Design and Prototyping of a Wearable Kinesthetic Haptic Feedback System to Support Mid-Air Interactions in Virtual Environments

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Abstract. This paper focuses on the study of mid-air gestural interaction and haptic means of immersion in virtual environments to design a wearable kinesthetic feedback system based on vibro-tactile feedback mechanisms. The paper gives special attention to the design and prototyping of the wearable system and the use of low-cost optical hand tracking devices. The complete implementation of the system is comprised of a motion tracking sensor, used to identify and monitor the user's hand position and gestures, and a wearable device based on low-cost microcontroller technologies and vibration motors for producing the haptic rendering. The wearable device is mounted on the user's hand (fingers, palm and wrist), with the aim of producing feedback in real time when interacting with virtual objects in virtual environments. In this paper we present the design of the wearable kinesthetic feedback system, the implementation of the haptic rendering mechanisms and a preliminary evaluation of its usability from a user experience perspective.

Keywords: Mid-Air Interaction, Wearables, Vibro-Tactile Feedback, Haptics.

1 Introduction

Gestural interactions and more specifically mid-air interactions present a number of benefits and problems [1, 2]. One of the most mentioned difficulties users experience when interacting with natural interfaces that involve touchless manipulations is related to the absence of tactile feedback. This results in a number of consequent issues such as the inability to differentiate between intended and unintended interactions referred to as the Midas Problem [3], the continuous-active nature of the gestural interaction [4], and among others the lack of haptic feedback that assists in fine tuning and refining manipulations [5] by combining multiple senses, perceptions and actions such as visual, haptic, sense of depth, spatial proximity, grasping etc [6–9]. While the cutaneous system employs receptors embedded in the skin, and the kinesthetic system those receptors that are located in muscles, tendons, and joints, the haptic sensory system acts on the basis of combinatory mechanism which employs both cutaneous and kinesthetic receptors [10]. The haptic system is characterized in terms of a bidirectional communication channel that living organisms incorporate to sense and interact with their environment. The haptic system is coupled by an active procedure controlled by both movement and touch and therefore combine both mid-air and touch interactions.

Thus, as a key point in the mitigation of the weaknesses of mid-air interaction, the aim of this paper is to study the use of vibro-tactile feedback in mid-air interactions by implementing a wearable device that will provide haptic feedback based on the creation of haptic rendering patterns. Towards this goal, the paper discusses a number of research and design challenges. First, it outlines related concepts, mid-air interaction, vibro-tactile and cutaneous haptic feedback, and haptic rendering. Next, it reviews a number of related projects and research works that employ tactile and mid-air interaction technologies. It provides a detailed description of the design decisions and prototyping steps towards the implementation of a vibro-tactile wearable device for supporting tactile feedback in mid-air interactions. Finally, we include a short report on a pilot study and outline current research activities of the design team of an ongoing research experiment that utilizes the device in use cases that involve interactions in virtual environments.

2 Mid-Air interaction and Haptic Feedback

In recent years the combination of haptic, wearable technologies uncovered new ways in providing tactile feedback while gesturing in mid-air [11]. These interfaces are very useful in situations where the actual device or interface poses limitations and thus restrict user performance. These limitations arise for a number of reasons and are related to a) the physical characteristics of the interface or the device, b) the users' concurrent activities, c) the context of use including the cultural or physical environment. For example, small device interfaces such as touchscreens on smart-watches often hinder users from interacting with them. Concurrent activities that the users perform might prohibit them to interact by using interaction styles such as touch, tangible or voice. Context is also playing an important role, for example in environmental conditions where the users are unable to employ other interaction styles such as underwater, or in severe weather conditions, or even in contexts where cultural rules, rituals and behavior regulations direct users to use only gestural interactions.

2.1 Mid-Air Interaction

Mid-Air Interaction is defined as a form of human computer interaction in which an action is carried out without the mechanical contact between the user and any part of a device or system. It is considered a particular form of a natural user interaction, more specifically a kinesthetic and gestural interaction, that employs touchless or contact-free manipulations of digital content and is based on the identification of bodily movements, usually of the hands [12]. It imparts greater naturalness from what we are used to in our everyday lives when we interact with traditional human-computer interfaces, and thus provides new ways of interacting through simple and intuitive body movements [13, 14].

The most notable mid-air interaction systems, at the time of writing this paper, are the Nintendo Wii platform which incorporates the Wiimote remote controller and has motion sensing capabilities that allow the user to interact with and manipulate items on screen via gesture recognition and pointing, the Microsoft Kinect which is based on the MS Kinect sensor and implements two cameras (color and depth camera) and an array of microphones. Kinect is accompanied by an SDK that provides tracking of human movements by the use of two skeletons of 25 points in total [15] and the Leap Motion Controller (Ultraleap), an optical hand tracking module that specifically captures the movements of hands.

2.2 Vibro-tactile Haptic feedback

Tactile interaction is related to all aspects of touch and body movements and the application of these senses to the field of human-computer interaction [16]. Tactile interaction is a field that refers to the ways in which people communicate and interact through the sensation of touch. This kind of interaction offers an extra dimension in virtual environments, adds a sense of immersion in them and are usually encountered in the use of vibrations in contact with the skin. When referring to tactile feedback, we usually mean vibrations while the vibrotactile feedback is the feedback offered by the vibrations of a device in the hand of the user.

Dynamic feedback also works through haptic vibrations, but particularly in conjunction with an on-screen action. Dynamic feedback is typically found on controllers in computer games, for example, the pursuit of naturalness and resistances. These are, therefore, essential forces that stop the user's movement providing an additional sense of immersion. These two feedback mechanisms are often combined. In most tactile feedback systems, vibrotactile feedback is used either by vibration sensors or by other feedback techniques and mechanisms such as ultrasound or air pressure. These vibrational stimuli when they come into direct contact with the skin cause different sensations in proportion to the frequency and intensity used.

2.3 Haptic Rendering and Haptic Patterns

Haptic rendering is the process by which the user can touch, feel, and manipulate virtual objects [10, 17]. It aims to improve the user’s experience in a virtual environment and provide a natural and intuitive interface. A case of tactile performance is the transmission of information about the physical properties of the object such as shape, elasticity, texture, mass, etc. The tactile performance, based on the method used, can provide many different feedback senses. According to Salisbury et al [18], the tactile performance algorithms calculate the correct interaction forces between the visual representation of the interface within the virtual environment and the virtual objects that constitute it. A typical tactile feedback algorithm is synthesized by many factors to be effective. In this paper, we study a simple collision-detection algorithm that identifies collisions between objects in the virtual environment and provides information on where, when, and ideally, to what extent collisions have occurred. This is represented as a haptic feedback pattern that is rendered according to specific interaction scenario needs and aims to produce the appropriate feedback to the users. Haptic patterns are leveraged to enhance perceptual and sensory feedback and response, convey useful information, and enhance usability instead of ‘beautifying’ interactions unnecessary to the user experience.

2.4 Related Projects

There is a growing number of research projects that explore the potentials of using a combination of haptic feedback and mid-air interactions. In this section we present an overview of the research works that are related to our project. These can be grouped in two major categories, mid-air interactions that make use of electromechanical means to produce haptic feedback, and experimental methods that investigate alternative methods to produce haptic feedback. We also present research works related to mid-air interaction that combine depth camera motion tracking and haptics. According to Freeman et al. [19], there are four types of tactile feedback that can be used in mid-air interactions, tactile ultrasonic measurements, remote feedback from a ring worn on the pointer, remote feedback from a clock set worn on the wrist, and feedback directly from the phone (when held). In their experiment they focused on two different tactile responses: continuous and discrete. The results of this study identified that the discrete feedback did not give a great sense of feeling compared to the continuous, but many users preferred it as it was less disturbing compared to the continuous vibration. In their study Mazzoni et al. [20] presented the development of a wearable device that aims to enhance musical mood in cinematic entertainment through tactile sensations (vibration feedback). This research showed that vibrational stimuli at low intensity and frequency, causes tranquility to users, while vibrational stimuli with low intensity, but in higher frequencies, increase their motivation to interact. Vibrations of high intensity and high frequency had a major impact on the user’s experience. A method that combines mid-air interactions and haptic feedback was developed by Feng et al. [21] who presented a waterproof, lightweight and small tactile device, worn on the finger, which consists of 4 3D printed microscopic airbags. The implementation is based on air pressure by a high-frequency speaker to provide tactile feedback to the user. Vivoxie introduced a pair of gloves (PowerClaw) that can produce temperature senses to its users (cold and heat). This device stimulates the skin and allows the senses of heat, cold, vibration and roughness of objects to simulate virtual reality. The device has limited power management and the actuators consume a big amount of electricity when switching between hot and cold, so it is not yet possible to wirelessly use the gloves [22].

The Leap Motion sensor is well known in this research field for mid-air interactions but still there are a few consumer products developed to provide vibrotactile feedback while using this sensor. Thought there are some good research examples around this field, as presented by Nguyen et al. [4], who developed a tactile feedback glove, with vibration sensors and an Arduino Mini Pro microcontroller, in mid-air interaction with the Leap Motion sensor. The conclusions of the evaluation showed that generally with the use of the glove the work was better compared to that without it [4]. A wearable device presented by Kim et al. [23], is based on vibration and heat feedback. They present a similar comparative evaluation to Nguyen et al. study, and identify that tactile support provide greater immersion to users.

In the following, some of the consumer products mentioned before, which provide vibrotactile feedback in addition to Leap Motion sensors interactions, are presented.

A well-known product is UltraHaptics, a multipoint, tactile, ultrasonic airborne system that uses ultrasound to deliver tactile feedback to specific parts of the user's hands. For the evaluation of this system some experiments were performed to highlight feedback points with different touch properties and their recognition in smaller divisions. The results of this evaluation showed that it can create individual feedback points with high precision and that users have the ability to distinguish between different frequencies and vibrations [24]. Another example in tactile interaction with the Leap Motion sensor is Gloveone, which is a wearable device that provides users with tactile feedback by allowing them to interact with virtual objects on the computer screen or in virtual reality headsets. Users can feel the shape, weight, textures of the objects displayed on the screen, and can interact with them. In addition, they are able to feel sound waves, raindrops even the intensity of a virtual fire. It uses ten vibration sensors, which, depending on the object or the desired sensation, adjusts the provided vibration intensity. Finally, for better motion detection it uses independent finger tracking with 6 IMU (3 axes), manual orientation with 1 IMU (9 axes) and contact areas for digital and reliable gesture recognition. The VRtouch is also a wearable tactile feedback device, except that this technology is worn on each finger individually. It has a magnetic fastening system that makes it easier to place on each finger, it is light-weighted and has well-designed ergonomics, helping to exploit the natural and enjoyable user experience. It also supports the Leap Motion sensor and other similar positioning and movement systems.

3 Research and Design Considerations

The design phase of the wearable system followed an iterative process and initially involved research and data gathering, the modeling of collected data, and finally the formation of the design framework and the definition of design requirements and design specifications [25]. The research and framework definition phase were followed by a design phase which mainly involved the production of prototypes of the wearable system and a formative evaluation.

3.1 Design Requirements and Specifications

Based on desktop research, user research and contextual inquiry we collected requirements for the design of the wearable device [26]. By using recent research work on guidelines for designing wearable devices [27, 28], we have identified a need for a wearable device that can deliver tactile feedback to the user, be portable and have good ergonomics. It should provide a sense of safety and security and support users to wear it even in scenarios that require long term usage. It should be capable of adapting to the different needs of each user (anthropometric/physiology factors, hygiene, aesthetics, comfort, wearability, physical activity interference, supporting mid-air movement). Requirements for the wearable should be related to its ergonomics and ease of use, while tactile feedback should focus on providing immersion. The following table represents some design requirements and specifications that guided our design.

Table 1. Design requirements and specifications for the wearable system.

Design Requirements	Design Specifications
Product aesthetics: Be aesthetically simple, not to attract the attention of the user	Simple aesthetic, use of black fabric. Small number of additional components on the device.
Wearability: Size	Thin fabric and components (board and sensors) of small size.
Wearability: Be light-weighted	Lightweight fabric, components, board and sensors.
Comfort: Do not warm up the user's hand when wearing it.	Thin fabric and no use of fabric in the inside part of the device.
Comfort: Be easy to wear and remove, non-slippery.	Use Velcro in two places for easy placement and removal from the hand.
Anthropometry/Physiology: Respond to many users with different hand sizes.	Elastic fabric and Velcro to change its size depending on the size of the user's hand.
Appropriate Body Placement: The fabric shouldn't be tight on the user's hand.	Do not consist of tight fabrics.
Learnability: The user should understand how the device is worn.	Have external and internal indications in order to be easier for the user to place it on his /her hand.
Physical Activity Interference: Do not hinder the user's movements when wearing it.	Place the objects on the device in appropriate points to facilitate movements of the hand.
Wearability: portable.	Portable device operation using battery.
Safety: The user shouldn't perceive sensors and cables, so that they feel safe when wearing it.	Sensors and cables covered with fabric in such a way not to be perceived by the user.
Interaction and Ease of use: The vibrotactile feedback shouldn't be too intense, so that it doesn't cause annoyance to the user.	Low intensity and short duration of vibrotactile feedback.
Interaction and Ease of use: Vibrotactile feedback should have a good match to real time actions and be realistic.	Match vibrotactile feedback with the depiction of the application, for example, when the tool comes into contact with the figurine to trigger feedback.
Operational Lifetime: Long battery life.	Use of a long-life lithium battery (750mAh).
Connectivity: Easy connection of the device with the application.	Connect the device to the computer via Bluetooth.
Compatibility: The technology used should be compatible with Unity engine.	Using the ESP32 DevKit, compatible with the Unity engine.
Reliability and Fault Tolerance: Make the system efficient and effective.	Fast and accurate system response without interference due to the use of the wearable device.

3.2 Prototyping

The prototyping phase focused on enhancing an existing application [29] on the basis of the wearable device prototype that included the haptic feedback mechanisms. In this context the research team designed and developed a wearable prototype system, to enhance mid-air interaction and usability in the Cycladic sculpture application through vibrotactile feedback.

The focus was to enrich the interactions of the existing application using the wearable device prototype developed in this work. In this application the user constructs a Cycladic sculpture with mid-air hand movements using the Leap Motion controller. The interaction scenario involved three sub-scenarios or stages where the user is using three different sculpting tools to perform a number of tasks.

To amplify usability and user experience, we incorporated vibro-tactile haptic feedback in mid-air interactions. The first vibro-tactile feedback (user's palm) is activated upon tool selection while a wrong tool selection is expressed by a vibration with different intensity and sharpness. The vibration responses vary at each stage in terms of their intensity, duration, and the actual location on the hand in which they are activated. The focus of the designed haptic patterns was to provide a realistic feedback to the user depending on the interaction scenario at hand. For these reasons we carefully identified the points where the user would feel pressure and vibration if he performed the task in real life and based on these, we designed the haptic patterns for each feedback mechanism on every scenario.

Physical prototype of the wearable device.

The prototyping of the wearable device took place in two different phases (low-fidelity and medium-fidelity prototypes). The first focused in designing iteratively the early model of the actual wearable glove and initiate the technological tests of the actual hardware while the second mainly focused in understanding and designing the actual interactions and combine hardware, software and the physical wearable product.

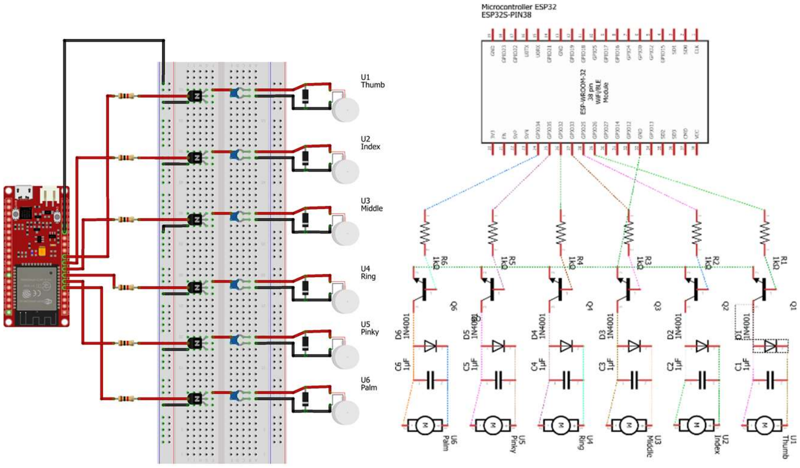

Fig. 1. Circuit Layout and Schematic of the vibration sensor circuit, ESP32 Devkit microcontroller, vibration motors, 1KΩ resistors, 2N2222 NPN transistors, 1N4001 diode rectifiers, 1μF ceramic capacitors and a breadboard.

The hardware that was used for the prototyping of the wearable device included, a desktop computer for running the actual application that the users interacted with, a Leap Motion controller for the capturing the position and the movements of the users' hand, a microcontroller devkit based on Espresif ESP32 board for doing the calculations related to the haptic feedback mechanisms and providing the means of wireless communication (Wi-Fi and Bluetooth) with the desktop computer, six coin vibration motors for the vibrotactile feedback placed on the edges of each finger and the center of the palm, a rechargeable lithium battery (750mAh). The physical product was designed by the use of elastic fabric for the main body of the wearable device glove, black Velcro stripes for controlling and providing variable size fit for the wearable device and flexible ribbon cables for connecting the vibration motors to the microcontroller.

The software used in this project was based on Arduino IDE for compiling the code of the microcontroller and Unity and the Unity Scripting API for the developing the desktop application and calculating the interactions. The schematic presented on the figure below provides an overview of the final wearable device configuration at a prototyping level.

Table 2. Pins to which the motors are associated, their designation in the code, the position on the board and the position on the wearable device.

MotorPin (code)	Pin (on board)	Correspondence with location to the wearable device
MotorPin1	22	Thumb
MotorPin2	28	Index
MotorPin3	27	Middle
MotorPin4	26	Ring
MotorPin5	25	Pinky
MotorPin6	24	Centre of the palm

Vibrotactile feedback.

As mentioned earlier, the vibro-tactile feedback was designed on the basis of a haptic mechanism that provided variable intensity, customizable duration, and location on the hand depending on the desirable interaction.

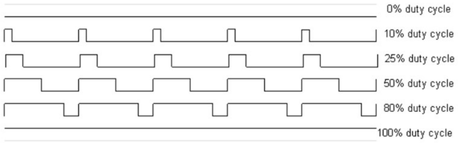

Fig. 2. Circuit diagram generated by the frequency of the PWM signal.

Intensity.

The vibration intensity in each case on the sensor is defined by the frequency of the PWM signal, which in most pins is about 490 Hz. At Arduino Uno and similar boards, pin 5 and 6 have a frequency of about 980 Hz. Pulse Width Modulation (PWM) is a technique for achieving analogue results with digital media. The digital control is used to create a square wave, a signal that is on and off. The PWM signal is a digital square wave, frequency being constant, but this fraction of the time at which the signal is activated (the duty cycle) can be between 0% and 100%. This on-off pattern can simulate the voltages between on (5 Volt) and off (0 Volts) by changing the amount of time the signal passes over the time the signal erases. The variable value is the operating cycle: between 0 (always closed) and 255 (always open) and only integer numbers (int) are allowed. In this case, the variable value was set to 255 and in each case divided by a number. That is, the operating cycle is always 100% until it changes. The larger the number by which this variable is divided, the lower the vibration sensor intensity.

Duration.

The duration of a vibratory feedback is defined by the Delay command. This command determines how long the sensor is running and any other command. The syntax of the command is: delay (ms) and the number entered in brackets is measured in milliseconds.

Location on the wearable device.

In each interaction of the user with the system, the vibrational responses differ with respect to the palm points of the user on which they are activated each time.

Prototyping the physical wearable device.

In the first stage of fabrication of the wearable device we used leather that was cut and punched with special tools. Velcro was placed in two points so that it can be easily worn and adjust in size and four black elastic fabrics were sewn, for placement at the fingertips. This construction did not go further due to difficulties encountered with the material. Leather, although was a durable material, it finally appeared heavy and rigid and the addition of extra parts to it was difficult. It did not meet the design specifications of the wearable device in terms of weight and aesthetics as well as the proper operation of the leap motion sensor. Hand detection was tested with the Leap Motion sensor while the wearable device was placed in the user's hand and there were significant errors in the detection of hand and finger movements due to reflections developed from the material's surface.

In the second stage, the ends of the positive and negative cable of the vibration sensors were attached with wires so that they have longer length when placed on the device.

Fig. 3. Vibration motor sewed on elastic fabric.

Materials that have been considered most suitable for the construction of the wearable device were then selected based on the criteria and specifications set above. The basic material for the "body" of the device is a black elastic fabric. At this stage, the central vibration motor was placed and sewed at the center of the palm on a 16 x 17 cm cut fabric. Velcro was also glued (as shown in figure 3) across the main area of the palm closed at the point between the thumb and the index. Further on, the fabric was sewed around the rest of the actuator motors and their cables and across the body of the wearable glove above the finger areas. An additional key part of the device is the elastic ribbons (1.5 * 3.5cm), which act as rings/fasteners and make it easy to place the sensors on the user's fingers. These parts were placed and then glued around the fingertips so that when the glove is worn the motors lie at the inner part of the fingertips and the cables goes around and over the fingers. At this stage, the different pieces of the device were placed on the hand in order to proceed with its construction. The purpose of this was to make some tests before sewing these parts to the rest of the device, to be as customizable as possible and applied to different hand sizes.

Fig. 4. Elastic "runner" joint stitched around a sensor cable

At this point, the first motor, which is placed on the user's thumb, was stitched at a distance of 10.5cm from the fabric located at the middle left, at the distance between the two Velcros. This distance corresponds to the measurements of the average distance of the thumb from the rest of the palm. When a user bends his thumb, there must be the appropriate margin to make this move. The same applies for the rest of the motors. Still to achieve a greater fluctuation in the size of the parts ending at the fingertips, in addition to the elastic fabric surrounding the wires, the wires were positioned in such a way so that this flexible behavior to exist. More specifically, the two wires on the inside of the fabric form small folds, resulting in the fabric being elongated, the wires being unaffected but helping to form this movement. Hereupon, the five actuator motors where attached to the area close to the fingertips and were sewed on the main body of the wearable device. For the flexible wires not to be exposed at the top of the device they were boxed / woven together with the actual fabric.

Fig. 5. Medium fidelity prototype

During the final design iteration few changes were made regarding the form of the device. These changes were made on the inside of the device, as some tests showed that the fabric inside the palm made it difficult to accurately detect the hand by the leap motion sensor. A part of the fabric was removed from the inside of the device as shown above on Figure 5.

4 Early Evaluation of Usability

During the iterative design processes, analyzed in the previous sections, we completed a number of formative evaluations with regards to the use of the wearable device in terms of the application scenarios. The purpose of the experimental evaluation of the wearable device was to determine its usability, the expediency of using haptic feedback in the specific application and whether it improves the users experience. On this basis, we also performed a comparative study regarding the use of the application in two distinct situations, one where interactions took place with mid-air interactions only and a second where the application was enhanced by the haptic wearable device. The evaluations criteria are divided in four categories, based on their characteristics. These are portability, usability, tactile feedback and user experience.

4.1 Evaluation Objectives and Criteria

Evaluation Protocol. First, we briefly described the system to the participants, then they were given a questionnaire, which included demographic characteristics, so that we could separate them into categories. After that, they used the system with and without the wearable device. Each time they used the system the participants completed a NASA TLX questionnaire, in order to compare the factors between the two. Finally, they completed a questionnaire based on their overall experience and the SUS usability questionnaire (Brooke, 1996), for the wearable device.

User Participants and Tasks. We interviewed 32 users (16 women, 16 men), most of whom where students (ages 18-30) and academics (ages 30 and above) who completed the sculpting scenarios in two situations (with and without haptic feedback).
The participants were separated at random in two groups:

- Group 1: Participants who used the application first using the wearable device and then without the wearable device.
- Group 2: Participants who used the application first without the wearable device and then with the wearable device.

These groups were also divided into two sub-groups based on their age:

- Sub-group A: Participants under the age of 30, mainly students participated in this group.
- Sub-group B: Participants over the age of 30, mainly academics and staff of the university community participated in this group.

4.2 Early observations and evaluation results

The majority of users 75% indicated that the haptic feedback session was more immersive. Some male users 12.5%, experienced problems in wearing the device because their actual physiological characteristics (larger hands) where beyond the upper limits of the devices size. These users indicated problems in performing the tasks primarily because they were not able to fully or easily close their hands when grasping the virtual tools. The majority of users (more than 90%) stated that they better understood the sculpting operations they performed, they felt more confident in grasping, manipulating and using the virtual tools as well as touching and exploring solid geometric objects in the 3D environment. We identified that users tented to explore by touching objects in the 3D scenes when wearing the haptic device something that was not performed without it. Six users 19% experienced problems when the motion sensor stopped tracking their hands and had to re-initialize the scenarios. This happened in both sessions, 4 times with the wearable device and 2 times without it. One of these users found a workaround to initialize the identification of the hands in runtime by inserting and removing spontaneously both hands in the detection area. Three users stated that they preferred the vibration feedback generated from the motor located in their palm while others showed no preference. Most users 65.6% preferred transient vibration events (short-lived vibrations) compared to continuous events while most users 84.5% proposed to implement a calibration mechanism for the vibration intensity, something we implemented in later versions.

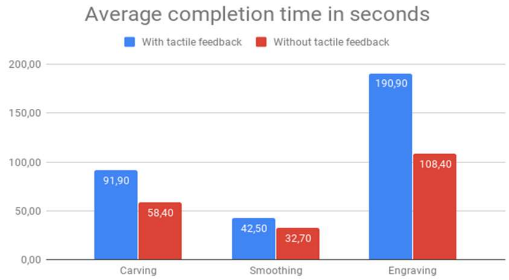

Fig. 6. Results of the comparative study of the average time taken to complete tasks, with and without haptic feedback, in seconds.

Design Considerations after the evaluation.
The results of the experiment were positive in terms of adding the wearable device to this system. Things to improve include, the improvement of the haptic textures related to the scenarios, the introduction of a better calibration mechanism of the haptic feedback intensity depending on user preference and finally the actual re-design of the physical wearable device to afford a better leap sensor detection, left handed users and the possibility for multiple gloves for both hand support.

5 Conclusion and future work

This paper presented the research, design and prototyping of a vibro-tactile wearable device that adds haptic feedback when performing mid-air interactions. The role of vibro-tactile feedback has been extensively analyzed and similar commercial interaction systems and applications have been reviewed and presented. The wearable device was designed for complementing a VR sculpting application that incorporates mid-air interactions. The haptic feedback provided by the device, aims to simulate specific tasks related to the sculpting scenarios at hand.

The comparative study performed during the formative evaluation sessions, revealed the differences in the interaction between the original mid-air only application and the one enhanced with haptic feedback. We identified that the difficulty of understanding depth in the virtual environment in the first case was heavily improved when the haptic feedback was introduced with the wearable. User's perception of depth and the identification of the exact location of her/his hand in space was improved both in terms of actual performance based on metrics (time and accuracy) but also based on evidence acquired from interviews that captured usability and user experience (ease of use, cognitive overload in performing the tasks).

Moreover, an interesting finding indicated that the overall user's immersion was also enhanced because of the haptic feedback mechanisms. The majority of users stated that they better understood the sculpting operations they performed, they felt more confident in grasping, manipulating, and using the virtual tools as well as touching and exploring solid geometric objects in the 3D environment.

This work provided an initial starting point for further research in this area and set the basis for further investigation of other aspects related to the use of vibro-tactile feedback mechanisms in mid-air interaction. We currently perform a second comparative study related to the evaluation of workload when using or not mid-air haptic feedback mechanisms in tasks performed in virtual environments.

References

1. Attwenger, A.: Advantages and Drawbacks of Gesture-Based Interaction. Grin Verlag (2017).
2. Bruder, G., Steinicke, F., Sturzlinger, W.: To Touch or Not to Touch?: Comparing 2D Touch and 3D Mid-air Interaction on Stereoscopic Tabletop Surfaces. In: Proceedings of the 1st Symposium on Spatial User Interaction. pp. 9–16. ACM, New York, NY, USA (2013). https://doi.org/10.1145/2491367.2491369.
3. Spano, L.D.: Developing Touchless Interfaces with GestIT. In: Paternò, F., de Ruyter, B., Markopoulos, P., Santoro, C., van Loenen, E., and Luyten, K. (eds.) Ambient Intelligence. pp. 433–438. Springer, Berlin, Heidelberg (2012). https://doi.org/10.1007/978-3-642-34898-3_39.
4. Nguyen, V.T.: Enhancing touchless interaction with the leap motion using a haptic glove. Comput. Sci. (2014).
5. O'hara, K., Harper, R., Mentis, H., Sellen, A., Taylor, A.: On the naturalness of touchless: Putting the "interaction" back into NUI. ACM Transactions on Computer-Human Interaction (TOCHI). 20, 5 (2013).
6. Ernst, M.O., Banks, M.S.: Humans integrate visual and haptic information in a statistically optimal fashion. Nature. 415, 429 (2002).
7. Ernst, M.O., Banks, M.S., Bülthoff, H.H.: Touch can change visual slant perception. Nature neuroscience. 3, 69 (2000).
8. Ernst, M.O., Bülthoff, H.H.: Merging the senses into a robust percept. Trends in cognitive sciences. 8, 162–169 (2004).
9. Gepshtein, S., Burge, J., Ernst, M.O., Banks, M.S.: The combination of vision and touch depends on spatial proximity. Journal of Vision. 5, 7–7 (2005).
10. Lin, M.C., Otaduy, M.: Haptic Rendering: Foundations, Algorithms, and Applications. CRC Press (2008).
11. Maereg, A.T., Nagar, A., Reid, D., Secco, E.L.: Wearable Vibrotactile Haptic Device for Stiffness Discrimination during Virtual Interactions. Front. Robot. AI. 4, (2017). https://doi.org/10.3389/frobt.2017.00042.
12. Fogtmann, M.H., Fritsch, J., Kortbek, K.J.: Kinesthetic Interaction: Revealing the Bodily Potential in Interaction Design. In: Proceedings of the 20th Australasian Conference on Computer-Human Interaction: Designing for Habitus and Habitat. pp. 89–96. ACM, New York, NY, USA (2008). https://doi.org/10.1145/1517744.1517770.
13. de la Barré, R., Chojecki, P., Leiner, U., Mühlbach, L., Ruschin, D.: Touchless Interaction-Novel Chances and Challenges. In: Jacko, J.A. (ed.) Human-Computer Interaction. Novel Interaction Methods and Techniques. pp. 161–169. Springer, Berlin, Heidelberg (2009). https://doi.org/10.1007/978-3-642-02577-8_18.
14. Vogiatzidakis, P., Koutsabasis, P.: Gesture Elicitation Studies for Mid-Air Interaction: A Review. MTI. 2, 65 (2018). https://doi.org/10.3390/mti2040065.
15. Zhang, Z.: Microsoft Kinect Sensor and Its Effect. IEEE MultiMedia. 19, 4–10 (2012). https://doi.org/10.1109/MMUL.2012.24.

16. Carter, J., Fourney, D.: Research Based Tactile and Haptic Interaction Guidelines. In: GOTHI-05. p. 9 (2005).
17. Bicchi, A., Buss, M., Ernst, M.O., Peer, A.: The Sense of Touch and Its Rendering: Progress in Haptics Research. Springer (2008).
18. Salisbury, K., Conti, F., Barbagli, F.: Haptic rendering: introductory concepts. IEEE Computer Graphics and Applications. 24, 24–32 (2004). https://doi.org/10.1109/MCG.2004.1274058.
19. Freeman, E., Brewster, S., Lantz, V.: Tactile Feedback for Above-Device Gesture Interfaces: Adding Touch to Touchless Interactions. In: Proceedings of the 16th International Conference on Multimodal Interaction. pp. 419–426. ACM, New York, NY, USA (2014). https://doi.org/10.1145/2663204.2663280.
20. Mazzoni, A., Bryan-Kinns, N.: Mood Glove: A haptic wearable prototype system to enhance mood music in film. Entertainment Computing. 17, 9–17 (2016). https://doi.org/10.1016/j.entcom.2016.06.002.
21. Feng, Y.-L., Fernando, C.L., Rod, J., Minamizawa, K.: Submerged Haptics: A 3-DOF Fingertip Haptic Display Using Miniature 3D Printed Airbags. In: ACM SIGGRAPH 2017 Emerging Technologies. pp. 22:1–22:2. ACM, New York, NY, USA (2017). https://doi.org/10.1145/3084822.3084835.
22. PowerClaw, https://vivoxie.com/en/powerclaw/index, last accessed 2020/05/04.
23. Kim, M., Jeon, C., Kim, J.: A Study on Immersion and Presence of a Portable Hand Haptic System for Immersive Virtual Reality. Sensors. 17, 1141 (2017). https://doi.org/10.3390/s17051141.
24. Carter, T., Seah, S.A., Long, B., Drinkwater, B., Subramanian, S.: UltraHaptics: Multipoint Mid-air Haptic Feedback for Touch Surfaces. In: Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology. pp. 505–514. ACM, New York, NY, USA (2013). https://doi.org/10.1145/2501988.2502018.
25. Goodwin, K.: Designing for the Digital Age: How to Create Human-centered Products and Services. John Wiley & Sons (2009).
26. Benyon, D.: Designing interactive systems: a comprehensive guide to HCI and interaction design. Pearson, Boston (2013).
27. Partheniadis, K., Stavrakis, M.: Design and evaluation of a digital wearable ring and a smartphone application to help monitor and manage the effects of Raynaud's phenomenon. Multimed Tools Appl. (2019). https://doi.org/10.1007/s11042-018-6514-3.
28. Kordatos, G., Stavrakis, M.: Design and evaluation of a wearable system to increase adherence to rehabilitation programmes in acute cruciate ligament (CL) rupture. Multimed Tools Appl. (2019). https://doi.org/10.1007/s11042-019-08502-3.
29. Vosinakis, S., Koutsabasis, P., Makris, D., Sagia, E.: A Kinesthetic Approach to Digital Heritage Using Leap Motion: The Cycladic Sculpture Application. In: 2016 8th International Conference on Games and Virtual Worlds for Serious Applications (VS-GAMES). pp. 1–8. IEEE (2016). https://doi.org/10.1109/VS-GAMES.2016.7590334.