Design of a wearable tactile feedback device to support navigation of visually impaired individuals

Design and feasibility study of a wireless vibro-tactile wristband to provide navigation instructions through haptic feedback to visually impaired people navigating unknown environments.

Author: **Pierre-Louis Soulié**

Matricola: **962505**

Supervisor: **Prof. Mario Covarrubias (Politecnico di Milano)**

Co-Supervisor: **Prof. Liwei Lin (University of California, Berkeley)**

Master of Science in Design and Engineering

School of Design

Politecnico di Milano

Contents

1 Abstract

EN Visual impairment is a common issue that affects millions of people worldwide and can have a significant impact on their daily lives. Navigation in unknown environments can be particularly challenging for individuals with visual impairments, leading to feelings of disorientation and vulnerability. To address this issue, the design of a tactile feedback wristband aimed at helping people with visual impairments navigate in unknown environments is presented in this paper. This device incorporates a 3x3 vibrotactile array to display vibration patterns and provides real-time navigation information to the user. The device was designed with a focus on enhancing the user's confidence and intuition, making it user-friendly and accessible for people with visual impairments. To evaluate the device, two experiments were run with participants. The first experiment aimed to characterize the vibration patterns, while the second tested the device in real-life conditions. The results of these experiments demonstrate the effectiveness of the device in providing reliable and accurate navigation information with an improvement of 20% between an intuitively designed vibration patterns set and a set that was designed using the results of the user experiment as design considerations.

IT La disabilità visiva è un problema comune che colpisce milioni di persone in tutto il mondo e può avere un impatto significativo sulla loro vita quotidiana. La navigazione in ambienti sconosciuti può essere particolarmente impegnativa per le persone con disabilità visiva, con conseguente sensazione di disorientamento e vulnerabilità. Per affrontare questo problema, in questo articolo viene presentata la progettazione di un braccialetto con feedback tattile per aiutare le persone con disabilità visive a navigare in ambienti sconosciuti. Questo dispositivo incorpora un array vibrotattile 3x3 per visualizzare modelli di vibrazione e fornire informazioni di navigazione in tempo reale all'utente. Il dispositivo è stato progettato con l'obiettivo di migliorare la fiducia e l'intuizione dell'utente, rendendolo facile da usare e accessibile per le persone con disabilità visive. Per valutare il dispositivo, sono stati condotti due esperimenti con i partecipanti. Il primo esperimento mirava a caratterizzare i modelli di vibrazione, mentre il secondo ha testato il dispositivo in condizioni reali. I risultati di questi esperimenti dimostrano l'efficacia del dispositivo nel fornire informazioni di navigazione affidabili e precise, con un miglioramento del 20% tra un set di modelli di vibrazione progettato intuitivamente e un set progettato utilizzando i risultati degli esperimenti come considerazioni di progettazione.

2 Nomenclature

VIP Visually Impaired Person

PWM Pulse Width Modulation

LRA Linear Resonant Actuator

MCU Microcontroller

LED Light-Emitting Diode

AC Alternative Current

DC Direct Current

PLA PolyLactic Acid

VR Virtual Reality

3 Introduction

Touch is one of the five crucial senses that humans rely on to evolve in their surroundings and interact with each other. Indeed, we are equipped with a vast and sophisticated somatosensory system that enables us to feel our physical environment in a variety of ways [1]. Our skin is consequently populated by a multitude of sensors that react to various types of stimuli such as temperature changes, electric currents or pain [2]. Mechanoreceptors respond to stimuli of mechanical nature such as pressure, stretch or vibration. Haptics, the science of conveying tactile sensations [3], leverages these particular sensors and has recently become a critical topic of research for industries like robotics and consumer electronics.

This research focuses on the design and feasibility study of a wireless vibrotactile wristband as a navigation aid for visually impaired people navigating unfamiliar environments. This report details the research process, results, and potential avenues for further investigation.

The study comprises three distinct parts. First, a literature review was conducted to evaluate the state-of-the-art of haptic technologies, initially in general domains such as virtual reality, surgery, and rehabilitation, before focusing on assistive technologies for visually impaired people and navigation aids. Then, a feasibility study was carried out through user experiments to assess the effectiveness of different vibration patterns in conveying information, as well as defining considerations for the device's user experience design. Finally, the device was tested and validated in a real-life setting to verify the results of the previously defined considerations.

The objective of this study is to contribute to the development of wearable haptic feedback devices and demonstrate the potential of tactile cues to provide in real-time instructions to the user. Before programming the human somatosensory system eventually becomes feasible, vibrohaptic feedback will remain the dominant method for implementing tactile sensations [4]. The findings of this research may have implications for the design and implementation of future wearable vibrotactile feedback devices as navigational aids, as well as other potential applications in fields such as sports, surgery, rehabilitation, and gaming.

4 Motivation

4.1 Previous Works

The Lin Laboratory has conducted previous research on two projects, namely the development of a standalone vibrotactile array for immersion in VR (See Figure 1) and the creation of a soft electromechanical stimulation patch (See Figure 2).

The standalone vibrotactile array was designed and prototyped to investigate the ability of individuals to sense various vibration patterns using their hand. The feasibility study aimed to enhance the user's immersion in VR/AR environments by providing a larger surface of haptic interaction. On the other hand, the soft electromechanical stimulation patch developed by the Lin Laboratory utilizes low-voltage power and has the potential to provide future users with a high-resolution wearable vibrotactile array. This can be implemented in artificial skins, among other things, to provide a new dimension of immersion in VR or seamless assistive technologies. To bridge the gap between these two previous projects, the motivation behind developing a wearable vibrotactile array that can be placed on the forearm to provide haptic feedback instructions was initiated.

While the standalone vibrotactile array aimed to recreate haptic sensations on the hand of the user during VR experiences, it may not be practical in situations where users need to move their hands freely. Meanwhile, the soft vibrotactile patch is still a cutting-edge technology that requires complex hardware to work efficiently, making wearing it on the skin a challenge. It may also not provide accurate and precise haptic feedback instructions.

Therefore, developing a wearable vibrotactile array that can be worn on the forearm would provide the user with accurate and precise haptic feedback instructions while also allowing them to move their hands freely. This can have a variety of applications in fields such as sports, rehabilitation, and gaming where users may require haptic feedback instructions to improve their performance or experience.

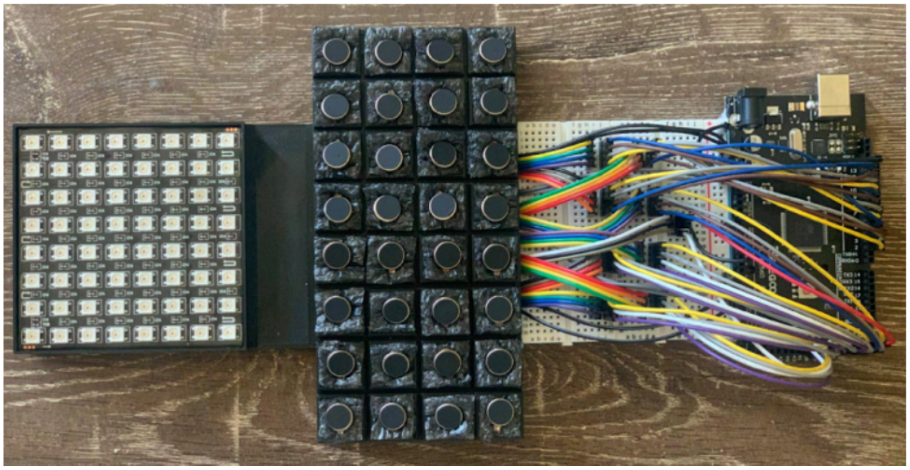

Figure 1: Previous prototype of standalone vibrotactile array for hand immersion in VR.

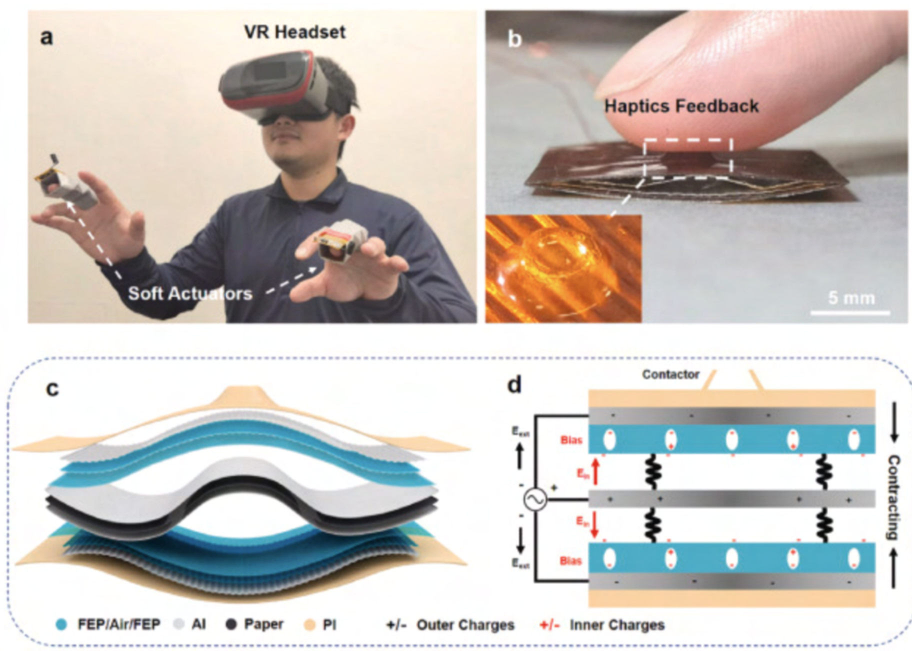

Figure 2: New low-voltage powered solft electromechanical stimulation patch.

4.2 Purpose and Significance of the Study

4.2.1 Overview of Visual Impairment

Visual impairment, which includes a range of conditions from partial vision loss to complete blindness, is a global health issue affecting millions of people worldwide. According to the World Health Organization (WHO), it is estimated that there are over 285 million people in the world with visual impairments of whom 39 million are blind, with uncertainties of 10–20%. People 50 years and older represent 65% and 82% of visually impaired and blind, respectively. [5] In many low-income countries, visual impairments are often caused by avoidable factors such as lack of access to eye care and eye health services, while in high-income countries, age-related conditions such as macular degeneration and cataracts are the leading causes.

Visual impairments can have a significant impact on individuals' daily lives, affecting their ability to work, participate in social activities, and carry out basic activities of daily living. It can also lead to feelings of disorientation and vulnerability, especially when navigating unknown environments. The prevalence of visual impairments is expected to increase in the coming years due to aging populations, making it even more important to address this issue and improve access to eye health services and assistive technologies.

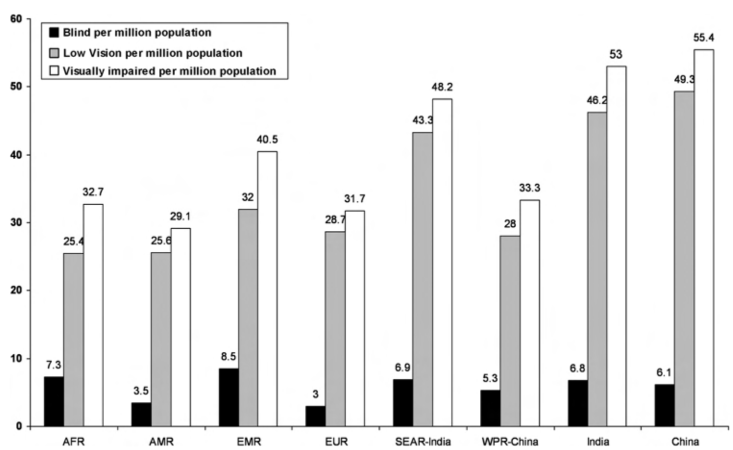

Figure 3: Relationship between the age of people who are blind, degree of visual impairments, and thenumber of visually impaired [6]

4.2.2 Challenges of Visually Impaired People

Visually impaired individuals face a range of challenges in their daily lives. Some of the major challenges include:

- **Mobility and navigation:** Navigating unfamiliar environments can be difficult for VIP, leading to feelings of disorientation and vulnerability. This can make it challenging for them to move around independently and access new places.

- **Accessibility:** VIP often face accessibility barriers in the built environment, making it difficult for them to move around and participate in social and work activities.

- **Technology:** Many VIP have limited access to assistive technologies, such as screen readers and magnifying software, that could help them better access information and carry out daily tasks.

- **Education:** VIP may face challenges in accessing educational materials and participating in classroom activities.

- **Employment:** VIP may face barriers to employment, including a lack of accessible technology in the workplace and negative attitudes from employers.

- **Social isolation:** VIP may experience social isolation and limited opportunities to participate in social activities, leading to feelings of loneliness and reduced quality of life.

- **Cost of assistive devices:** Many assistive devices for VIP can be expensive, making it difficult for some individuals to access them.

These challenges can greatly impact the quality of life and independence of VIP, making it important to address these issues and improve access to assistive technologies and services.

In this research work, the emphasis is put on addressing the mobility and navigation, technology access and cost of assistive device challenges. The aim of this work is to allow a VIP to navigate unfamiliar environments and have access to technologies like navigation aids. Also, the cost of the final device will be detailed, to understand if it is economically viable.

5 Literature Review

5.1 Related Research Works

5.1.1 In General Domains

Outside the scope of assistive technologies, vibrohaptic feedback has been a central topic of research in fields such as medicine, education and human interactions like Virtual and Augmented Reality. For example, to regulate the breath of people being treated for cancer via radiation therapy, Israr et al. developed a vibrotactile array to assist convalescents in managing their respiration during a treatment [7]. Their device provides an inexpensive and portable solution that leads to more efficient radiation therapies with the help of simple haptic cues. In the field of surgery, in an attempt to mimic affective touch, Huisman et al. experienced with an array providing vibrations on the lower arm of subjects [8]. They were able to simulate gentle stroking sensations that were perceived as similar to human caress. In the field of surgery this time, Gerald et al. designed a haptic feedback glove to assist surgeons performing colonoscopy during minimally invasive surgery thanks to pressure actuators [9].

To address the challenge of enhancing user immersion in VR games many groups developed devices with haptic feedback. For instance, Chen et al. built custom controllers with embedded tactile pin arrays [10]. They were able to show in a user study that their solution allowed participants to identify cardinal and ordinal directions with an accuracy of at least 79%. Other groups attempted to provide users with a better perception of their surrounding like Tadesse et al. who developed a wearable haptic device for stiffness discrimination of objects during virtual interactions [11], or Martinez et al. that came up with a new way of identifying virtual 3D geometric shapes thanks to a various vibrotactile actuators sewed on a glove [12].

The diversity of these research works shows how vibrohaptic feedback can be leveraged to propose solutions to various real-world problems.

5.1.2 In Assistive Technologies

In the field of assistive technologies, Wu et al. designed a vibrotactile array embedded in a vest to explore contour perception. Their method proved to be efficient in conveying the information of simple shapes such as circles and squares with vibrations to visually impaired people [13]. For instance, Kyung et al. have developed a compact vibrotactile module to implement it in a pen-like device. They were able to demonstrate their prototype's ability to convey Braille patterns to visually impaired people to help them better understand and interact with GUI interface [14]. Still in an attempt to make software interfaces accessible to blind people, Jayant et al. developed V-Braille, a novel way to haptically represent Braille characters on a standard mobile phone using the touch-screen and vibration. Their preliminary study with deaf-blind Braille users found that, with minimal training, V-Braille could be used to read individual characters and sentences [15].

In the field of navigation, Ma et al. embedded vibroactuators on a wristband to explore new ways of helping drivers of automated vehicles stay aware of their surroundings while not looking at the road [16]. They could successfully convert graphical markers into the vibration patterns to reduce the driver's memory burden and improve the accuracy of recognizing the patterns. On another note, both Salazar et al. and Kammoun et al. developed wristbands to help pedestrians finding their way thanks to tactile navigation instructions. They successfully achieved wayfinding performances comparable to classic methods using audio cues [17] [18].

The promising results of these various research works confirmed the potential of application of haptic feedback in a device to assist visually impaired individuals navigate unknown environments.

6 Methods

6.1 Design of the Wearable Device

The subject of this work is a wearable vibration-based haptic array that can be used to create localized feedback. It is separated in three distinct parts: the vibrotactile array wristband that is being placed on the subject's forearm, the control interface and the visual feedback interface (See Figure 4). Off-the-shelf electromechanical components were used to build it. It was theorized that users would be able to differentiate with their forearm the localization and directionality of virtual stimuli through the use of this array.

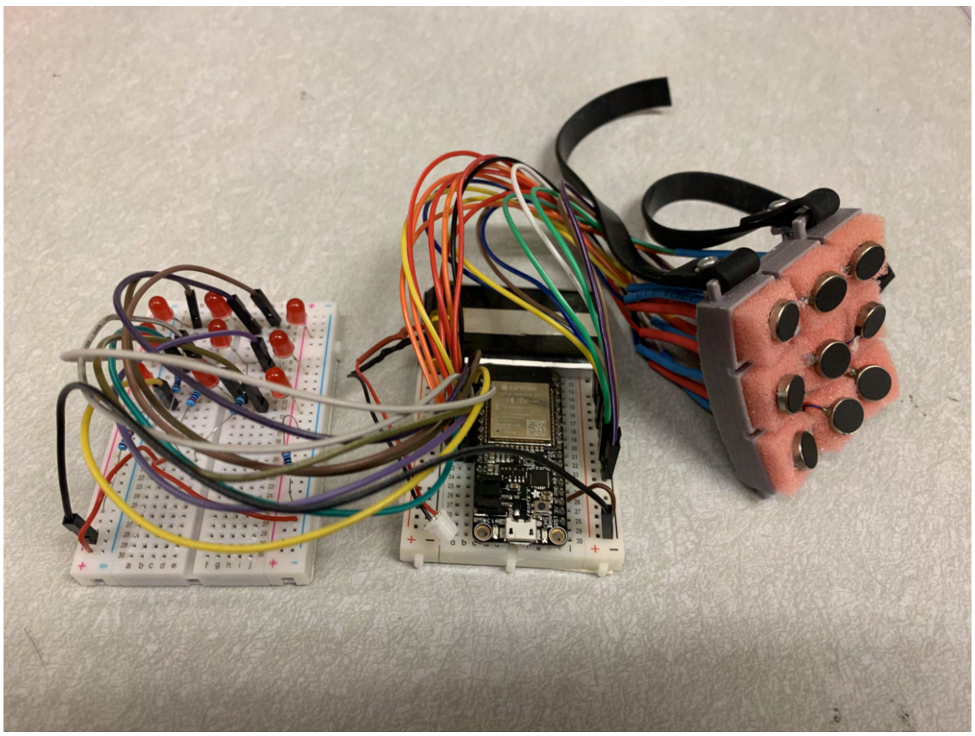

Figure 4: From left to right: Visual Feedback Interface, Micro-controller, Vibrotactile Array.

6.1.1 Vibro-tactile Array

The initial prototype was first produced in the form of a 3x3 array of vibration motors embedded on a random piece of flexible foam (see Figure 5). The foam was added on the design to solve a problem of vibration isolation. Indeed, a more rigid material would not allow for user recognizability between actuated cells.

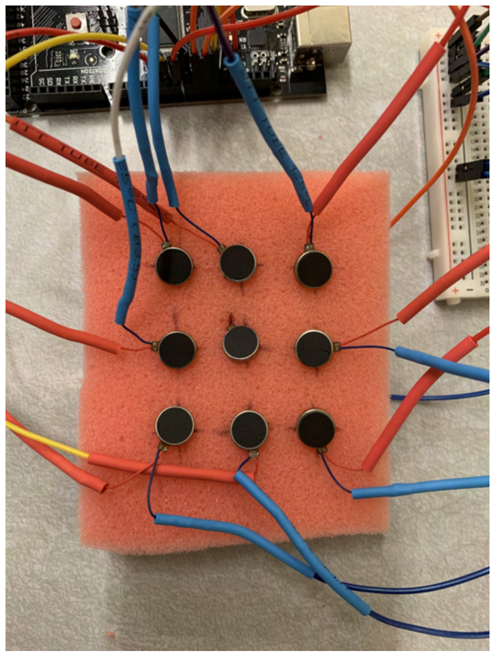

Figure 5: First exploratory iteration of the 3x3 vibrotactile array.

The actuators are Linear Resonant Actuators (LRA). These actuators are typically powered by an AC voltage. LRAs are electromechanical devices that produce a vibratory force by oscillating a mass back and forth (See Figure 6). They work on the principle of resonant frequency, where the mass of the actuator is set into resonance by an AC signal with a frequency equal to the natural frequency of the actuator. This resonance produces a high amplitude vibration at the desired frequency. The LRA motors used for this experiment are flat and cylindrical (See Figure 7). They have a diameter of 10 mm, are 3 mm thick and their rated speed is 12000 RPM.

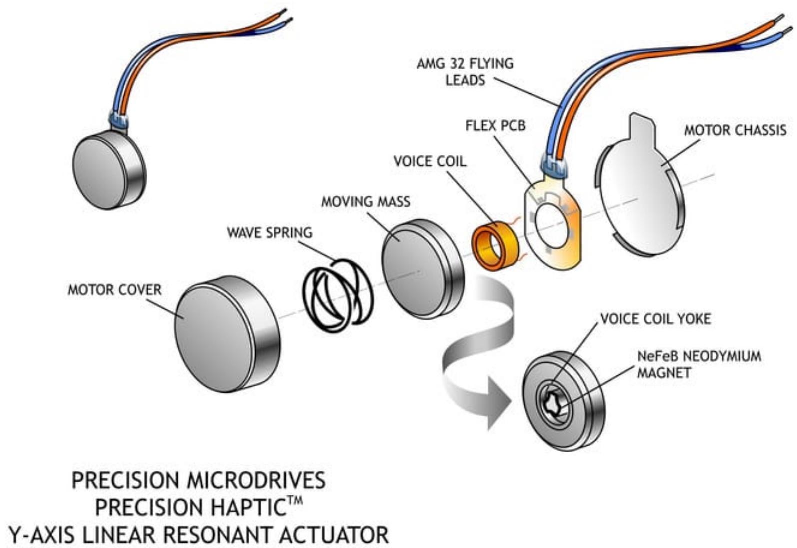

Figure 6: Exploded view of the Linear Resonant Actuator used in the device.

Figure 7: Macroscopic picture of the LRA.

6.1.2 Wristband

The idea to make a device that would be worn on the forearm came from a previous study investigating the most suitable body parts for wearable vibration feedback in walking navigation. Indeed, Dim et al. demonstrated that the wrist, among other body parts like the hands, the waist or the neck, was the most suitable part to receive vibrotactile instructions during motion [19].

The decision to make a wristband was both a choice of practicity, being easy to attach and remove, and convenience, the device being less intrusive than on the other body parts mentioned above. To turn the vibrotactile array prototyped previously into a wearable wristband, a support was modeled and 3D-printed using PLA to host the pieces of foam while the LRAs were glued to hold in place (See Figure 8). Two rubber straps were attached to dedicated buckles using bolts to create the wristband. Each extremity of the LRAs was welded to a set of jumper wires to be connected to the breadboard hosting the microcontroller's board (See Figure 9).

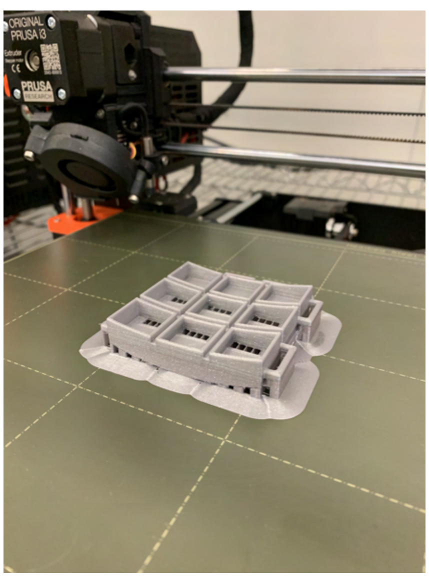

Figure 8: 3D Printing of the vibrotactile array holder.

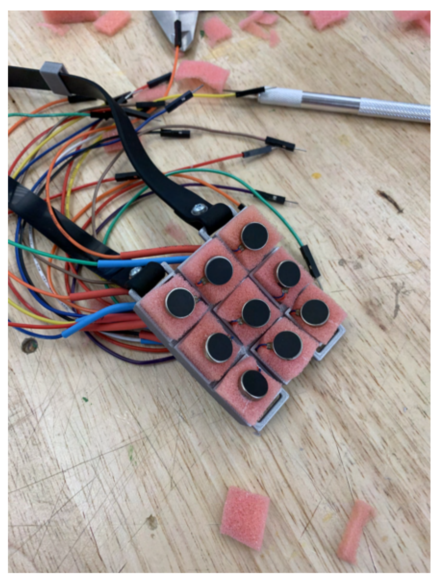

Figure 9: Prototype of the vibrotactile wristband.

This schematic depicts the position of the vibrotactile array on the user's forearm (See Figure 10). The positioning of the array on the forearm is shown to be on the underside of the arm, just above the wrist. This position was chosen to maximize the accuracy of haptic feedback instructions and to ensure that the array remains in place even during movement.

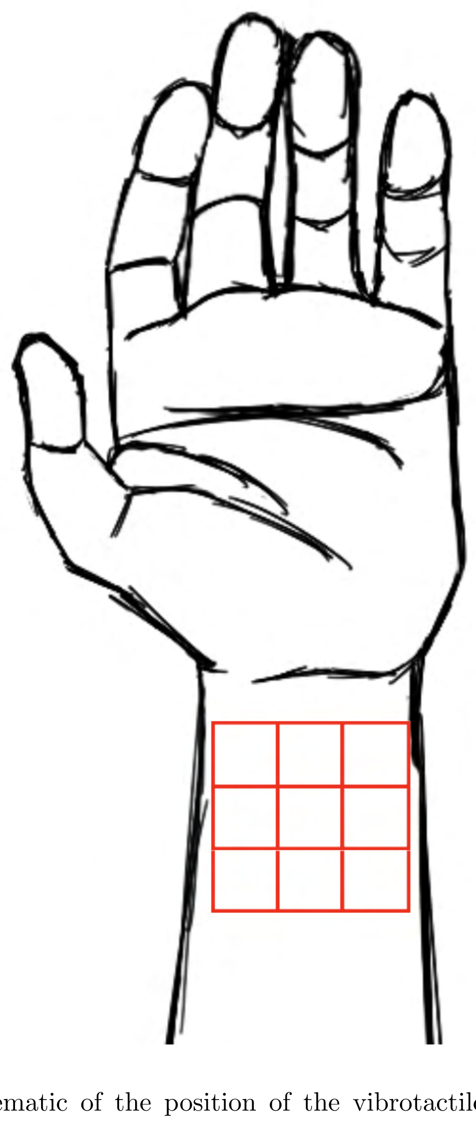

Figure 10: Schematic of the position of the vibrotactile array on the user's forearm.

6.2 Design of the Control System

6.2.1 Microcontroller

The ESP32 is a highly integrated chip that includes Wi-Fi and Bluetooth connectivity, as well as a range of peripherals, such as GPIOs, analog-to-digital converters (ADCs), and pulse-width modulation (PWM) modules (See Figure 12). The chip also includes a dual-core 32-bit microprocessor, which allows for high-performance computing capabilities. The ESP32 is designed to be low-power, with power consumption optimized for battery-powered IoT applications. The chip also supports a range of power-saving modes, including sleep and deep sleep modes, which allow the device to conserve power when not in use. All these reasons make it a microprocessor of choice to make the prototype. The device will need to receive punctual data-stream from the server to actuate the LRAs when a new navigation instruction is needed using the Bluetooth connectivity included in the micro-controller. On another note, in order to actuate the LRAs an AC signal will be simulated thanks to the pulse-width modulation (PWM) modules.

The development board that will be used is the HUZZAH32 developed by Adafruit (See Figure 11). The main advantage of this board is the integration of a JST port to power the board using a 3.7/4.2V Lithium-Polymer (LiPo) battery. This feature assures the wearability of the device.

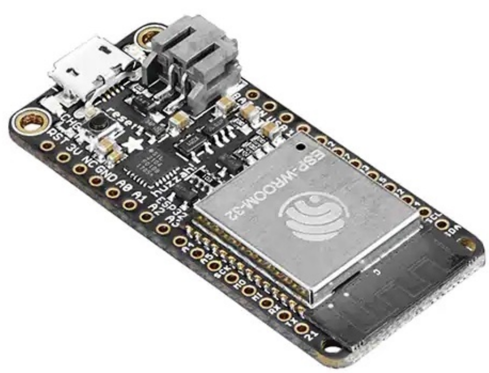

Figure 11: Picture of the Adafruit HUZZAH32 - ESP32 Feather board.

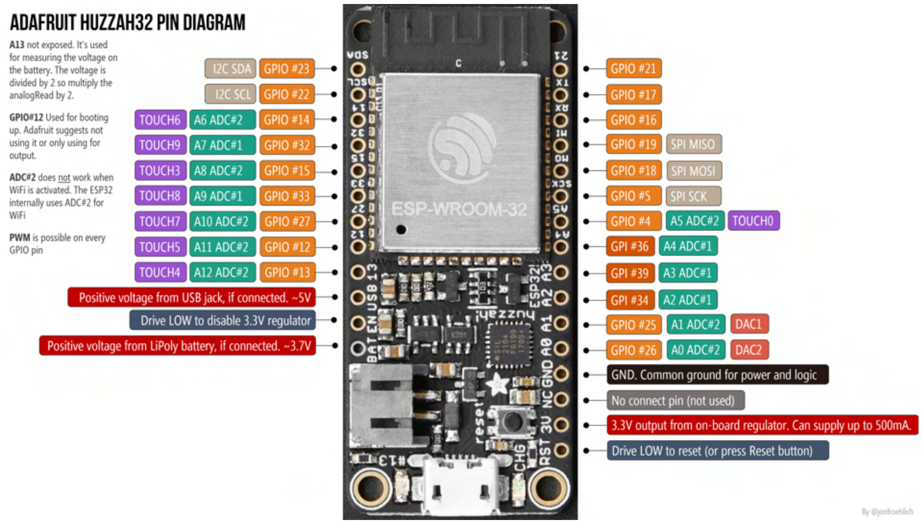

Figure 12: Pinouts Schematics of the Adafruit HUZZAH32 - ESP32 Feather board.

6.2.2 Pulse Width Modulation (PWM)

Pulse Width Modulation (PWM) is a technique used in electronics and control systems to control the power delivered to a load, such as a motor or LED. PWM works by varying the width of a pulse of electrical current that is applied to the load. The duty cycle of the pulse, which is the ratio of the pulse width to the time of the pulse, determines the amount of power delivered to the load. [20]

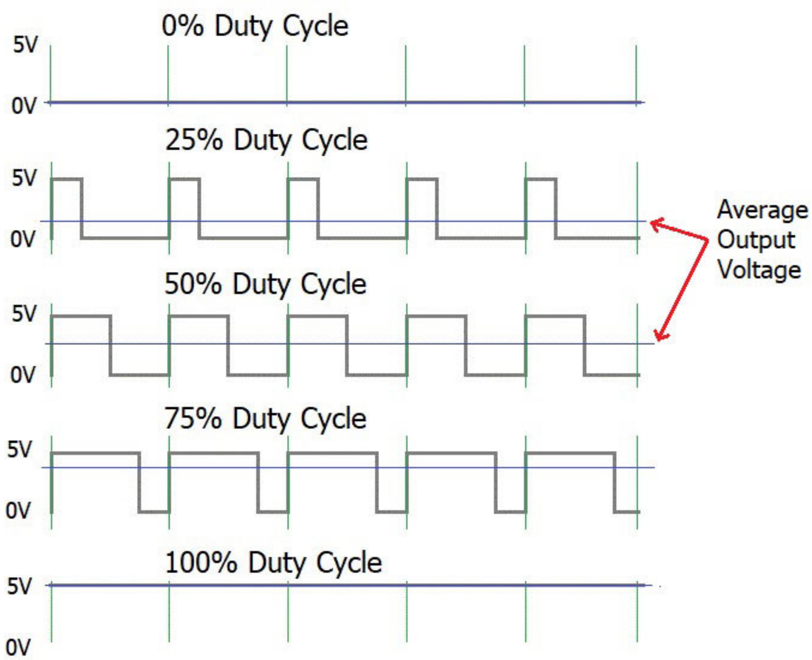

Figure 13: PWM principle: Average Output Voltage based on Duty Cycle

PWM can be used to simulate an AC voltage by rapidly switching the polarity of a DC voltage to create a waveform that approximates an AC voltage. By rapidly switching the polarity of the DC voltage, a waveform that approximates an AC voltage can be created. This technique, called pulse-width modulation inverter or PWM inverter, is commonly used in applications such as motor control. By using this PWM technique, the ESP32 is able to deliver an AC voltage ranging from 0.0V to 3.3V and hence control the amplitude of vibration of the LRA.

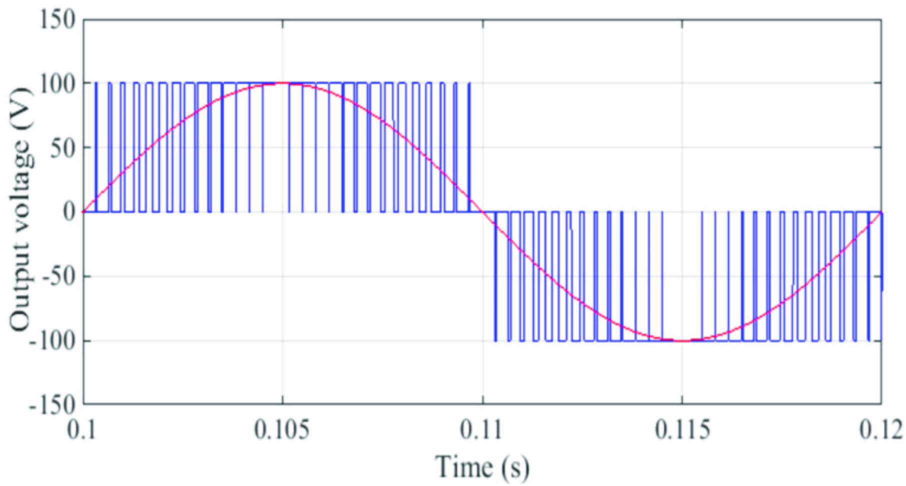

Figure 14: PWM inverter: Waveform creation.

6.2.3 Bluetooth Low Energy

Bluetooth Low Energy (BLE) is a wireless communication technology designed for low-power consumption, which allows devices to communicate with each other over short distances using radio waves. BLE is a variant of the standard Bluetooth technology (Refer to Table 1), optimized for low power consumption, making it ideal for applications such as Internet of Things (IoT) devices, wearables, and other battery-powered devices. BLE uses the 2.4 GHz frequency band and operates using the master-slave communication model. The devices that initiate communication are called masters, while the devices that respond to the communication are called slaves.

One of the key benefits of BLE is its low power consumption. BLE devices typically consume a fraction of the power of traditional Bluetooth devices, allowing them to run on small batteries for extended periods of time, with a range of over a 100 meters. This communication protocole is perfect for the development of the wearable haptic feedback in the sense that it does not require a constant data-stream to provide direction instructions. This protocole will for example allow us to connect the device to a computer or smartphone to send the navigation instructions.

Specifications	*Classic Bluetooth*	*Bluetooth Low Energy*
Range	100 m	Greater than 100 m
Data rate	1-3 Mbps	125 kbps - 2 Mbps
Application throughput	0.7 - 2.1 Mbps	0.27 Mbps
Frequency	2.4 GHz	2.4 GHz
Latency	100 ms	6 ms
Time lag	100 ms	3 ms
Power consumption	1 W	0.01 - 0.50 W
Peak current consumption	less than 30 mA	less than 15 mA

Table 1: Comparison between Classic Bluetooth and Bluetooth Low Energy.

6.2.4 Control Interface

The Arduino IDE is used to write a *C++* code that will be uploaded on the micro-controller. The IDE will allow us to select a USB port and use the built-in USB Serial Monitor to send commands to the device. Multiple functions have been coded to respond to each command, to insure that all vibration patterns are actionable on the vibrotactile array in order to test its capabilities (Refer to Table 2).

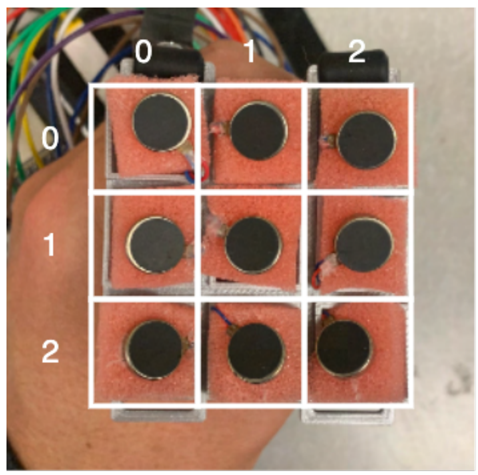

Figure 15: Description of the coordinate system used by the control interface.

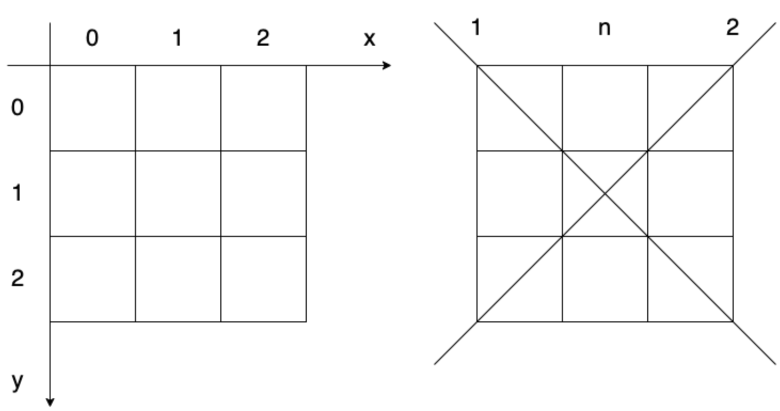

Figure 16: Description of the coordinate system used by the control interface.

The following table details the vibration patterns and their related command and arguments to be entered in the Serial Monitor. For row and columns, only one coordinate is required. Regarding the diagonals, their n number is described in the figure above (See Figure 16)

Vibration pattern	Command	Arguments
Single cell	z	(x1, y1, time)
Double cells	d	(x1, y1, x2, y2, time)
Triple cells	t	(x1, y1, x2, y2, x3, y3, time)
Quadruple cells	q	(x1, y1, x2, y2, x3, y3, x4, y4, time)
Straight path	p	(x_start, y_start, x_end, y_end, time)
Full column	h	(x, time)
Full row	v	(y, time)
Full diagonal	x	(n, time)
Single cell - adjust. voltage	i	(x1, y1, voltage, time)

Table 2: List of commands designed for the characterization.

Here is for a instance a list of potential commands that can be entered in the Serial Monitor:

d002210

This will activate the cells of coordinates (0,0) and (2,2) during 1.0s.

p002020

This will activate cells one after the other following a straight path between the cells of coordinates (0,0) and (2,0) during 2.0s (0.66s each).

x110

This will activate all the cells of the first diagonal at the same time during 1.0s.

i113020

This will activate the cell of coordinates (1,1) with a voltage intensity of 3.0V during 2.0s.

6.2.5 Visual Feedback Interface

To ensure that the right command was entered in the Serial Monitor and verify the correctness of the wiring, a visual feedback interface was designed using a breadboard and LEDs (See Figure 17). It appears very effective in this scenario because LEDs can be powered with the same PWM technique as LRAs, hence each LED was connected to the same GPIO of its corresponding LRA. 270 Ohm resistors were connected in the most effective way to drive current from the micro-controller to the ground.

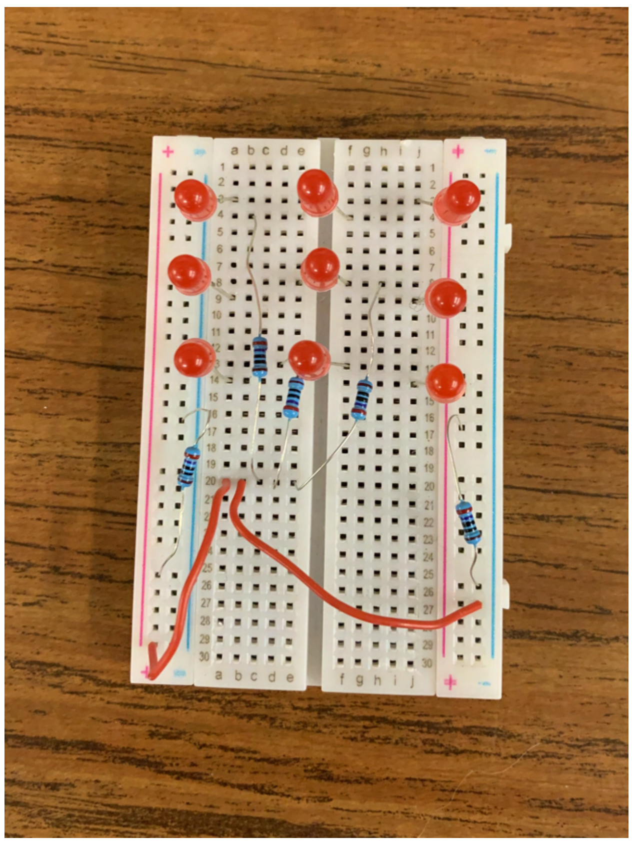

Figure 17: Picture of the visual feedback interface.

6.3 Cost Estimation of the Device

The estimated cost of the device comprising a breadboard, 9 red LEDs, 6 resistors, a 3D printed support measuring 5cm x 5cm x 2 cm, 9 Round Linear resonant actuators, an ESP32 on a HUZZAH32 board, jump wires, rubber straps, and a 3700 mAh LiPo Battery is around $60 based on current market prices.

The cost breakdown for each component is as follows:

- 1x breadboard: $3
- 9x red LEDs: $0.10 per LED, total of $0.90
- 6x resistors: $0.05 per resistor, total of $0.30
- 1x 3D Printed support (5cm x 5cm x 2 cm): $5
- 9x Round Linear resonant actuators: $1.50 per actuator, total of $13.50
- 1x ESP32 on a HUZZAH32 board: $20
- 2x Jump wires: $5
- 1x Rubber straps: $3
- 1x 3700 mAh LiPo Battery: $10

It is important to note that prices may vary depending on the supplier, location, and quantity of the components purchased. However, this estimation provides a rough idea of the potential cost of building a device with the listed components.

7 Characterization

7.1 User Experiment

To investigate the capabilities of the vibrotactile array and characterize it, a user experiment was designed. The corresponding interview scenario is presented in Appendix A, while the outcomes were documented using an interview sheet displayed in Appendix B.

The study recruited ten healthy participants, comprising six males and four females aged between 21 and 35 years old. Eight of the participants were right-handed, while two were left-handed, and none of them had any prior experience with the prototype. In their research on the analysis of various vibrations patterns to guide blind people, Durá-Gil et al. demonstrated that sighted people are suitable for testing the patterns [21]. Hence, for a matter of convenience no blind person was involved in the characterization of the device.

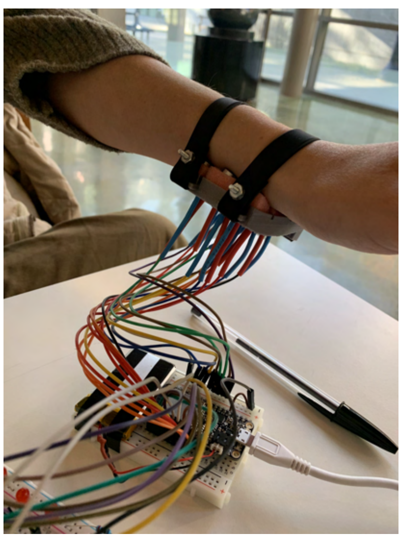

Figure 18: The vibrotactile array worn on the wrist.

Figure 19: Participant taking the assessment.

7.1.1 Open-Ended Questions

At the beginning of the experiment, the participants were briefed on our research topic. We provided an overview of the study, defined vibrohaptic feedback, and explained the procedures that would be followed. Each interview lasted approximately 45 minutes, during which time the participants were encouraged to ask questions and share their observations regarding their haptic sensations.

Prior to commencing the vibrotactile experiments, the participants were requested to share their previous experiences with haptic feedback and how it had influenced their level of immersion when playing video games or using electronic devices. Subsequently, they were introduced to the prototype and underwent a calibration process to ensure that they all began at a similar initial baseline before proceeding with the tests.

The participants were instructed to assume a particular arm position that would enhance their comfort during the test. Specifically, the interior of their forearm was required to align with the top of the array (refer to Figure 18).

During the tests, the participants were instructed to wear headphones that played white noise, while the LED array was concealed from view using an object, preventing them from seeing their hand on the device. This was done to ensure that the participants relied solely on their sense of touch when attempting to identify the vibrating patterns that were presented to them (refer to Figure 19).

7.1.2 Single Cell Localization

The objective of the initial test was to assess whether or not the participants could correctly position individual vibrating LRA on a corresponding grid (refer to Appendix A). Six cells of the grid were activated in sequence over a period of one second, and the participants were requested to identify the location of each vibrating cell after each activation. In order to ensure that the vibrating cells were evenly distributed, each row had two and each column had two activated cells (see Figure 20).

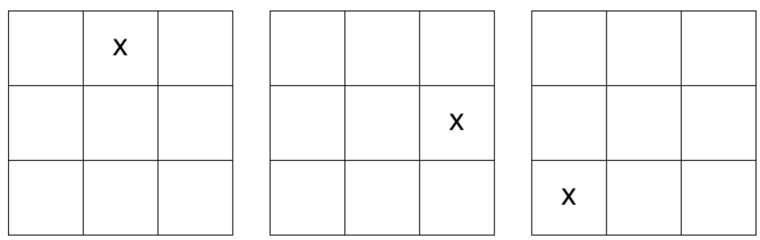

Figure 20: Example of inputs tested during the single cell localization assessment.

There was a total of 60 outputs assessed between the 10 subjects. As shown on the Figure 21, the results showed that 60% of the answers were correct, indicating that the participants were able to correctly identify the vibrating cell. This is a rather satisfying result when comparing it to the probability of chance, which is 16.7% (1/6). In another 35% of cases the error was the smallest possible, when the subjects indicated an adjacent cell to the one that was actually activated. This means that in 95% of cases, the participants were able to either guess correctly or right next to the vibrating motor. The most common mistake made was a row confusion, where participants had difficulty distinguishing between cells that were located in the same row.

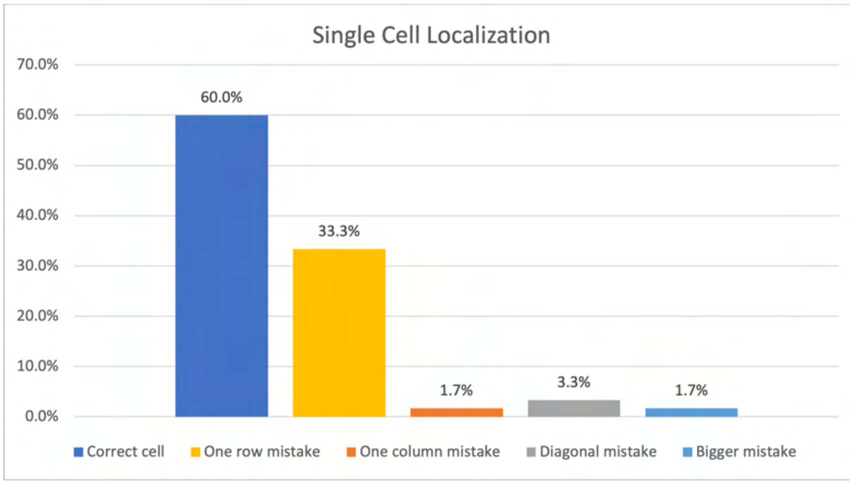

Figure 21: Results of the 120 single cell localization tests, averaged from the 10 participants.

7.1.3 Straight Paths Localization

In order to conduct a more thorough investigation into the participants' ability to recognize patterns of vibrating cells on the grid, they were instructed to identify straight lines of consecutively activated cells. These lines were triggered in various directions, including vertically, horizontally, and diagonally. Each time, three cells were activated in succession to create a directional line (See Figure 22). The direction could be cardinal or ordinal.

In the initial 6 sets of sequences, each lasting 1.0 seconds, the cells were activated successively for 0.33 seconds each. In order to examine how the participants would react to faster speeds, the total activation times for the 12 remaining sequences were progressively changed in increments ranging from 0.5 seconds to 2.0 seconds.

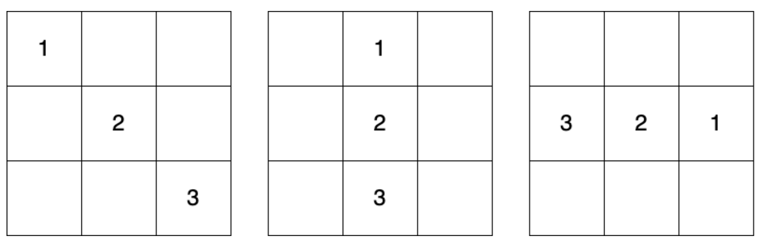

Figure 22: Example of inputs tested during the straight path in cardinal and ordinal directions localization assessment.

There was a total of 60 outputs assessed between the 10 subjects. As shown on the Figure 23, the results showed that 46.7% of the answers were correct, indicating that the participants were able to correctly identify the vibrating lane. In another 45% of cases the error was the smallest possible, when the subjects indicated a direction located in a row or diagonal adjacent to the one that was activated. In 91.7% of cases, the participants were able to guess correctly the sense of the actuation (i.e. Right to Left or Left to Right). The most common mistake made was a diagonal mistake, where participants had difficulty distinguishing between two directions with a 45° orientation difference, representing 36.7% of the errors.

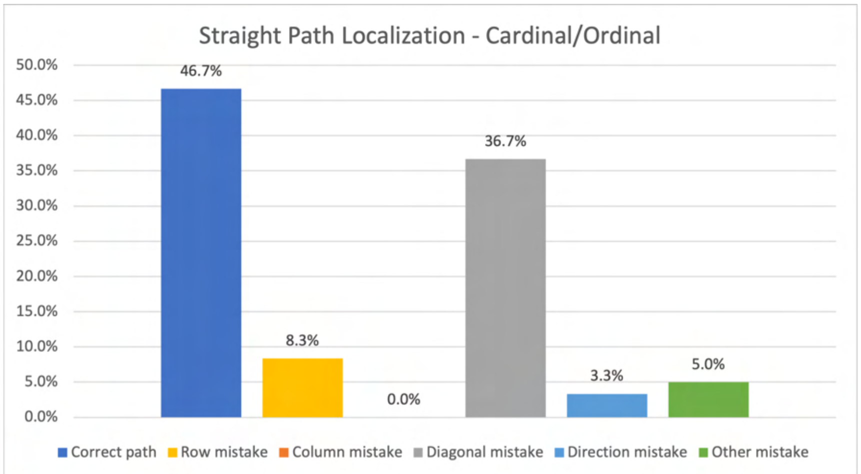

Figure 23: Results of the 60 cardinal/ordinal straight paths localization tests, averaged from the 10 participants.

In the following 12 sets of sequences, and in order to examine how the participants would react to faster speeds, the total activation times were progressively changed in increments ranging from 0.5 seconds to 2.0 seconds. The actuated path could be located anywhere on the array this time (See Figure 25).

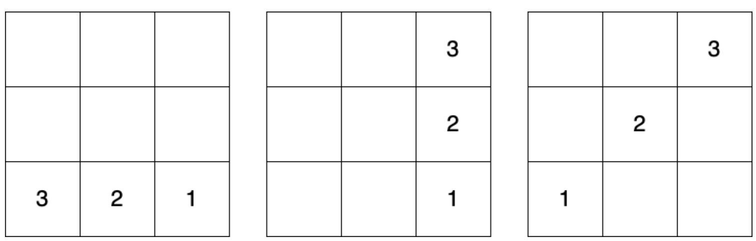

Figure 24: Example of inputs tested during the straight path localization assessment.

There was a total of 120 outputs assessed between the 10 subjects. As shown on the Figure 25, the results showed that 50.8% of the answers were correct, indicating that the participants were able to correctly identify the vibrating lane. In another 45% of cases the error was the smallest possible, when the subjects indicated a direction located in a row or diagonal adjacent to the one that was activated. This means that in 90.8% of cases, the participants were able to guess correctly the sense of the actuation (i.e. Right to Left or Left to Right). The most common mistake made was again a diagonal mistake, representing 25.8% of the errors.

On another note, as seen on the Figure 26, the amount of correct answers raises from 43.3% to 53.3% when the time of actuation raises from 0.5s to 1.0s, before stabilizing around 50% for higher durations.

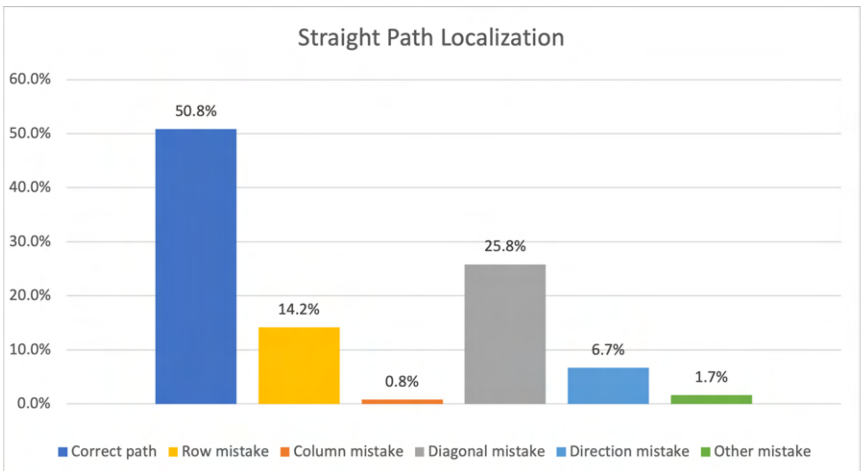

Figure 25: Results of the 120 straight paths localization tests with varying time of actuation, averaged from the 10 participants.

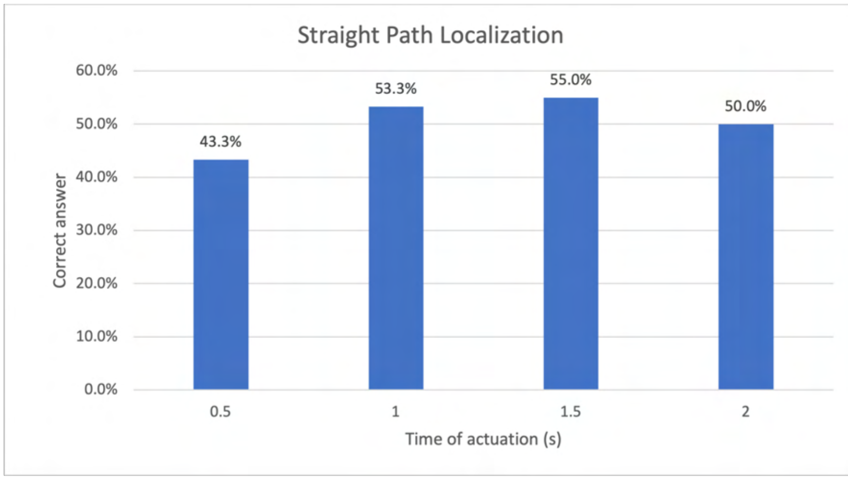

Figure 26: Comparison of the amount of correct answers depending on the actuation time.

7.1.4 Straight Lane Localization

Previously, the motors had been programmed to vibrate one after the other, with no simultaneous activation. In order to assess the participants ability to distinguish between adjacent cells that were triggered simultaneously, they were required to identify between 12 different sequences of 3 motors that were activated at the same time in a row, column or diagonal. As during the second part of the straight path experiment, in this test the total actuation time is varying between 0.5 and 2.0 seconds (see Figure 27).

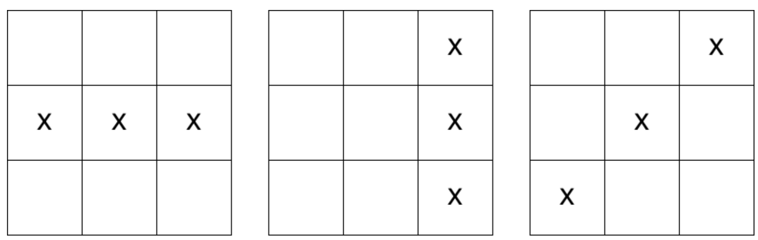

Figure 27: Example of inputs tested during the straight lane localization assessment.

There was a total of 120 outputs assessed between the 10 subjects. As seen on the Figure 28, the results showed that 42.5% of the answers were correct, indicating that the participants were able to correctly identify the vibrating lane. This is a rather satisfying result when comparing it to the probability of chance, which is 12.5% (1/8). In another 40% of cases the error was the smallest possible, when the subjects indicated an adjacent vibrating row, column or diagonal to the one that was actually activated. This means that in 82.5% of cases, the participants were able to either guess correctly or right next to the vibrating lane. The most common mistake made was a diagonal mistake, where participants had difficulty distinguishing between two lanes with a 45° orientation difference, representing 29.2% of the errors.

On another note, as seen on the Figure 29, the amount of correct answers seems to be stable (around 45%) no matter the duration of actuation. However, there is a drop to 30% of correct answers for 1.5s, but it will be considered as an isolated measurement gap since no explanation could be found.

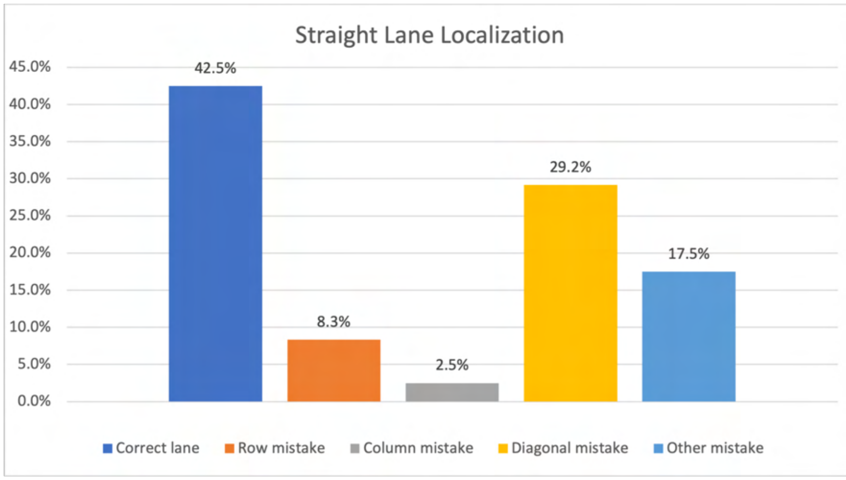

Figure 28: Results of the 120 straight lane localization tests with varying time of actuation, averaged from the 10 participants.

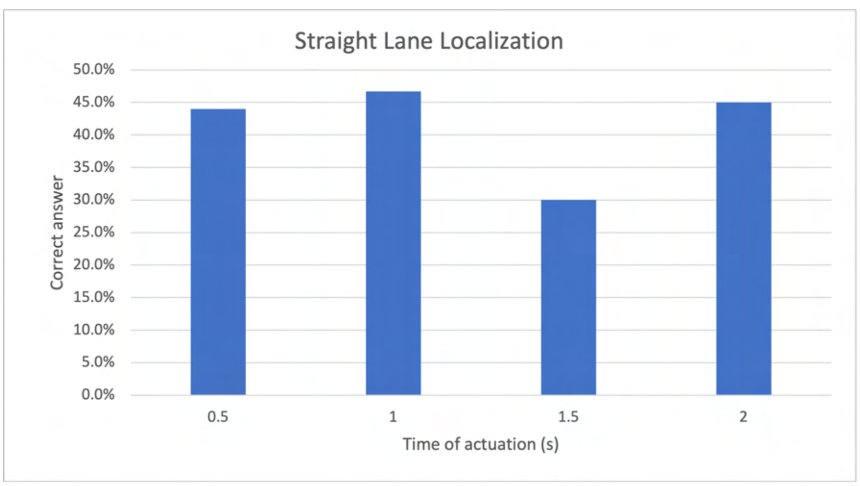

Figure 29: Comparison of the amount of correct answers depending on the actuation time.

7.1.5 Neighbor Cells Localization

Same as the previous experiment, the participants were asked to distinguish simultaneously vibrating adjacent but in a random shape this time. They were required to identify between 2 and 4 neighbor cells activated at the same time.

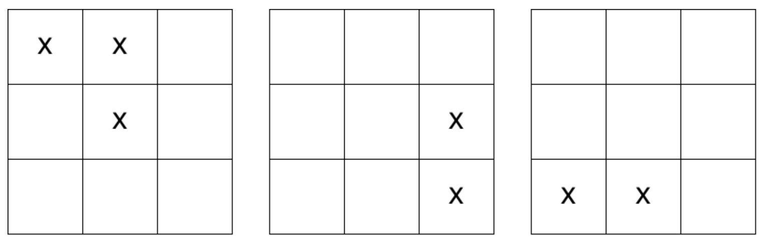

Figure 30: Example of inputs tested during the neighbor cells localization assessment.

There was a total of 120 outputs assessed between the 10 subjects. As shown on the Figure 31, the results showed that 21.7% of the answers were correct, indicating that the participants were able to correctly identify the vibrating lane. This is a much less satisfying result when compared with the previous experiments. In another 38.3% of cases the error was the smallest possible, which was the most common mistake, when the subjects selected one wrong vibrating cell, added one or forgot one. This means that in 60% of cases, the participants were almost able to guess the pattern correctly. The most common mistake made was when the subjects selected two wrong vibrating cells.

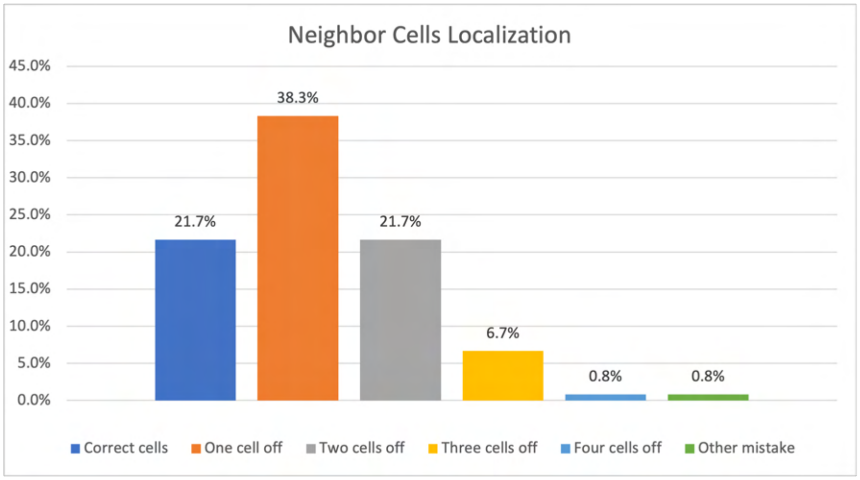

Figure 31: Results of the 120 neighbor cells localization tests with varying time of actuation, averaged from the 10 participants.

7.1.6 Sensitivity Assessment

In this experiment, the sensitivity of the participants was assessed for a single vibrating cell through single cell positioning incremented in intensity and duration. Six different cells were activated for each test, and the following intensity iterations were used: 1.0, 1.3, 1.7, 2.0, 2.3, 2.7, 3.0, and 3.3 volts. The time iterations used were 0.1, 0.2, 0.3, 0.4, and 0.5 seconds. In order to ensure that the vibrating cells were evenly distributed, each row had two and each column had two activated cells (see Figure 32).

After analyzing the results, the average intensity was found to be 1.61 volts, while the average time was 0.17 seconds.

These findings suggest that the optimal positioning of a single vibrating cell should involve a voltage intensity of at least 1.61 volts and a time of actuation of at least 0.17 seconds.

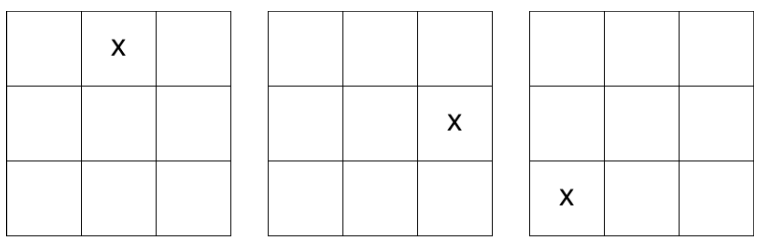

Figure 32: Example of inputs tested during the sensitivity assessment.

7.2 Qualitative User Feedback

Participants were invited to respond to the 7 statements presented in the "Methods" section using a Likert scale with 5 possibilities:

1. Strongly Disagree
2. Disagree
3. Neutral
4. Agree
5. Strongly Agree

The following questions were asked to the participants of this qualitative survey:

1. **"I can localize single vibrating cells well on the HFAB."**
2. **"I can assess straight vibrating paths well on the HFAB."**
3. **"I can assess straight vibrating paths well even when speed increases."**
4. **"I can assess vibrating rows, columns, and diagonals well on the HFAB."**
5. **"I can identify different neighbor cells vibrating at the same time well on the HFAB."**
6. **"I think vibrations patterns could be designed with the HFAB."**
7. **"I think the HFAB is comfortable to wear."**
8. **"I think the HFAB should be worn around the dominant wrist."**
9. **"I think the HFAB could be used to give information in real-time to the user.**
10. **"I think the HFAB could be used as a navigation assisting device."**

The corresponding results are displayed in Figure 33. The first five statements are based on the ability of the user to recognize certain vibration patterns. As it can be seen on the graph, the participants are pretty confident when it comes to identifying single vibrating cells (Q1) or straight vibrating paths with a steady speed (Q2). However, they showed less confidence in assessing the location of straight vibrating paths with varying speed (Q3) and vibrating rows, columns and diagonals (Q4). Finally, participants presented more concerns about identifying well different neighbor cells vibrating simultaneously (Q5). The five following statements are made as a direct feedback regarding the development and use of the device.

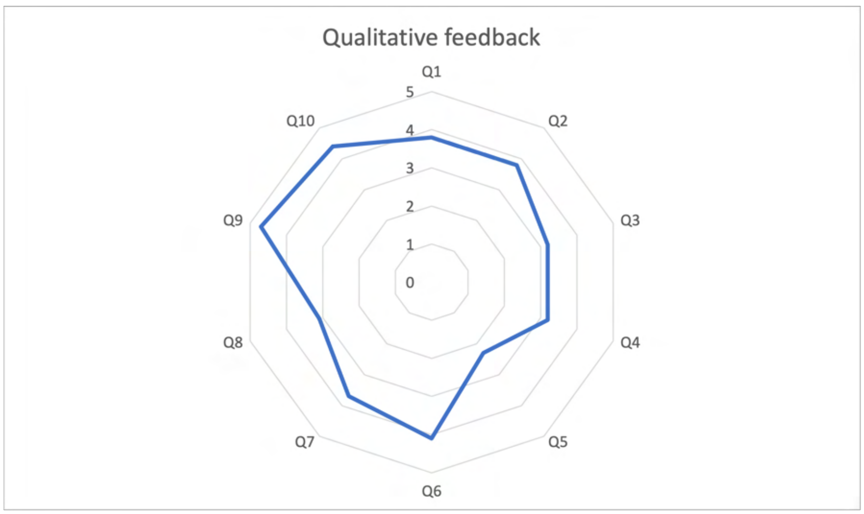

Figure 33: Qualitative user feedback answers.

7.3 Design Considerations

The results from user experiments provided valuable insights into the design considerations necessary for creating intuitive and clear vibro-tactile instructions. The feedback from the users helped to identify the most effective vibro-tactile patterns for conveying information, the ideal placement of the vibro-tactile elements on the forearm, and the appropriate intensity and frequency of the vibrations.

7.3.1 Vibration Patterns To Privilege

- **Horizontal Vibration Path:**
  Succession of actuated cells moving laterally on the array are easier to sense to indicate a direction.

- **Spaced Multiple Vibrating Cells:**
  Cells can vibrate simultaneously if they are spaced enough to allow for each one's perception.

- **Spaced Multi-Row Vibrating Cells:**
  Vertical direction should be shown by jumping one row to allow for better differentiation.

- **Multiple Actuation of Cell(s):**
  People need multiple actuation when specific cells are vibrating.

- **Use Different Rows for Different Directions:**
  Changing the row of actuation when showing a different direction can help for a better differentiation.

- **Make Shapes Drawing Longer:**
  Use more space to draw shapes gives more time to the user to recognize the shape.

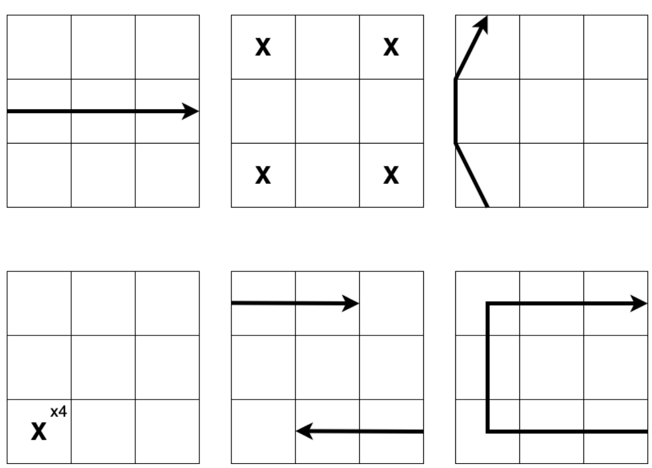

Figure 34: Vibration Patterns to privilege when designing a set of vibrotactile instructions.

7.3.2 Vibration Patterns To Avoid

1. **Moving Lane of Vibrating Cells:**
   Moving a full lane of vibrating actuators can be confusing for the user.

2. **Neighbor Vibrating Cells:**
   Vibrating direct neighbor cells are difficult to differentiate.

3. **Lane of Vibrating Cells:**
   Vibrating lanes of cell are confusing for the user.

4. **One-time Actuation of Cell(s):**
   The one time actuation of a cell doesn't give enough time to the user to focus and recognize the cell.

5. **Vertical Vibrating Path:**
   Succession of actuated cells moving vertically can lead to confusion when indicating a direction.

6. **Multiple Vibrating Paths:**
   Multiple successions of actuated cells present too much information for the user to recognize properly.

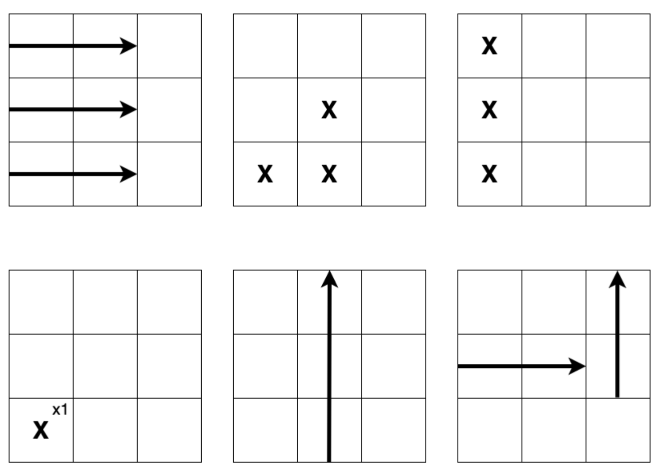

Figure 35: Vibration Patterns to avoid when designing a set of vibrotactile instructions.

8 Testing and Evaluation

8.1 Final Prototype

In order to ensure that the device could be tested in real-life conditions, a wearable support system was designed and 3D-printed for the control system. The support system was designed to be lightweight and comfortable to wear, while also providing secure attachment points for the vibrotactile wristband and the control unit.

In addition to the support system, some wire-management was necessary to prevent any LRA from disconnecting while in motion. This was particularly important to ensure the reliability of the device during testing, as any loss of connectivity could impact the accuracy of the navigation instructions provided to the user. The LiPo battery was connected to the JST port of the HUZZAH32 to provide power to the micro-controller. Finally, the C++ code was modified to allow for Serial Monitoring through BLE, enabling navigation instructions to be sent remotely to the device via Bluetooth. This allowed for real-time transmission of the navigation instructions to the user.

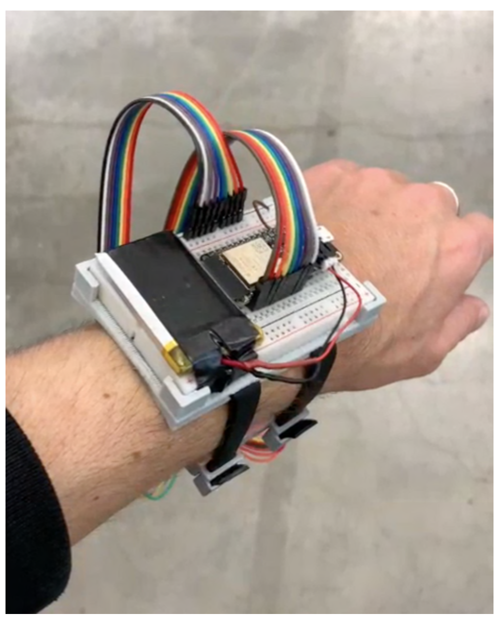

Figure 36: Final version of the prototype with micro-controller board holder.

8.2 Path Navigation Experiment

8.2.1 Design of the Navigation Instructions

To validate the results obtained from the user experiment and verify the design considerations discussed previously, a real-life testing was conducted. The testing aimed to compare the effectiveness of two different sets of vibration patterns designed for the device.

The first set was designed intuitively, without taking into consideration the results of the user experiment. In this set, each direction ("Forward", "Right", "Left", "U-Turn" (aka "Backward")) is indicated by translating a horizontal or vertical lane, whereas "Stop" and "Arrived" are represented by a vibrating cross and a double tap in the center, respectively (See Figure 37). It was theorized that exploiting the maximum of actuators for each instruction would make the patterns easier to perceive for the user.

The second set, on the other hand, was designed using the findings of the user experiment (i.e. the design considerations discussed previously) to inform the navigation instructions. In this set, "Right" and "Left" are indicated by a single vibrating path from left to right, right to left respectively. "Forward" is a double-tap on the center of the array. "Stop" is a double-vibrating square. "U-Turn" is a path going all around the array, while "Arrived" is a 6-time actuation of the center of the array (See Figure 38). It was theorized that this vibration pattern set would prove to be more efficient than the Set 1.

The hypothesis behind this real-life testing was that the set of vibration patterns designed using the results of the user experiment would prove to be more effective in providing accurate navigation instructions.

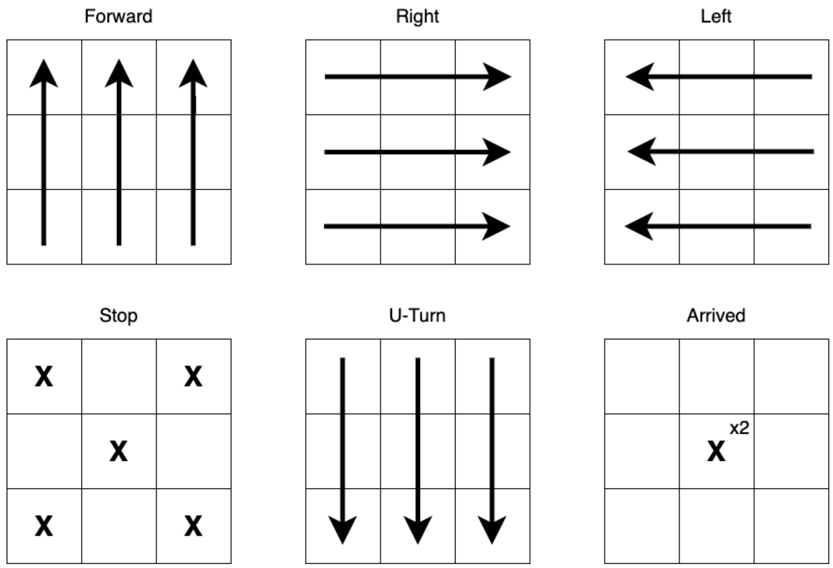

Figure 37: Instruction Set 1: Intuitive initial vibration patterns.

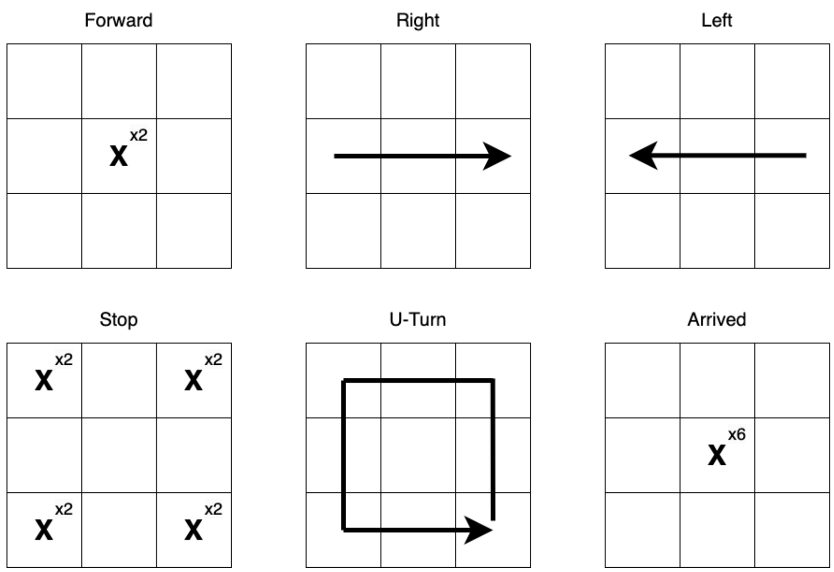

Figure 38: Instruction Set 2: Vibration patterns after the user experiment.

8.2.2 Path Navigation Testing

The path navigation testing involved 5 participants who were required to follow two different paths (Refer to Table 3) while receiving navigation instructions remotely, including ”Forward”, ”Left”, ”Right”, ”Stop”, ”U-Turn”, and ”Arrived”. The instructions were sent an equal number of time for each path, and the participants were blindfolded to simulate the experience of being visually impaired. As mentioned before, in their research on the analysis of various vibrations patterns to guide blind people, Durà-Gil et al. demonstrated that blind-folded sighted people are suitable for testing the patterns [21]. The objective of the experiment was to evaluate which of the two sets of instructions, Instruction Set 1 (Refer to Figure 37) or Instruction Set 2 (Refer to Figure 38), was more effective in guiding the participants along the paths. Two paths were designed to prevent participants to guess navigation instructions from one vibration pattern set to the other.

During the testing the device sent a haptic signal (single vibrating center cell) every 2 seconds when moving to ensure that the participant did not feel anxious when blindfolded. The goal was to help the participants stay oriented and to provide them with a sense of security while navigating unfamiliar paths. The instructions were sent remotely from a computer using the BLE Serial Port of the ESP32.

Figure 39: Participant following the vibro-tactile instructions sent remotely.

Figure 40: Final prototype worn by the participant during the testing.

8.2.3 Results of the Navigation Testing

Looking at the individual instruction accuracies for Set 2 (See Figure 42), all of the instructions had an accuracy of at least 90%, with some instructions, such as Stop and Arrived, having accuracy rates of 95% and 100%, respectively. This indicates that the design considerations from the user experiment were effective in improving the accuracy of these vibration patterns.

In contrast, Set 1 had a lower accuracy rate for all instructions (See Figure 41), with the U-Turn instruction having the lowest accuracy rate at only 53%. This suggests that Set 1 was less effective in conveying the necessary information for navigation.

Based on the results of the path navigation testing, it can be concluded that Set 2 performed better than Set 1 in terms of accuracy. The total accuracy of Set 2 was 93%, which is significantly higher than the total accuracy of Set 1, which was only 72%.

Path 1:	
1. Forward	14. U-Turn
2. Right	15. Right
3. Right	16. Left
4. Left	17. Stop
5. Right	18. Forward
6. Stop	19. Right
7. Forward	20. Stop
8. U-Turn	21. Forward
9. Left	22. Left
10. Stop	23. Right
11. Forward	24. U-Turn
12. Left	25. Arrived
13. Left	

Path 2:	
1. Forward	14. Right
2. Right	15. Right
3. Right	16. Stop
4. Left	17. Forward
5. Stop	18. Right
6. Forward	19. Left
7. U-Turn	20. Right
8. Left	21. Left
9. U-Turn	22. Stop
10. Stop	23. Forward
11. Forward	24. Left
12. Left	25. Arrived
13. U-Turn	

Table 3: Sequence of navigation instructions for the two testing paths.

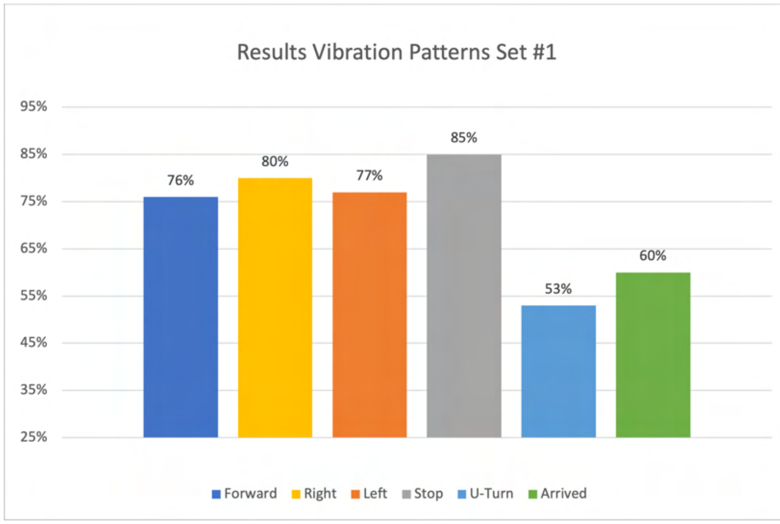

Figure 41: Results of the navigation instructions for the vibration patterns of the Set 1.

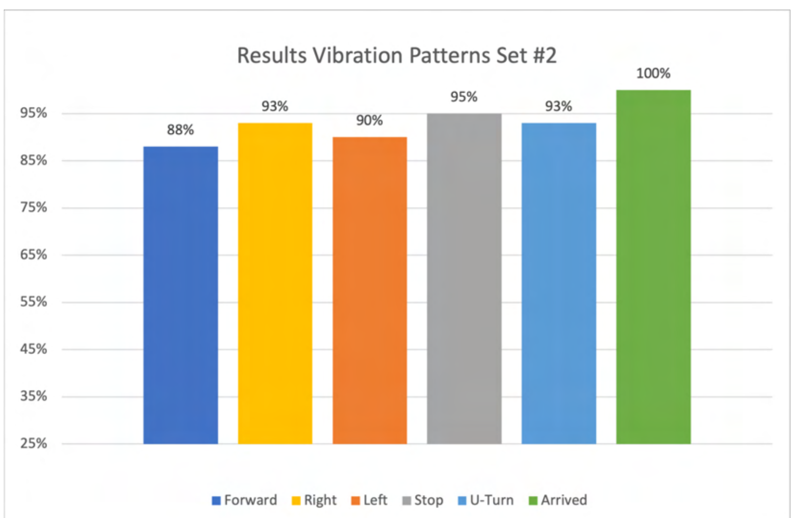

Figure 42: Results of the navigation instructions for the vibration patterns of the Set 2.

9 Conclusion

9.1 Summary and Conclusions

In conclusion, this research successfully demonstrated the feasibility and effectiveness of a wireless vibrotactile wristband as a navigation aid for visually impaired people navigating unfamiliar environments. The wearability of the device was demonstrated through the design and 3D-printing of a wearable support and wire-management to prevent any disconnections during movement. Through the user experiment, we identified the most effective vibration patterns for conveying navigation instructions to visually impaired individuals, leading to an improvement in accuracy of more than 20% when the patterns were designed according to the experiment results. However, this result is to take cautiously because it is highly dependent on the result of each individual pattern to the path navigation testing experiment.

The results of this study have implications for the development of wearable haptic feedback devices, not only for navigation aids for visually impaired people but also for potential applications in fields such as sports, rehabilitation, and gaming. The findings may also inform the design and implementation of future assistive technologies for visually impaired individuals. Further investigations could focus on improving the resolution of the vibrotactile array, optimizing the user experience design, and exploring the device's performance in more complex environments. Overall, this research contributes to the advancement of wearable haptic feedback technology and its potential to enhance the lives of visually impaired individuals.

9.2 Suggestions for Future Research

There are several potential areas for further research on the wireless vibrotactile wristband designed for visually impaired navigation.

One potential avenue is to conduct further experiments, testing the device with blind participants, to evaluate the effectiveness of the device with people suffering from visual impairment in a real-life setting. This could also involve testing the device in different environments, such as indoor and outdoor settings, to see how it performs in different scenarios.

Another area for future exploration is the experimentation of different array shapes and resolutions. For instance, circular or 3D arrays could be explored to determine if they provide more accurate navigation instructions. Decreasing the resolution of the array could also potentially enhance the precision and reliability of the device by giving more space to draw shapes and lines.

Additionally, while the focus was put on designing shapes and it could be beneficial to design vibration patterns with varying voltage intensity and frequency of vibration to see how this affects the accuracy and reliability of the device. This could potentially lead to more customizable and personalized navigation instructions for each individual user.

Finally, the implementation of an API (i.e. OpenStreetMap) could be explored to automate the navigation process and turn the device into an option to consider for visually impaired individuals.

10 Acknowledgements

I would like to take this opportunity to express my sincere gratitude to several individuals who played a significant role in the successful completion of my research project.

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Finally, I would like to express my appreciation to everyone who contributed to my research project in one way or another. Thank you all for your support, guidance, and encouragement throughout this journey.

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11 Appendix

11.1 Appendix A: User Experiment Assessment Scenario

Interview Scenario #1 – Haptic Feedback Array Band (HFAB)

First Part: Introducing the subject to the research

1) **Introduce** ourselves
2) **Define** haptic feedback
3) **Provide context** to the interview:
    a. We are conducting research to examine user compatibility of the HFAB
    b. Give an outline
4) Say that for practical reasons we will record some of the interview but **protect their privacy**.
    a. Ask if it would be ok to use images of the interview in future reports/publications.
    b. Ask if it would be ok to quote them anonymously in future reports/publications.
5) Inform that **they can stop the interview** at any time.
6) Make sure they are **not under the influence of anything** that could alter their senses.
7) Ask their **age**, **gender**, and **dominant hand**.
8) Ask if they have any questions.

(recording starts here)

Second Part: Open-ended questions about the research

1) Describe your experience with haptic feedback, for example when playing video games or using electronic devices.
2) In your own words, how does haptic feedback impact your experience when using electronic devices?

(recording ends here)

Third Part: Vibrohaptic feedback localization, directionality, sensitivity assessment and patterns

Note: For every input, all the possible solutions are not tested in order to prevent the subjects from guessing the next input and rely only on their sense of touch.

1) **Baseline:** Before beginning the experiment, the selected subject's wrist is measured (length and width) and taken in photograph. The wristband is then attached around the subject's wrist and tighten according to the user's demand. The cells are actuated to check if the subject can feel them. This is essentially a calibration step to see if the wristband is well attached on the subject's arm. For the sequences described below the subject uses their preferred arm. They also wear headphones playing white noise and the device is hidden so they cannot see it. The subject will therefore only be helped by their sense of touch.

2) **Single cells** across the array are actuated for 1 sec and must be localized on a corresponding grid. Proposed sequence of six inputs:

z0110 – z2210 – z1010 – z0210 – z2110 - z1110

	3	
1	6	5
4		2

3) **Straight paths – cardinal directions.** Straight paths are activated in 1 second and the resulting vector must be assessed on a corresponding grid. The arm stays in the same position. Proposed sequence of six inputs to represent all cardinal and two ordinal directions:

p002210 – p012110 – p101210 – p022010 – p121010 – p210110

SE

1		
	2	
		3

E

1	2	3

S

	1	
	2	
	3	

NE

		3
	2	
1		

N

	3	
	2	
	1	

W

3	2	1

4) **Different straight paths** are activated on the array at various speeds and the subject is asked to assess the resulting vector on a corresponding grid. The arm stays in the same position. The goal is to see at which speed the subject's ability to identify the paths drops. Proposed sequence of twelve inputs:

p002205 – p000215 – p210110 – p002005 – p220020 - p200210 – p220215 – p222005 – p022015 – p022210 – p121015 - p012120

1		
	2	
		3

1		
2		
3		

3	2	1

1	2	3

3		
	2	
		1

		1
	2	
3		

3	2	1

		3
		2
		1

		3
	2	
1		

1	2	3

	3	
	2	
	1	

1	2	3

5) **Different columns, rows and diagonals** are activated on the array for varying times and the subject is asked to identify the cells on a corresponding grid. The arms stays in the same position. Proposed sequence of twelve inputs:

h120 – v210 – x215 – v105 – x110 – h205
x115 – v005 – h105 – h220 – x205 – v110

X	X	X

		X
		X
		X

		X
	X	
X		

	X	
	X	
	X	

X		
	X	
		X

X	X	X

X		
	X	
		X

X		
X		
X		

X	X	X

X	X	X

		X
	X	
X		

	X	
	X	
	X	

6) Between two and four **neighbor cells** are activated at the same for varying times and the subject is asked to count/identify them on a corresponding grid. The arm stays in the same position. Proposed sequence of twelve inputs:

t00101120 - d212210 - d021215 - q1011202120 - d011115 - t11211205 – d001010 - q0212011105 - t020112110 - d111220 - d202105 - t01101115

X	X	
	X	

		X
		X

X	X	

	X	X
	X	X

X	X	

	X	X
	X	

X	X	

X	X	
X	X	

X		
X	X	

	X	
	X	

		X
		X

	X	
X	X	

7) A **sensitivity assessment based on voltage** input is conducted. Single cells are activated during 2s with incremental force. The subject is asked to assess when the vibration becomes noticeable and locate it on the corresponding grid with the **corresponding iteration number**. Proposed sequence of six inputs:
Voltage input: **1.0 – 1.3 – 1.7 – 2.0 – 2.3 – 2.7 – 3.0 – 3.3** (Stop when sensed) (XX is replaced by the corresponding input)

i10XX20 – i21XX20 – i02XX20 – i20XX20 – i01XX20 – i11XX20

	x	

		x

x		

		x

x		

	x	

8) A new **sensitivity assessment based on time** is conducted. Single cells are activated at maximum voltage during an incremental time. The subject is asked to assess when the vibration becomes noticeable and locate it on the corresponding grid with the **corresponding iteration number**. Proposed sequence of six inputs:
Time inputs: **0.1 – 0.2 – 0.3 – 0.4 – 0.5** (Stop when sensed)

z11XX – z02XX – z21XX – z00XX – z12XX – z10XX

	x	

x		

		x

x		

	x	

	x	

Fourth Part: Qualitative feedback Likert style

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

1) I can localize single vibrating cells well on the HFAB

2) I can assess straight vibrating paths well on the HFAB

3) I can assess straight vibrating paths well even when speed increases

4) I can assess vibrating rows, columns, and diagonals well on the HFAB

5) I can identify different neighbor cells vibrating at the same time well on the HFAB

6) I think vibrations patterns could be designed with the HFAB

7) I think the HFAB is comfortable to wear

8) I think the HFAB should be worn around the dominant wrist

9) I think the HFAB could be used to give information in real-time to the user

10) I think the HFAB could be used as a navigation assisting device

Fifth Part: Wrap up

1) Thank the subject for their time
2) Ask if they would be interested in a follow up interview/demo when the HFAB is integrated to help during navigation in foreign environments
3) Remind them that we will protect their privacy and will not use the recordings outside of the study
4) Ask if they have any questions or feedback

11.2 Appendix B: User Experiment Assessment Sheet

Interview Sheet #1 – Haptic Feedback Array Band (HFAB)

First Part: Introducing the subject to the research

- Name:
- Age:
- Gender:
- Dominant hand:

Questions or notes:

Second Part: Open-ended questions about the research

(recorded)

Third Part: Vibrohaptic feedback localization, directionality and sensitivity assessment

1) Baseline, calibration:
- Wrist length:
- Wrist width:

Questions or notes:

2) Single cell localization:

Questions or notes:

3) Straight path – cardinal directions localization:

1

2

3

4

5

6

Questions or notes:

4) Straight path localization with varying speed:

1

2

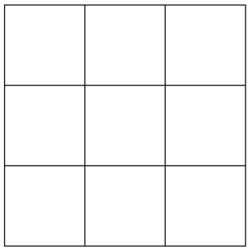
3

4

5

6

7



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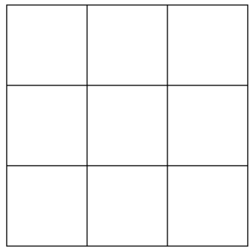

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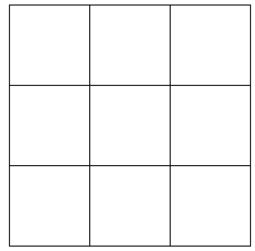

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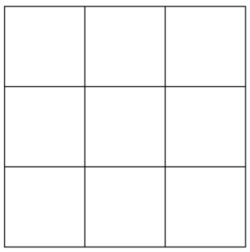

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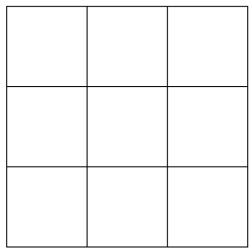

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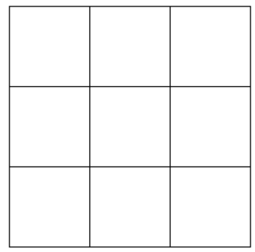
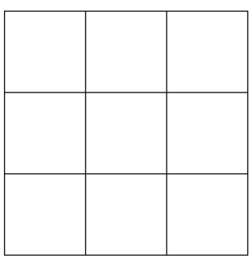


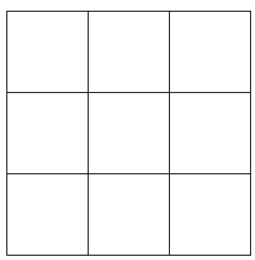
Questions or notes:

5) Columns, rows and diagonals localization:

1



2



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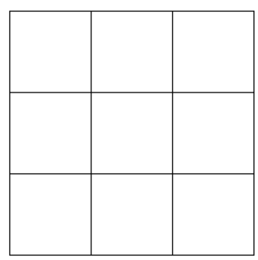

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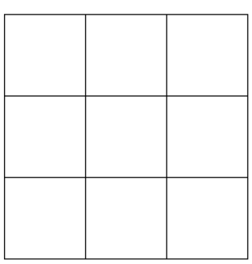

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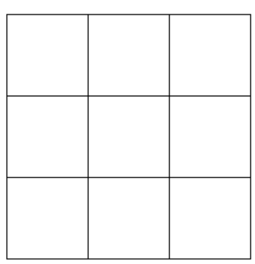

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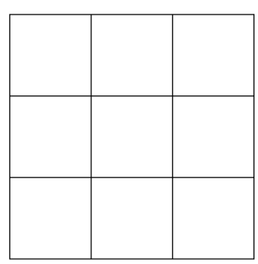

7

8

9

10

11

12

Questions or notes:

6) 2-4 neighbor cells localization:

1

2

3

4

5

6

7

8

9

10

11

12

Questions or notes:

7) Sensitivity assessment based on voltage:

1

2

3

4

5

6

Questions or notes:

8) Sensitivity assessment based on time:

1

2

3

4

5

6

Questions or notes:

Fourth Part: Qualitative feedback Likert style

1) **I can localize single vibrating cells well on the HFAB:**

Strongly Disagree Disagree Neutral Agree Strongly Agree

2) **I can assess straight vibrating paths well on the HFAB:**

Strongly Disagree Disagree Neutral Agree Strongly Agree

3) **I can assess straight vibrating paths well even when speed increases:**

Strongly Disagree Disagree Neutral Agree Strongly Agree

4) **I can assess vibrating rows, columns, and diagonals well on the HFAB:**

Strongly Disagree Disagree Neutral Agree Strongly Agree

5) **I can identify different neighbor cells vibrating at the same time well on the HFAB:**

Strongly Disagree Disagree Neutral Agree Strongly Agree

6) **I think vibrations patterns could be designed with the HFAB:**

Strongly Disagree Disagree Neutral Agree Strongly Agree

7) **I think the HFAB is comfortable to wear:**

Strongly Disagree Disagree Neutral Agree Strongly Agree

8) **I think the HFAB should be worn around the dominant wrist:**

Strongly Disagree Disagree Neutral Agree Strongly Agree

9) **I think the HFAB could be used to give information in real-time to the user:**

Strongly Disagree Disagree Neutral Agree Strongly Agree

10) **I think the HFAB could be used as a navigation assisting device:**

Strongly Disagree Disagree Neutral Agree Strongly Agree

Fifth Part: Wrap Up

Questions or notes: