	30.2	27.6	25.8	27.3	26.4	22.9
Min:	4944.0	4916.0	4907.0	4939.0	4907.0	4907.0	4878.0	4888.0	4907.0	4907.0
Max:	5047.0	5070.0	5070.0	5384.0	5070.0	5033.0	5033.0	5009.0	5042.0	5009.0
Outliers:	0 (0.0%)	0 (0.0%)	0 (0.0%)	4 (2.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)

Table C.3: UWB ranging results with anchor A positioned 3 m and anchor B positioned 5 m from the wearable

<i>Anchor A</i>	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	3078.0	3081.1	3080.9	3087.0	3085.5	3106.8	3104.4	3096.7	3138.2	3133.8
Mean error:	43.0	46.1	45.9	52.0	50.5	71.8	69.5	61.7	103.2	98.8
MAE:	45.6	47.0	46.1	53.8	50.9	72.6	70.2	62.7	103.2	98.8
Var:	771.5	1148.1	759.7	839.5	720.2	777.2	696.5	1059.8	461.2	999.0
Std dev:	27.8	33.9	27.6	29.0	26.8	27.9	26.4	32.6	21.5	31.6
Min:	3015.0	2996.0	3034.0	3010.0	3010.0	3010.0	3010.0	3010.0	3048.0	3085.0
Max:	3151.0	3165.0	3165.0	3146.0	3146.0	3184.0	3146.0	3146.0	3184.0	3221.0
Outliers:	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	4 (2.0%)

<i>Anchor B</i>	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	4850.1	4850.4	4846.1	4852.6	4849.0	4855.2	4858.3	4853.6	4855.1	4853.2
Mean error:	-170.9	-170.6	-174.9	-168.4	-172.0	-165.8	-162.7	-167.4	-165.9	-167.8
MAE:	170.9	170.6	174.9	168.4	172.0	165.8	162.7	167.4	165.9	167.8
Var:	730.7	921.5	603.2	704.5	951.8	1010.0	1114.5	1019.4	671.1	801.8
Std dev:	27.0	30.4	24.6	26.5	30.9	31.8	33.4	31.9	25.9	28.3
Min:	4780.0	4775.0	4752.0	4789.0	4785.0	4789.0	4771.0	4733.0	4771.0	4808.0
Max:	4911.0	4907.0	4925.0	4925.0	4925.0	4963.0	4963.0	4935.0	4902.0	4949.0
Outliers:	138 (69.0%)	170 (85.0%)	174 (87.0%)	166 (83.0%)	166 (83.0%)	147 (73.5%)	143 (71.5%)	168 (84.0%)	170 (85.0%)	128 (64.0%)

Table C.4: UWB ranging results with anchor A positioned 5 m and anchor B positioned 3 m from the wearable

<i>Anchor A</i>	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	4881.9	4873.1	4866.7	4885.5	4879.6	4895.9	4887.8	4893.8	4880.3	4882.2
Mean error:	-139.2	-147.9	-154.3	-135.5	-141.4	-125.0	-133.2	-127.2	-140.7	-138.8
MAE:	139.2	147.9	154.3	135.5	141.4	125.0	133.2	127.2	140.7	138.8
Var:	644.5	868.2	929.5	1220.6	723.8	1274.9	480.1	835.6	610.4	781.3
Std dev:	25.4	29.5	30.5	34.9	26.9	35.7	21.9	28.9	24.7	28.0
Min:	4817.0	4808.0	4799.0	4775.0	4832.0	4794.0	4794.0	4817.0	4836.0	4836.0
Max:	4958.0	4949.0	4944.0	4944.0	4968.0	4968.0	4968.0	4986.0	4911.0	4949.0
Outliers:	60 (30.0%)	69 (34.5%)	115 (57.5%)	86 (43.0%)	134 (67.0%)	48 (24.0%)	37 (18.5%)	27 (13.5%)	29 (14.5%)	33 (16.5%)
<i>Anchor B</i>	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	3014.2	3001.4	3010.8	3001.5	3003.1	3020.9	3001.2	3010.0	3018.7	3018.6
Mean error:	-20.8	-33.6	-24.2	-33.5	-31.9	-14.1	-33.8	-25.0	-16.3	-16.4
MAE:	32.2	34.2	31.0	36.7	36.4	32.1	36.4	34.9	24.7	27.2
Var:	1138.7	511.1	974.2	703.8	793.3	2053.0	512.5	1170.2	541.2	809.6
Std dev:	33.7	22.6	31.2	26.5	28.2	45.3	22.6	34.2	23.3	28.5
Min:	2944.0	2954.0	2930.0	2944.0	2944.0	2944.0	2944.0	2935.0	2973.0	2954.0
Max:	3095.0	3066.0	3095.0	3085.0	3085.0	3333.0	3085.0	3071.0	3085.0	3085.0
Outliers:	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	3 (1.5%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)

D Two-anchor measurements performed at X, outside the trigger zone

This appendix shows the measurements conducted at X TU Delft. The test setup included the wearable, two anchors and the haptic motor. Measurements were performed for distances of two to eight meters, varying in distance to both anchors. The wearable was positioned outside the trigger zone.

Table D.1: UWB ranging results with anchor A at 4 m and anchor B at 6 m from the wearable, with the wearable outside the trigger zone (3000–3500 mm)

<i>Anchor A</i>	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	3975.2	3978.9	3975.6
Mean error:	-24.8	-21.1	-24.4
MAE:	35.1	33.0	36.6
Var:	981.6	976.0	1130.9
Std dev:	31.3	31.2	33.6
Min / Max:	3923.0 / 4050.0	3923.0 / 4050.0	3923.0 / 4050.0
Outliers:	0 (0.0%)	0 (0.0%)	0 (0.0%)
<i>Anchor B</i>	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	5956.9	5960.8	5961.6
Mean error:	-43.1	-39.2	-38.4
MAE:	44.9	40.1	40.6
Var:	1035.6	830.1	874.9
Std dev:	32.2	28.8	29.6
Min / Max:	5886.0 / 6054.0	5853.0 / 6016.0	5853.0 / 6054.0
Outliers:	0 (0.0%)	0 (0.0%)	0 (0.0%)

Table D.2: UWB ranging results with anchor A at 6 m and anchor B at 4 m from the wearable, with the wearable outside the trigger zone (3000–3500 mm)

<i>Anchor A</i>	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	6095.8	6093.1	5905.8
Mean error:	95.8	93.1	-94.2
MAE:	95.8	93.1	94.2
Var:	1208.2	1447.8	1370.2
Std dev:	34.8	38.1	37.0
Min / Max:	6021.0 / 6190.0	6002.0 / 6176.0	5825.0 / 5961.0
Outliers:	29 (14.5%)	10 (5.0%)	1 (0.5%)
<i>Anchor B</i>	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	3934.5	3930.3	4023.2
Mean error:	-65.5	-69.7	23.2
MAE:	65.5	69.7	28.3
Var:	744.9	748.2	500.3
Std dev:	27.3	27.4	22.4
Min / Max:	3848.0 / 3999.0	3863.0 / 3984.0	3952.0 / 4078.0
Outliers:	1 (0.5%)	0 (0.0%)	0 (0.0%)

Table D.3: UWB ranging results with anchor A at 8 m and anchor B at 2 m from the wearable, with the wearable outside the trigger zone (3000–3500 mm)

<i>Anchor A</i>	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	7875.0	7899.2	7907.6
Mean error:	-125.0	-100.8	-92.3
MAE:	125.0	100.8	92.3
Var:	1094.2	1422.6	1176.2
Std dev:	33.1	37.7	34.3
Min / Max:	7769.0 / 7999.0	7821.0 / 7957.0	7821.0 / 7957.0
Outliers:	25 (12.5%)	8 (4.0%)	8 (4.0%)
<i>Anchor B</i>	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	2089.0	2021.1	2021.9
Mean error:	89.0	21.1	21.9
MAE:	89.0	23.2	29.4
Var:	722.8	562.7	724.2
Std dev:	26.9	23.7	26.9
Min / Max:	2018.0 / 2144.0	1961.0 / 2074.0	1961.0 / 2083.0
Outliers:	1 (0.5%)	0 (0.0%)	0 (0.0%)

E Two-anchor measurements performed at X, inside the trigger zone

This appendix presents the measurements conducted at X TU Delft. The test setup included the wearable, two anchors and the haptic motor. Measurements were performed for distances of three to seven meters, varying in distance to both anchors. The wearable was positioned inside the trigger zone.

Table E.1: UWB ranging results with anchor A at 7 m and anchor B at 3 m from the wearable, with the wearable inside the trigger zone (2750–3250 mm)

<i>Anchor A</i>	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
Successful:	163 (81.5%)	186 (93.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	7263.4	7352.9	7078.0	7076.6	7112.2	7115.6
Mean error:	263.4	352.9	78.0	76.6	112.2	115.6
MAE:	263.4	352.9	78.3	77.2	113.5	116.2
Var:	384921.8	827443.9	1472.8	1629.4	2013.5	1362.0
Std dev:	620.4	909.6	38.4	40.4	44.9	36.9
Min / Max:	7019.0 / 12801.0	7024.0 / 12844.0	6991.0 / 7146.0	6954.0 / 7202.0	6930.0 / 7221.0	6968.0 / 7198.0
Outliers:	135 (82.8%)	158 (84.9%)	0 (0.0%)	5 (2.5%)	33 (16.5%)	31 (15.5%)
False pos	-	-	-	-	-	-
False neg	-	-	-	-	-	-
<i>Anchor B</i>	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	3139.7	3131.1	3177.8	3166.2	3190.2	3193.3
Mean error:	139.7	131.1	177.8	166.2	190.2	193.3
MAE:	140.1	131.9	177.8	166.2	190.2	193.3
Var:	1324.5	1376.9	1506.3	1744.7	2919.3	1858.7
Std dev:	36.4	37.1	38.8	41.8	54.0	43.1
Min / Max:	2959.0 / 3226.0	2959.0 / 3226.0	3001.0 / 3249.0	3029.0 / 3249.0	3015.0 / 3296.0	3015.0 / 3296.0
Outliers:	104 (52.0%)	45 (22.5%)	168 (84.0%)	162 (81.0%)	170 (85.0%)	180 (90.0%)
False pos	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
False neg	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)

Table E.2: UWB ranging results for three wearable orientations with anchor A at 5 m and anchor B at 7 m from the wearable, with the wearable inside the trigger zone (4750–5250 mm)

<i>Anchor A</i>	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	5214.4	5211.8	5114.6	5119.3	5199.1	5197.8
Mean error:	214.4	211.8	114.6	119.3	199.1	197.8
MAE:	214.4	211.8	114.6	119.6	199.1	197.8
Var:	3507.2	1851.6	1607.0	1184.6	4079.4	4259.7
Std dev:	59.2	43.0	40.1	34.4	63.9	65.3
Min / Max:	5023.0 / 5309.0	5080.0 / 5314.0	5005.0 / 5216.0	4968.0 / 5234.0	5014.0 / 5295.0	5014.0 / 5295.0
Outliers:	171 (85.5%)	187 (93.5%)	34 (17.0%)	27 (13.5%)	159 (79.5%)	168 (84.0%)
False pos	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
False neg	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
<i>Anchor B</i>	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	104 (52.0%)	97 (48.5%)
Mean dist:	7029.4	7037.9	7045.4	7042.3	7220.2	7241.1
Mean error:	29.4	37.9	45.4	42.3	220.2	241.1
MAE:	53.7	47.1	52.3	48.9	224.8	241.9
Var:	3233.5	1593.1	2065.9	1577.9	562580.3	714587.4
Std dev:	56.9	39.9	45.5	39.7	750.1	845.3
Min / Max:	6841.0 / 7127.0	6930.0 / 7113.0	6883.0 / 7174.0	6916.0 / 7127.0	6949.0 / 14255.0	6973.0 / 13111.0
Outliers:	1 (0.5%)	0 (0.0%)	1 (0.5%)	0 (0.0%)	46 (44.2%)	29 (29.9%)
False pos	-	-	-	-	-	-
False neg	-	-	-	-	-	-

Table E.3: UWB ranging results for three wearable orientations with anchor A at 7 m and anchor B at 5 m from the wearable, with the wearable inside the trigger zone (4750–5250 mm)

<i>Anchor A</i>	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
Successful:	122 (61.0%)	123 (61.5%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	8081.8	8387.1	7094.1	7090.9	7154.3	7165.9
Mean error:	1081.8	1387.1	94.1	90.9	154.3	165.8
MAE:	1081.8	1387.1	94.4	93.3	154.3	165.8
Var:	5930248.6	9291515.0	1736.9	1837.4	1118.3	1374.3
Std dev:	2435.2	3048.2	41.7	42.9	33.4	37.1
Min / Max:	7043.0 / 21800.0	7048.0 / 21739.0	6968.0 / 7193.0	6921.0 / 7207.0	7001.0 / 7226.0	7010.0 / 7263.0
Outliers:	113 (92.6%)	117 (95.1%)	31 (15.5%)	7 (3.5%)	165 (82.5%)	164 (82.0%)
False pos	-	-	-	-	-	-
False neg	-	-	-	-	-	-
<i>Anchor B</i>	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	5101.2	5104.7	5091.1	5095.4	5148.2	5151.8
Mean error:	101.2	104.7	91.1	95.4	148.2	151.8
MAE:	104.0	106.4	92.9	95.7	148.2	151.8
Var:	1509.5	1183.6	1485.9	1383.4	1351.6	1756.8
Std dev:	38.9	34.4	38.5	37.2	36.8	41.9
Min / Max:	4902.0 / 5201.0	4902.0 / 5173.0	4944.0 / 5230.0	4991.0 / 5192.0	5000.0 / 5211.0	5014.0 / 5258.0
Outliers:	9 (4.5%)	25 (12.5%)	14 (7.0%)	14 (7.0%)	88 (44.0%)	104 (52.0%)
False pos	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
False neg	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)

F Components of the final test setup

Table F.1 presents the list of the components used in the final test setup for in the swimming pool, including a link to the website where it was bought.

Table F.1: List of components from the final test setup

Component	
Arduino Uno Rev3 - ATmega328	(Electronics, 2026a)
Creator One kit - Pozyx	(Pozyx, 2026)
DRV2605L Linear Actuator Haptic Breakout	(Electronics, 2026b)
MicroSD card breakout board+	(Electronics, 2026d)
Philips geheugenkaart (SD card)	(Philips, 2026)
Lithium Ion Batterij - 3.7 V 2200 mAh	(Solutions, 2026)
Lipo Rider Plus (Charger/Booster) - 5 V/2.4 A USB Type C	(Electronics, 2026c)
USB A to USB B cable	

G Land-based benchmark measurements with the final test setup

This appendix shows the measurements conducted at X TU Delft. The test setup included the wearable, one or two anchors, the haptic motor, the SD module and the battery. Measurements with a single anchor were performed for distances of three to ten meters. The wearable was positioned outside the trigger zone, apart from a distance of four meters. Measurements with two anchors were performed for distances of two to eight meters, varying in distance to both anchors. The wearable was positioned both outside and inside the trigger zone.

Table G.1: UWB ranging results for the final test setup at a distance of 3 m from the anchor, with the wearable outside the trigger zone (3750–4250 mm)

	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	3024.0	3010.1	2992.3
Mean error:	24.0	10.1	-7.7
MAE:	28.5	22.5	20.8
Var:	789.1	669.8	580.0
Std dev:	28.1	25.9	24.1
Min / Max:	2954.0 / 3104.0	2949.0 / 3066.0	2940.0 / 3071.0
Outliers:	0 (0.0%)	0 (0.0%)	0 (0.0%)

Table G.2: UWB ranging results for the final test setup at a distance of 4 m from the anchor, with the wearable inside the trigger zone (3750–4250 mm)

	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	4029.1	4014.5	4013.3
Mean error:	29.1	14.5	13.3
MAE:	40.4	28.7	27.4
Var:	1406.2	1039.4	807.8
Std dev:	37.5	32.2	28.4
Min / Max:	3863.0 / 4129.0	3933.0 / 4101.0	3942.0 / 4087.0
Outliers:	0 (0.0%)	0 (0.0%)	0 (0.0%)
False pos	0 (0.0%)	0 (0.0%)	0 (0.0%)
False neg	0 (0.0%)	0 (0.0%)	0 (0.0%)

Table G.3: UWB ranging results for the final test setup at a distance of 5 m from the anchor, with the wearable outside the trigger zone (3750–4250 mm)

	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	4951.5	4942.8	4935.6
Mean error:	-48.5	-57.2	-64.4
MAE:	49.1	57.2	64.7
Var:	787.0	760.5	827.5
Std dev:	28.1	27.6	28.8
Min / Max:	4860.0 / 5033.0	4874.0 / 5005.0	4846.0 / 5028.0
Outliers:	0 (0.0%)	0 (0.0%)	1 (0.5%)

Table G.4: UWB ranging results for the final test setup at a distance of 6 m from the anchor, with the wearable outside the trigger zone (3750–4250 mm)

	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	5928.5	5926.7	5923.2
Mean error:	-71.5	-73.3	-76.8
MAE:	71.7	73.4	76.8
Var:	1009.0	1065.6	936.3
Std dev:	31.8	32.6	30.6
Min / Max:	5843.0 / 6007.0	5839.0 / 6012.0	5839.0 / 5984.0
Outliers:	2 (1.0%)	6 (3.0%)	2 (1.0%)

Table G.5: UWB ranging results for the final test setup at a distance of 7 m from the anchor, with the wearable outside the trigger zone (3750–4250 mm)

	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	6894.3	6883.4	6908.9
Mean error:	-105.7	-116.6	-91.1
MAE:	105.7	116.6	91.2
Var:	1144.5	1227.9	1050.3
Std dev:	33.8	35.0	32.4
Min / Max:	6785.0 / 6963.0	6799.0 / 6982.0	6822.0 / 7010.0
Outliers:	13 (6.5%)	33 (16.5%)	6 (3.0%)

Table G.6: UWB ranging results for the final test setup at a distance of 8 m from the anchor, with the wearable outside the trigger zone (3750–4250 mm)

	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	7894.5	8022.7	7908.9
Mean error:	-105.5	22.7	-91.1
MAE:	108.4	40.6	91.1
Var:	2369.6	1984.2	1584.6
Std dev:	48.7	44.5	39.8
Min / Max:	7788.0 / 8295.0	7891.0 / 8126.0	7807.0 / 8004.0
Outliers:	35 (17.5%)	0 (0.0%)	15 (7.5%)

Table G.7: UWB ranging results for the final test setup at a distance of 9 m from the anchor, with the wearable outside the trigger zone (3750–4250 mm)

	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	9368.0	9309.4	9257.6
Mean error:	368.0	309.4	257.6
MAE:	532.0	464.3	401.9
Var:	2711816.9	1904516.1	1573041.3
Std dev:	1646.8	1380.0	1254.2
Min / Max:	8745.0 / 21735.0	8712.0 / 14236.0	8740.0 / 14180.0
Outliers:	50 (25.0%)	30 (15.0%)	43 (21.5%)

Table G.8: UWB ranging results for the final test setup at a distance of 10 m from the anchor, with the wearable outside the trigger zone (3750–4250 mm)

	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	9812.0	9839.6	9886.8
Mean error:	-188.0	-160.4	-113.2
MAE:	188.0	172.6	187.3
Var:	1386.0	5644.5	72453.2
Std dev:	37.2	75.1	269.2
Min / Max:	9725.0 / 9899.0	9739.0 / 10302.0	9655.0 / 12332.0
Outliers:	166 (83.0%)	138 (69.0%)	122 (61.0%)

Table G.9: UWB ranging results for the final test setup with anchor A at 2 m and anchor B at 8 m from the wearable, with the wearable outside the trigger zone (3000–3500 mm)

<i>Anchor A</i>	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	2083.6	2100.1	2100.8
Mean error:	83.6	100.1	100.8
MAE:	83.6	100.1	100.8
Var:	479.0	606.1	398.2
Std dev:	21.9	24.6	20.0
Min / Max:	2018.0 / 2148.0	2022.0 / 2158.0	2041.0 / 2172.0
Outliers:	0 (0.0%)	8 (4.0%)	1 (0.5%)
<i>Anchor B</i>	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	7807.1	7804.2	7800.3
Mean error:	-192.9	-195.8	-199.7
MAE:	192.9	195.8	199.7
Var:	1150.2	1070.2	1457.1
Std dev:	33.9	32.7	38.2
Min / Max:	7722.0 / 7882.0	7727.0 / 7924.0	7709.0 / 7891.0
Outliers:	173 (86.5%)	191 (95.5%)	178 (89.0%)

Table G.10: UWB ranging results for the final test setup with anchor A at 4 m and anchor B at 6 m from the wearable, with the wearable outside the trigger zone (3000–3500 mm)

<i>Anchor A</i>	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	4058.5	4070.5	4064.8
Mean error:	58.5	70.5	64.8
MAE:	58.6	70.5	64.8
Var:	457.2	599.7	564.1
Std dev:	21.4	24.5	23.7
Min / Max:	3989.0 / 4115.0	4008.0 / 4125.0	4003.0 / 4134.0
Outliers:	0 (0.0%)	0 (0.0%)	0 (0.0%)
<i>Anchor B</i>	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	5878.7	5860.4	5866.4
Mean error:	-121.3	-139.6	-133.6
MAE:	121.3	139.6	133.6
Var:	1324.7	1015.7	1163.6
Std dev:	36.4	31.9	34.1
Min / Max:	5806.0 / 5961.0	5787.0 / 5961.0	5773.0 / 5965.0
Outliers:	59 (29.5%)	86 (43.0%)	66 (33.0%)

Table G.11: UWB ranging results for the final test setup with anchor A at 6 m and anchor B at 4 m from the wearable, with the wearable outside the trigger zone (3000–3500 mm)

<i>Anchor A</i>	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	6011.8	6025.6	6032.7
Mean error:	11.8	25.6	32.7
MAE:	21.7	28.3	34.9
Var:	614.4	536.5	660.9
Std dev:	24.8	23.2	25.7
Min / Max:	5956.0 / 6091.0	5970.0 / 6082.0	5965.0 / 6096.0
Outliers:	0 (0.0%)	0 (0.0%)	0 (0.0%)
<i>Anchor B</i>	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	3877.8	3859.9	3857.1
Mean error:	-122.2	-140.1	-142.9
MAE:	122.2	140.1	142.9
Var:	1011.4	807.9	914.6
Std dev:	31.8	28.4	30.2
Min / Max:	3787.0 / 3947.0	3792.0 / 3942.0	3764.0 / 3938.0
Outliers:	34 (17.0%)	84 (42.0%)	86 (43.0%)

Table G.12: UWB ranging results for the final test setup with anchor A at 8 m and anchor B at 2 m from the wearable, with the wearable outside the trigger zone (3000–3500 mm)

<i>Anchor A</i>	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	7981.1	7960.9	8004.3
Mean error:	-18.9	-39.1	4.3
MAE:	25.8	41.5	21.3
Var:	672.5	732.0	731.8
Std dev:	25.9	27.1	27.1
Min / Max:	7905.0 / 8060.0	7901.0 / 8032.0	7938.0 / 8088.0
Outliers:	0 (0.0%)	0 (0.0%)	0 (0.0%)
<i>Anchor B</i>	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	1906.7	1929.1	1900.4
Mean error:	-93.3	-70.9	-99.6
MAE:	93.3	71.1	99.6
Var:	885.2	956.7	1068.3
Std dev:	29.8	30.9	32.7
Min / Max:	1831.0 / 1966.0	1858.0 / 2013.0	1817.0 / 1999.0
Outliers:	6 (3.0%)	0 (0.0%)	9 (4.5%)

Table G.13: UWB ranging results for the final test setup with anchor distances of 3 m and 7 m, tested in both test setups and with the wearable inside the trigger zone (2750–3250 mm)

<i>Anchor A</i>	Run 1	Run 2	Run 3	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	3142.2	3143.8	3143.8	7037.6	7046.1	7049.3
Mean error:	142.2	143.8	143.8	37.6	46.1	49.3
MAE:	142.2	143.8	143.8	43.5	49.2	51.7
Var:	945.4	1437.1	1187.3	1478.9	1205.0	1399.4
Std dev:	30.7	37.9	34.5	38.5	34.7	37.4
Min / Max:	3076.0 / 3245.0	3038.0 / 3231.0	3048.0 / 3221.0	6898.0 / 7151.0	6958.0 / 7132.0	6968.0 / 7160.0
Outliers:	91 (45.5%)	107 (53.5%)	95 (47.5%)	1 (0.5%)	0 (0.0%)	3 (1.5%)
False pos	0 (0.0%)	0 (0.0%)	0 (0.0%)	-	-	-
False neg	0 (0.0%)	0 (0.0%)	0 (0.0%)	-	-	-
<i>Anchor B</i>	Run 1	Run 2	Run 3	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	6865.9	6852.0	6802.2	3015.4	2997.9	3023.7
Mean error:	-134.1	-148.0	-197.8	15.4	-2.1	23.7
MAE:	134.1	165.7	197.8	32.2	28.6	37.3
Var:	2405.1	7962.6	1497.2	1325.7	1410.3	1460.6
Std dev:	49.0	89.2	38.7	36.4	37.6	38.2
Min / Max:	6733.0 / 6982.0	6724.0 / 7296.0	6687.0 / 6902.0	2874.0 / 3095.0	2851.0 / 3113.0	2926.0 / 3132.0
Outliers:	75 (37.5%)	115 (57.5%)	179 (89.5%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
False pos	-	-	-	0 (0.0%)	0 (0.0%)	0 (0.0%)
False neg	-	-	-	0 (0.0%)	0 (0.0%)	0 (0.0%)

Table G.14: UWB ranging results for the final test setup with anchor distances of 5 m and 7 m, tested in both test setups and with the wearable inside the trigger zone (4750–5250 mm)

<i>Anchor A</i>	Run 1	Run 2	Run 3	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	5044.8	5063.2	5060.8	7160.8	7095.0	7146.3
Mean error:	44.8	63.2	60.8	160.8	95.0	146.3
MAE:	46.0	63.3	62.2	160.9	95.3	146.4
Var:	935.9	860.8	1270.6	504100.7	1926.9	340726.8
Std dev:	30.6	29.3	35.6	710.0	43.9	583.7
Min / Max:	4935.0 / 5136.0	4996.0 / 5131.0	4897.0 / 5155.0	6996.0 / 15287.0	6968.0 / 7249.0	6987.0 / 15338.0
Outliers:	0 (0.0%)	0 (0.0%)	3 (1.5%)	18 (9.0%)	22 (11.0%)	38 (19.0%)
False pos	0 (0.0%)	0 (0.0%)	0 (0.0%)	-	-	-
False neg	0 (0.0%)	0 (0.0%)	0 (0.0%)	-	-	-
<i>Anchor B</i>	Run 1	Run 2	Run 3	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	6833.6	6822.1	6846.6	4878.8	4896.1	4899.7
Mean error:	-166.4	-177.9	-153.4	-121.2	-103.9	-100.3
MAE:	166.4	177.9	157.8	121.2	103.9	100.4
Var:	1746.2	1590.4	4736.1	1626.1	1315.8	1231.7
Std dev:	41.8	39.9	68.8	40.3	36.3	35.1
Min / Max:	6724.0 / 6944.0	6725.0 / 6916.0	6729.0 / 7132.0	4775.0 / 4986.0	4785.0 / 4977.0	4789.0 / 5005.0
Outliers:	126 (63.0%)	155 (77.5%)	134 (67.0%)	45 (22.5%)	18 (9.0%)	16 (8.0%)
False pos	-	-	-	0 (0.0%)	0 (0.0%)	0 (0.0%)
False neg	-	-	-	0 (0.0%)	0 (0.0%)	0 (0.0%)

H Measurements performed in the pool

This appendix presents the measurements conducted in the swimming pools. The test setup included the wearable, one anchor, the haptic motor, the SD module and the battery. Measurements were performed for distances of three to ten meters. The wearable was positioned outside the trigger zone, apart from a distance of four meters. Additional measurements were performed for distances of four to ten meters. The wearable was positioned in the middle of the swim lane and inside the trigger zone.

Table H.1: UWB ranging results for the pool test at a distance of 3 m from the anchor, with the wearable outside the trigger zone (3750–4250 mm)

	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	3103.2	3103.4	3097.1
Mean error:	3.2	3.4	-2.9
MAE:	23.3	22.9	19.1
Var:	871.8	724.4	647.8
Std dev:	29.5	26.9	25.5
Min / Max:	3038.0 / 3184.0	3048.0 / 3160.0	3034.0 / 3165.0
Outliers:	0 (0.0%)	0 (0.0%)	0 (0.0%)

Table H.2: UWB ranging results for the pool test at a distance of 4 m from the anchor, with the wearable inside the trigger zone (3750–4250 mm)

	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	4119.1	4101.8	4146.1
Mean error:	19.1	1.8	46.1
MAE:	30.9	27.6	52.1
Var:	1087.5	1231.0	1352.4
Std dev:	33.0	35.1	36.8
Min / Max:	4035.0 / 4209.0	3999.0 / 4204.0	4031.0 / 4223.0
Outliers:	0 (0.0%)	0 (0.0%)	0 (0.0%)
Alerts	200 (100.0%)	200 (100.0%)	200 (100.0%)
False pos	0 (0.0%)	0 (0.0%)	0 (0.0%)
False neg	0 (0.0%)	0 (0.0%)	0 (0.0%)

Table H.3: UWB ranging results for the pool test at a distance of 5 m from the anchor, with the wearable outside the trigger zone (3750–4250 mm)

	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	4993.9	4972.9	4978.7
Mean error:	-6.1	-27.1	-21.3
MAE:	17.6	30.3	26.1
Var:	566.0	675.6	607.9
Std dev:	23.8	26.0	24.7
Min / Max:	4921.0 / 5075.0	4902.0 / 5033.0	4893.0 / 5033.0
Outliers:	0 (0.0%)	0 (0.0%)	0 (0.0%)

Table H.4: UWB ranging results for the pool test at a distance of 7 m from the anchor, with the wearable outside the trigger zone (3750–4250 mm)

	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	7000.7	7067.2	7033.9
Mean error:	0.7	67.2	33.9
MAE:	23.7	67.8	38.5
Var:	983.3	1044.8	996.5
Std dev:	31.4	32.3	31.6
Min / Max:	6921.0 / 7109.0	6968.0 / 7179.0	6954.0 / 7123.0
Outliers:	0 (0.0%)	1 (0.5%)	0 (0.0%)

Table H.5: UWB ranging results for the pool test at a distance of 8 m from the anchor, with the wearable outside the trigger zone (3750–4250 mm)

	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	8138.8	8137.5	8238.0
Mean error:	38.8	37.5	138.0
MAE:	41.9	42.8	143.9
Var:	1029.5	1225.1	746729.5
Std dev:	32.1	35.0	864.1
Min / Max:	8060.0 / 8229.0	8046.0 / 8257.0	8060.0 / 16117.0
Outliers:	0 (0.0%)	2 (1.0%)	4 (2.0%)

Table H.6: UWB ranging results for the pool test at a distance of 9 m from the anchor, with the wearable outside the trigger zone (3750–4250 mm)

	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	9134.4	9116.0	9100.6
Mean error:	34.4	16.0	0.7
MAE:	39.5	28.1	27.8
Var:	1143.2	1049.4	1256.5
Std dev:	33.8	32.4	35.4
Min / Max:	9054.0 / 9214.0	9017.0 / 9195.0	8998.0 / 9261.0
Outliers:	0 (0.0%)	0 (0.0%)	1 (0.5%)

Table H.7: UWB ranging results for the pool test at a distance of 4 m from the anchor, with the wearable inside the trigger zone (3750–4250 mm)

	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	4137.5	4158.2	4166.3
Mean error:	37.5	58.2	66.3
MAE:	41.0	58.5	66.4
Var:	848.4	978.7	680.1
Std dev:	29.1	31.3	26.1
Min / Max:	4054.0 / 4200.0	4082.0 / 4251.0	4082.0 / 4237.0
Outliers:	0 (0.0%)	3 (1.5%)	0 (0.0%)
Alerts	200 (100.0%)	197 (98.5%)	200 (100.0%)
False pos	0 (0.0%)	0 (0.0%)	0 (0.0%)
False neg	0 (0.0%)	0 (0.0%)	0 (0.0%)

Table H.8: UWB ranging results for the pool test at a distance of 6 m from the anchor, with the wearable inside the trigger zone (5750–6250 mm)

	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	6161.4	6197.4	6187.6
Mean error:	61.4	97.4	87.6
MAE:	62.8	97.4	88.2
Var:	1178.2	899.0	1362.5
Std dev:	34.3	30.0	36.9
Min / Max:	6044.0 / 6251.0	6120.0 / 6270.0	6091.0 / 6284.0
Outliers:	2 (1.0%)	15 (7.5%)	4 (2.0%)
Alerts	198 (99.0%)	185 (92.5%)	196 (98.0%)
False pos	0 (0.0%)	0 (0.0%)	0 (0.0%)
False neg	0 (0.0%)	0 (0.0%)	0 (0.0%)

Table H.9: UWB ranging results for the pool test at a distance of 8 m from the anchor, with the wearable inside the trigger zone (7750–8250 mm)

	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	8137.0	8112.1	8105.9
Mean error:	37.0	12.1	5.9
MAE:	39.4	21.9	21.7
Var:	1062.9	607.7	879.3
Std dev:	32.6	24.7	29.7
Min / Max:	8079.0 / 8234.0	8037.0 / 8177.0	8027.0 / 8191.0
Outliers:	0 (0.0%)	0 (0.0%)	0 (0.0%)
Alerts	200 (100.0%)	200 (100.0%)	200 (100.0%)
False pos	0 (0.0%)	0 (0.0%)	0 (0.0%)
False neg	0 (0.0%)	0 (0.0%)	0 (0.0%)

I Measurements at water level in the pool, outside the trigger zone

This appendix shows the measurements conducted in the swimming pools. The test setup included the wearable, one anchor, the haptic motor, the SD module and the battery. Measurements were performed for distances of four, six and eight meters and for three tick_effects: 24, 34 and 56. The wearable was positioned outside the trigger zone.

Table I.1: UWB ranging results for the pool test at a distance of 4 m from the anchor, with the wearable outside the trigger zone (3000–3500 mm) and tick_effect 24

	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	4118.3	4106.8	4197.9
Mean error:	18.3	6.8	97.8
MAE:	29.8	27.0	97.8
Var:	1116.1	1090.0	1022.7
Std dev:	33.4	33.0	32.0
Min / Max:	4031.0 / 4218.0	4027.0 / 4204.0	4125.0 / 4283.0
Outliers:	0 (0.0%)	0 (0.0%)	15 (7.5%)

Table I.2: UWB ranging results for the pool test at a distance of 6 m from the anchor, with the wearable outside the trigger zone (3000–3500 mm) and tick_effect 24

	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	6085.6	6152.5	6150.6
Mean error:	-14.4	52.5	50.6
MAE:	31.4	54.0	51.8
Var:	1427.1	1109.5	1039.8
Std dev:	37.8	33.3	32.2
Min / Max:	5979.0 / 6209.0	6063.0 / 6251.0	6068.0 / 6213.0
Outliers:	0 (0.0%)	1 (0.5%)	0 (0.0%)

Table I.3: UWB ranging results for the pool test at a distance of 8 m from the anchor, with the wearable outside the trigger zone (3000–3500 mm) and tick_effect 24

	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	8035.1	8002.7	8035.0
Mean error:	35.1	2.7	35.0
MAE:	43.3	83.1	68.9
Var:	1720.2	180781.0	159214.8
Std dev:	41.5	425.2	399.0
Min / Max:	7957.0 / 8126.0	7887.0 / 13331.0	7896.0 / 12923.0
Outliers:	0 (0.0%)	2 (1.0%)	3 (1.5%)

Table I.4: UWB ranging results for the pool test at a distance of 4 m from the anchor, with the wearable outside the trigger zone (3000–3500 mm) and tick_effect 34

	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	4145.2	4084.3	4103.1
Mean error:	145.2	84.3	103.1
MAE:	145.2	84.3	103.1
Var:	766.9	784.1	1371.3
Std dev:	27.7	28.0	37.0
Min / Max:	4073.0 / 4214.0	4022.0 / 4162.0	4013.0 / 4209.0
Outliers:	70 (35.0%)	2 (1.0%)	16 (8.0%)

Table I.5: UWB ranging results for the pool test at a distance of 8 m from the anchor, with the wearable outside the trigger zone (3000–3500 mm) and tick_effect 34

	Run 1	Run 2	Run 3
Successful:	193 (96.5%)	200 (100.0%)	200 (100.0%)
Mean dist:	8442.8	8068.5	7919.9
Mean error:	442.8	68.5	-80.1
MAE:	449.2	81.3	80.1
Var:	1455998.7	231739.1	1330.6
Std dev:	1206.6	481.4	36.5
Min / Max:	7905.0 / 12876.0	7929.0 / 12834.0	7840.0 / 7990.0
Outliers:	24 (12.4%)	2 (1.0%)	3 (1.5%)

Table I.6: UWB ranging results for the pool test at a distance of 4 m from the anchor, with the wearable outside the trigger zone (3000–3500 mm) and tick_effect 56

	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	4108.5	4052.5	4045.8
Mean error:	108.5	52.5	45.8
MAE:	108.5	52.7	46.6
Var:	963.9	855.7	569.5
Std dev:	31.0	29.3	23.9
Min / Max:	4031.0 / 4200.0	3980.0 / 4162.0	3984.0 / 4106.0
Outliers:	17 (8.5%)	1 (0.5%)	0 (0.0)

Table I.7: UWB ranging results for the pool test at a distance of 6 m from the anchor, with the wearable outside the trigger zone (3000–3500 mm) and tick_effect 56

	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	6187.8	6188.6	6053.4
Mean error:	187.8	188.6	53.5
MAE:	227.7	198.0	56.0
Var:	92562.8	89114.1	1260.0
Std dev:	304.2	298.5	35.5
Min / Max:	5881.0 / 6949.0	5928.0 / 6822.0	5918.0 / 6181.0
Outliers:	74 (37.0%)	47 (23.5%)	1 (0.5%)

J Measurements at water level in the pool, inside the trigger zone

This appendix presents the measurements conducted in the swimming pools. The test setup included the wearable, one anchor, the haptic motor, the SD module and the battery. Measurements were performed for distances of four, six and eight meters and for three tick_effects: 24, 34 and 56. The wearable was positioned inside the trigger zone.

Table J.1: UWB ranging results for the pool test at a distance of 4 m from the anchor, with the wearable inside the trigger zone (3750–4250 mm) and tick_effect 24

	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	4172.9	4166.0	4165.3
Mean error:	72.9	66.0	65.3
MAE:	73.5	66.7	66.8
Var:	1271.8	921.7	1292.5
Std dev:	35.7	30.4	36.0
Min / Max:	4059.0 / 4261.0	4073.0 / 4237.0	4059.0 / 4256.0
Outliers:	5 (2.5%)	0 (0.0%)	1 (0.5%)
Alerts	195 (97.5%)	200 (100.0%)	199 (99.5%)
False pos	0 (0.0%)	0 (0.0%)	0 (0.0%)
False neg	0 (0.0%)	0 (0.0%)	0 (0.0%)

Table J.2: UWB ranging results for the pool test at a distance of 6 m from the anchor, with the wearable inside the trigger zone (5750–6250 mm) and tick_effect 24

	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	6091.8	6088.0	6116.3
Mean error:	-8.2	-12.0	16.3
MAE:	36.3	31.9	28.8
Var:	1871.6	1428.3	1065.8
Std dev:	43.3	37.8	32.6
Min / Max:	6007.0 / 6260.0	5988.0 / 6185.0	6035.0 / 6241.0
Outliers:	1 (0.5%)	0 (0.0%)	0 (0.0%)
Alerts	199 (99.5%)	200 (100.0%)	200 (100.0%)
False pos	0 (0.0%)	0 (0.0%)	0 (0.0%)
False neg	0 (0.0%)	0 (0.0%)	0 (0.0%)

Table J.3: UWB ranging results for the pool test at a distance of 4 m from the anchor, with the wearable inside the trigger zone (3750–4250 mm) and tick_effect 34

	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	4134.0	4002.7	4025.4
Mean error:	134.0	2.7	25.4
MAE:	134.0	42.1	33.6
Var:	1205.8	2759.6	969.1
Std dev:	34.7	52.5	31.1
Min / Max:	4050.0 / 4232.0	3853.0 / 4120.0	3928.0 / 4143.0
Outliers:	63 (31.5%)	0 (0.0%)	0 (0.0%)
Alerts	200 (100.0%)	200 (100.0%)	200 (100.0%)
False pos	0 (0.0%)	0 (0.0%)	0 (0.0%)
False neg	0 (0.0%)	0 (0.0%)	0 (0.0%)

Table J.4: UWB ranging results for the pool test at a distance of 6 m from the anchor, with the wearable inside the trigger zone (5750–6250 mm) and tick_effect 34

	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	5912.2	6420.7	5968.3
Mean error:	-87.8	420.7	-31.7
MAE:	103.5	522.6	38.1
Var:	5456.5	413967.0	1074.7
Std dev:	73.9	643.4	32.8
Min / Max:	5740.0 / 6237.0	5778.0 / 9908.0	5881.0 / 6059.0
Outliers:	27 (13.5%)	123 (61.5%)	0 (0.0%)
Alerts	199 (99.5%)	98 (49.0%)	200 (100.0%)
False pos	0 (0.0%)	0 (0.0%)	0 (0.0%)
False neg	0 (0.0%)	0 (0.0%)	0 (0.0%)

Table J.5: UWB ranging results for the pool test at a distance of 8 m from the anchor, with the wearable inside the trigger zone (7750–8250 mm) and tick_effect 34

	Run 1	Run 2	Run 3
Successful:	-	199 (99.5%)	195 (97.5%)
Mean dist:	-	12136.6	9406.1
Mean error:	-	4136.6	1406.1
MAE:	-	4136.6	1406.4
Var:	-	766762.1	1963326.2
Std dev:	-	875.6	1401.2
Min / Max:	-	8811.0 / 15357.0	7980.0 / 13280.0
Outliers:	-	199 (99.5%)	182 (93.3%)
Alerts	-	0 (0.0%)	14 (7.2%)
False pos	-	0 (0.0%)	0 (0.0%)
False neg	-	0 (0.0%)	0 (0.0%)

Table J.6: UWB ranging results for the pool test at a distance of 4 m from the anchor, with the wearable inside the trigger zone (3750–4250 mm) and tick_effect 56

	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	17 (100.0%)
Mean dist:	4355.1	4285.8	4324.9
Mean error:	355.1	285.8	324.9
MAE:	363.0	285.8	324.9
Var:	625008.2	1944.5	2104.1
Std dev:	790.6	44.1	45.9
Min / Max:	3811.0 / 10405.0	4167.0 / 4387.0	4246.0 / 4401.0
Outliers:	103 (51.5%)	160 (80.0%)	15 (88.2%)
Alerts	103 (51.5%)	40 (20.0%)	2 (11.8%)
False pos	0 (0.0%)	0 (0.0%)	0 (0.0%)
False neg	0 (0.0%)	0 (0.0%)	0 (0.0%)

Table J.7: UWB ranging results for the pool test at a distance of 6 m from the anchor, with the wearable inside the trigger zone (5750–6250 mm) and tick_effect 56

	Run 1	Run 2	Run 3
Successful:	200 (100.0%)	200 (100.0%)	200 (100.0%)
Mean dist:	6140.4	6027.0	5975.4
Mean error:	140.4	27.0	-24.6
MAE:	140.4	37.0	31.1
Var:	1201.6	1307.9	979.3
Std dev:	34.7	36.2	31.3
Min / Max:	6035.0 / 6232.0	5923.0 / 6143.0	5895.0 / 6044.0
Outliers:	86 (43.0%)	0 (0.0%)	0 (0.0%)
False pos	0 (0.0%)	0 (0.0%)	0 (0.0%)
False neg	0 (0.0%)	0 (0.0%)	0 (0.0%)