Master thesis

Thèse Haptique

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Contents

Abstract This thesis explores the development and integration of haptic feedback technologies to enhance the immersive qualities of digital interactions. Specifically, it investigates the three forms of haptic feedback: kinesthetic, thermal, and vibrotactile. The research aims to create enhanced and more engaging user experiences by bridging the gap between the physical and digital worlds.

Kinesthetic feedback is addressed by developing the ExoTouch haptic glove, which provides users with force feedback to simulate resistance and physical presence in virtual environments. The iterative design process led to several improvements, resulting in a more versatile and accessible device. Thermal feedback is examined by creating a thermal haptic vest that utilizes Peltier technology to simulate temperature changes. This allows users to experience environmental conditions such as warmth or cold in virtual reality scenarios. Finally, vibrotactile feedback is explored through a novel approach to transforming music into haptic sensations using a vibrotactile vest, providing users with an audio-haptic experience that enhances their connection to music.

The thesis addresses both the technical aspects and practical implementation challenges of these haptic technologies, highlighting the potential for each feedback modality to enrich digital interactions. Through the integration of kinesthetic, thermal, and vibrotactile feedback, the work contributes to the advancement of haptic systems. It demonstrates their ability to create more immersive and interactive experiences, with applications ranging from virtual reality to music and beyond.

1 Introduction

A trending subject in virtual reality (VR) research is the creation of truly immersive experiences. The immersiveness of an experience relies on convincing the user that what their senses are perceiving is real and forms a coherent whole. The more senses are stimulated during the experience coherently, the more challenging it becomes for the user to detach from the virtual world. Currently, the two most extensively exploited senses in VR are sight and hearing, typically through flat displays (such as screens and projections) or headsets that provide stereoscopic 3D vision.

The following critical sense to enhance VR immersion is touch [1]. Thus, in this work, we focus specifically on the domain of haptics.

Haptics refers to technology that transmits and reproduces touch sensations through electronic and mechanical means. It allows users to perceive tactile sensations, such as vibrations, movements, or forces, generally within an interactive user interface context, such as video games, robotics, or virtual reality. The goal of haptic technology is to enrich user experiences by adding a tactile dimension to digital interactions.

Haptic feedback can be categorized into three major types: kinesthetic feedback, vibrotactile feedback, and thermal feedback. Kinesthetic feedback represents the weight, forces, or shape of the object the user interacts with, providing a sense of physical presence and resistance. Vibrotactile feedback conveys the texture and vibrations that occur during contact between an object and the user, which are perceived by receptors in the user's skin. This type of feedback is crucial for conveying surface qualities and subtle interactions. Thermal feedback represents the temperature of virtual objects, adding realism by simulating the thermal properties of different materials.

This thesis falls within the virtual reality and human-computer interaction research domain, explicitly focusing on haptic technology. The aim is to bridge the gap between the physical and digital worlds by incorporating touch sensations into virtual experiences. By exploring kinesthetic, vibrotactile, and thermal feedback, the research seeks to enhance the immersive qualities of VR systems, making them more convincing and engaging for users. This interdisciplinary approach combines aspects of engineering, computer science, and perceptual psychology to develop and evaluate novel haptic systems for VR applications.

This thesis addresses the challenges involved in designing and implementing hardware and algorithms for kinesthetic, vibrotactile, and thermal feedback in virtual reality. It aims to understand how these technologies can individually contribute to enhancing the immersive experience, focusing on both technical solutions and their effectiveness in improving user interaction within virtual environments.

The present study explores these haptic modalities within VR applications, focusing on technical aspects and practical implementation challenges. Specifically, kinesthetic feedback is addressed through the development of Exotouch DIY force-feedback gloves inspired by the Lucid Glove, offering force feedback to simulate resistance and physical presence. Thermal feedback is investigated by creating a thermal suit prototype for VR that employs Peltier modules to create temperature variations, thereby simulating the thermal sensations of virtual objects. Vibrotactile feedback is examined through a vibrotactile haptic vest coupled to an algorithm that converts music into haptic sensations, enabling users to experience audio-driven vibrations in a tactile form.

These approaches represent promising directions for integrating touch and temperature sensations into virtual reality. To further understand the potential of these technologies, we will first examine the current state of research in this field.

State of the Art in Haptic Technologies for Virtual Reality

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2.1 Force-Feedback and Vibrotactile Haptic Systems

Tactile haptic devices for virtual reality encompass a variety of technologies designed to enhance user immersion through the sense of touch [2]. These devices can be broadly categorized into two main groups: force-feedback systems and vibrotactile devices [3]. Force-feedback systems, such as robotic arms and exoskeleton gloves, provide physical sensations like resistance, weight, and force, realistically simulating the interaction with virtual objects. These devices rely on actuators to generate forces that mirror the behavior of real-world objects, allowing users to perceive properties like hardness and inertia. On the other hand, vibrotactile devices focus on delivering high-frequency and low-frequency tactile sensations that replicate surface transients (micro-vibrations produced when we touch an object). This group includes wearable devices such as gloves, vests, and other accessories equipped with small actuators that produce vibrations to mimic the tactile feel of virtual surfaces. Together, these two types of haptic feedback systems—force-feedback and vibrotactile—work in synergy to provide a more comprehensive and immersive virtual reality experience. Despite their promise, these technologies face hardware complexity and cost challenges and ensure a balance between realism and user comfort, which are active areas of ongoing research.

2.1.1 Overview of Wearable Haptic Devices for Virtual Reality

Wearable haptic devices for virtual reality have gained significant attention as they offer the potential to create more immersive and interactive experiences by simulating the sense of touch. These devices provide tactile and force-feedback sensations, allowing users to engage with virtual environments realistically. The state of the art in wearable haptic technology includes a range of approaches, each designed to enhance user experience by incorporating a combination of kinesthetic and cutaneous feedback. The rapid evolution of wearable haptics is primarily driven by advancements in actuation technologies, miniaturization, and a growing interest in VR applications across various sectors, including entertainment, education, military, and healthcare [4].

A particular focus within wearable haptic technology is on force-feedback systems, specifically haptic gloves, which are crucial in delivering realistic interaction forces to users. Examples include exoskeleton-based gloves [5], which deliver precise force feedback to the fingertips using a series of elastic actuators inspired by human finger anatomy. Dexmo [6] presents an affordable and lightweight solution that captures hand movements and provides passive force feedback, making it suitable for a broader range of users. DextrES [7], a thin and lightweight haptic glove, utilizes electrostatic brakes to provide up to 20 N of holding force per finger, offering a balance between kinesthetic and cutaneous feedback. The MR glove [8] employs compact magnetorheological brakes, enabling significant torque feedback without the need for bulky remote actuators. SAM [9], a 7-degree-of-freedom portable arm exoskeleton, integrates local joint control to enhance the precision of virtual interactions. Additionally, LucidGloves [10], developed for affordability and accessibility, have been evaluated for suitability in medical education, indicating promising results for widespread use in extended reality environments.

Commercially available force-feedback gloves include HaptX [11] and SenseGlove [12], both delivering realistic force feedback to enhance VR interactions. Another notable example is the bHaptics TactGlove [13], which provides vibrotactile feedback using eccentric rotating mass (ERM) actuators, enabling tactile sensations for virtual interactions.

For wearable haptic technology involving the torso and the whole body, significant research has been conducted to develop vests and full-body suits that deliver either vibrotactile or force feedback or a combination of both. Examples of these systems include the Ilinx project [14], which is a multidisciplinary research effort that integrates vibrating actuators into garments to create a multisensory art installation involving sound, visuals, and haptics. Another study integrates tactile and thermal feedback in a multimodal virtual environment [15], enhancing the realism and user experience. The PA suit [16] provides high-resolution force feedback through pneumatic actuators to simulate strong collisions, such as the impact of an explosion, enhancing the sensation of presence in VR. The Synesthesia Suit [17], designed for a game called "Rez Infinite," offers an immersive embodied experience with vibrotactile sensations distributed across the body, enhancing the overall sensory integration of virtual experiences. Finally, the upper-body haptic suit developed for snake robot teleoperation [18] uses 40 vibrators to provide vibrotactile feedback corresponding to the movement of the snake robot, helping operators maintain spatial awareness in complex environments. These full-body and torso-focused systems demonstrate the potential of wearable haptics, both vibrotactile and force-feedback, to enhance immersion and realism in various VR applications.

Commercially, three leading solutions are implemented for wearable haptic feedback. The first is electrostimulation [19, 20], in which an electrical current is applied to the user's skin to stimulate muscles and generate haptic sensations. For vibrotactile vests, two primary solutions are available. The first type employs eccentric rotating mass (ERM) motors [21], which use an off-center mass to produce vibrations. This solution provides relatively strong feedback for the same power as other approaches but suffers latency due to the time needed for the motor to reach full speed. Additionally, ERM motors are limited to producing a single type of haptic sensation, typically described as a "buzz." The second type involves voice-coil actuators [22], which function similarly to speakers by using a coil and magnet to create vibrations on a surface in response to an audio signal. This approach, often called "HD Haptics," allows for a wide range of haptic sensations with higher fidelity. However, voice-coil actuators require significantly more power to produce the same feedback intensity as ERM motors.

2.2 Overview of Thermal Feedback in Virtual Reality

Thermal feedback for virtual reality (VR) has won increasing attention in recent years, with numerous studies exploring its role in enhancing immersive experiences [23]. Much of this research has focused on contact temperature feedback, which gives users the sensation of touching cold or hot surfaces. Notable examples include the "Thermal Display Glove for Interacting with Virtual Reality" and the "ThermAirGlove: A Pneumatic Glove for Thermal Perception and Material Identification in Virtual Reality" [24, 25]. These gloves have been used to investigate material identification based on temperature, demonstrating how temperature feedback can complement vibrotactile feedback to help users distinguish between different materials. For instance, while vibrations have been used to differentiate textures, the temperature can further inform users whether they are interacting with a cold surface, such as metal, or a warmer surface, like wood or plastic.

To enhance the design of thermal actuators and improve the understanding of thermodynamics in these interactions, models have been established to describe thermal exchanges between a finger and an object [26]. These models contribute to optimizing thermal feedback for VR, ensuring that the sensation provided is realistic and responsive.

In addition to the hardware that provides temperature feedback, other factors must also be considered. Research has shown that visual stimuli corresponding to thermal stimuli can enhance the overall temperature perception, making it more accurate [27]. Furthermore, external factors, such as a user's clothing, can significantly influence temperature perception [28]. These findings highlight the importance of a multisensory approach and environmental considerations when designing thermal feedback systems for virtual reality.

Various thermal rendering methods provide users with realistic temperature sensations in VR environments. These methods typically use thermoelectric devices, such as Peltier elements, which generate heat or cooling by transferring heat between two surfaces [29]. The response speed of thermal rendering can be enhanced by employing forced convection, which involves small fans to expedite the temperature change. Another common method involves fluid-based systems, where heated or cooled liquid is circulated through a wearable garment, allowing temperature to be evenly distributed across the skin. Furthermore, integrating adaptive control algorithms, which adjust thermal intensity based on real-time user feedback, has proven crucial in delivering consistent and comfortable thermal experiences. Additionally, chemical thermal rendering is a novel approach that delivers haptic sensations by applying liquid stimulants to the user's skin [30]. This method triggers distinct sensations such as tingling, numbing, stinging, warming, and cooling by using controlled doses of specific active ingredients. Implemented through a wearable patch, chemical haptics can provide a range of sensations, enhancing user immersion in virtual environments.

Peltier coolers, also known as thermoelectric coolers, operate based on the Peltier effect, which involves the transfer of heat between two conductive materials when an electric current is applied. These devices can be used to generate either heating or cooling effects, depending on the direction of the current. When applied to wearable technology, Peltier coolers create localized temperature variations that simulate thermal feedback. The simplicity of Peltier elements makes them particularly attractive for thermal haptic applications due to their ability to deliver both heating and cooling from a single compact unit.

The wearability of Peltier coolers presents unique challenges. Since human skin and ambient air are poor conductors of heat, Peltier coolers must operate within a highly resistive thermal environment, which impacts their efficiency. Advances have been made to improve their practicality for wearable use [31], including the development of flexible heatsinks [32] made from silicone elastomer, phase-change materials and graphite powder. These heatsinks are lightweight and durable, optimized to maintain effective heat dissipation while conforming to the body's movements. Additionally, wearable Peltier coolers have been designed to achieve efficient cooling with low power input [33], making them suitable for long-term applications in real-world settings, such as clothing or portable accessories. These innovations pave the way for more practical and effective on-body thermal management solutions, enhancing the immersive potential of thermal haptics in virtual environments.

2.3 Critique of the State of the Art and Definition of Research Objectives

The current state of the art in haptic feedback technology has made significant progress in recent years; however, several limitations hinder immersive experiences' full potential. Notably, one of the main areas for improvement is the lack of comprehensive full-body environmental feedback, which restricts the user's sense of presence and immersion in virtual environments. While various haptic devices exist, most are limited in scope, either providing feedback only to specific body parts (such as hands or feet) or focusing solely on one type of feedback, such as force or vibrotactile sensations.

Another critical weakness in the current research landscape is integrating multiple haptic modalities into a cohesive system that offers simultaneous feedback, including kinesthetic, thermal, and vibrotactile sensations. Most existing systems cannot deliver these types of feedback in an integrated manner, reducing the overall quality and coherence of the experience.

In response to these challenges, this research adopts a strategic approach to overcome these limitations. The primary objective is to develop haptic systems that extend beyond localized feedback, aiming for a more holistic approach that can provide full-body and environmental feedback. Several constraints are considered to achieve this, including the need for ergonomic, lightweight, and user-friendly devices that can be easily worn without hindering mobility.

The strategy also involves leveraging modularity in the design of haptic systems, allowing different feedback modalities to be combined and customized to suit specific applications. This modular approach not only addresses the need for scalability but also allows for future enhancements, such as integrating additional types of feedback or adapting the system for new use cases.

Ultimately, this research aims to contribute to developing more immersive, interactive environments by addressing the weaknesses of existing haptic technologies and offering a comprehensive solution that integrates kinesthetic, thermal, and vibrotactile feedback in a user-centric manner.

3 ExoTouch: Kinesthetic Haptic Systems for Virtual Reality

In this chapter, we will focus on one of the three main components of haptics: kinesthetic feedback. Kinesthetic feedback refers to sensations related to weight, force, and movement. In this chapter, we will explore kinesthetic feedback in detail, examining how it can enhance the interaction with virtual environments. Kinesthetic feedback is crucial in virtual reality (VR) as it allows users to feel the physical properties of virtual objects, such as their weight and resistance, which significantly enhances the sense of realism and immersion. Our project aims to develop a wearable force feedback exoskeleton that is affordable and accessible to do-it-yourself enthusiasts to bridge the gap between low-cost haptic devices like the Lucid Glove and high-end commercial solutions.

3.1 Developing a DIY Kinesthetic Feedback Exoskeleton for Volume Perception in Virtual Reality

The main goal of this work is to explore how we can provide a sense of volume and hardness in virtual reality through kinesthetic feedback. Feeling the physical properties of virtual objects, such as their size, shape, and resistance, is crucial for a realistic VR experience. To achieve this, we propose the development of a force feedback exoskeleton that can be built by an initiated do-it-yourselfer at an affordable price point of around 200€. It situates our device between the inexpensive Lucid glove and the costly commercial gloves, balancing cost and functionality. We plan to make it compatible with the Lucid Glove API, ensuring ease of use and integration with existing applications. The OpenGlove driver, which emulates a Steam hand controller, allows hand tracking in any game or application that already supports this type of controller. Our goal is to create a lightweight exoskeleton, allowing for extended wear. It will have a wireless autonomy of at least 2 hours, with the option for wired usage for longer sessions. Additionally, we aim to explore the potential of a do-it-yourself approach to make such advanced haptic devices more accessible to a wider audience.

3.2 LucidGlove prototype

To have a first contact with hand force feedback, we built the Lucid Glove [34], a cost-effective VR haptic glove that only requires potentiometers, servo motors, strings, and an ESP. It provided an excellent opportunity to experience force feedback in VR for the first time. Despite its merits, this prototype exhibited several significant limitations.

The Lucid Glove offers a low-cost entry point for force feedback in virtual reality, which makes it highly accessible to enthusiasts and

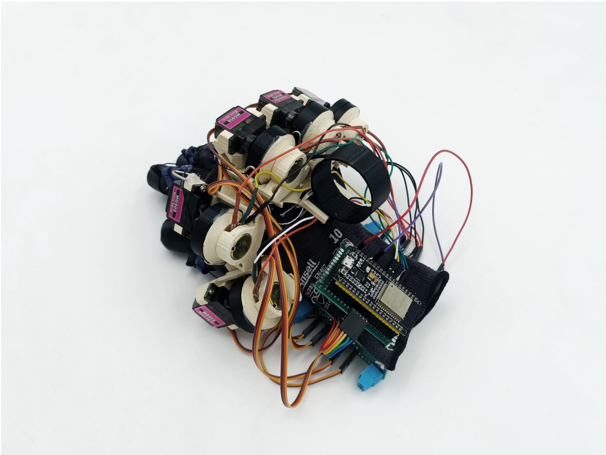


Figure 3.1: Packshot of the prototype Lucid Glove made at the DVIC

researchers. It allows for an initial exploration of kinesthetic feedback, offering users the ability to feel resistance when interacting with virtual objects. However, the Lucid Glove also presents notable drawbacks that limit its effectiveness as a robust haptic solution.

One of the major issues is related to hand tracking. The hand tracking is achieved through potentiometers linked to the strings that apply the force feedback. This approach induces errors due to the proximity of the servo motors and the limited precision of the potentiometers, which results in noisy data and reduces the overall accuracy of the glove. Additionally, the force feedback mechanism, which relies on small servo motors to block the spool of wire connected to the user's fingertips, must be more powerful. The servos take time to reach the desired position, leading to a lag in the haptic response. This latency means that the user's hand can often move beyond the intended stopping point before the servo engages, degrading the quality of the haptic feedback.

Another significant limitation is the general structure of the glove, which could be more convenient and efficient. The servo motors and spools are large, and the wiring needs to be tidier, contributing to a bulky glove that an external USB battery must power. Due to the high power consumption of the servos, the battery must be powerful, further adding to the weight and inconvenience. Additionally, the requirement to attach a headset controller to the back of the glove for 3D space tracking makes the glove even bulkier, resulting in a device that is challenging to use for extended periods. These limitations highlight the need for a more refined and user-friendly solution, which has informed the development of our ExoTouch project.

3.3 ExoTouch V1 prototype

The ExoTouch V1 is the first prototype of our haptic exoskeleton. This initial version aims to address the limitations identified in the Lucid Glove by offering a more refined, compact, and effective solution for delivering force feedback. The glove is developed with affordability, wearability, and modularity in mind, making it accessible to a broader range of users while maintaining functionality and ease of use.

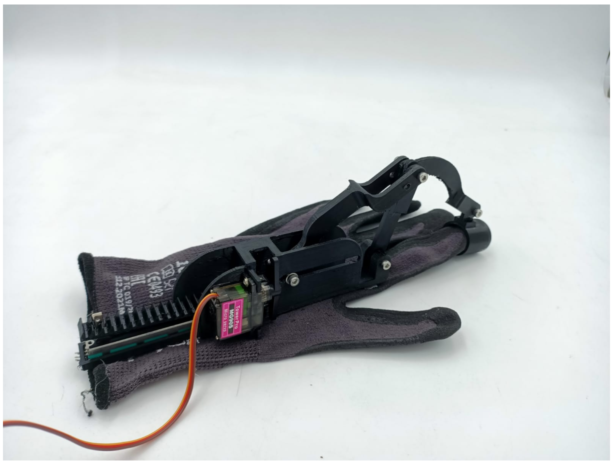


Figure 3.2: The second prototype of the ExoTouch, still under development.

3.3.1 Hand Tracking Solution

The hand tracking solution for ExoTouch V1 is a critical component that determines the device's accuracy and responsiveness. For this prototype, we chose to use linear potentiometers in combination with a lever arm mechanism to translate the circular movement of the user's fingers into linear displacement. This approach offers several advantages, including improved precision, adaptability to different hand sizes, and a compact design.

The lever arm system effectively converts the user's finger bending into linear motion, allowing the linear potentiometer to measure the level of finger flexion precisely. This design ensures smoother and more reliable tracking, which is crucial for maintaining hand movement detection accuracy and enhancing the virtual experience's realism.

The compact design of the lever arm mechanism also reduces the overall bulk of the tracking system, particularly on the back of the hand. It makes the exoskeleton more ergonomic and comfortable for extended use. By minimizing the footprint of the tracking system, we aim to create a wearable device that allows for natural movement and extended usage without discomfort.

The hand tracking solution also supports the ExoTouch design's modularity. Each finger module functions independently, simplifying troubleshooting, replacement, and potential upgrades. This modular design aligns with our goal of creating an accessible and customizable exoskeleton that can be assembled and adapted to meet individual needs.

3.3.2 Force-feedback

For this version, we opted for a binary force feedback mechanism, where the force is either fully applied or not. This decision was made

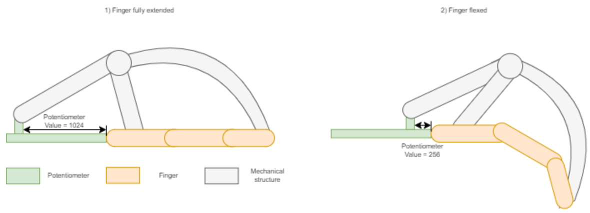


Figure 3.3: Diagram showing the structure that translates the circular bending motion of the finger to a linear motion on a potentiometer

to simplify the system's initial implementation and focus on testing the basic effectiveness of force feedback in a VR setting. The force feedback is applied using a servo motor that pushes a pin into a notched bar, thereby blocking either the retraction or extension of the fingers. This binary approach provides a straightforward means of simulating resistance, allowing users to experience a fundamental sense of object interaction in virtual environments. While this solution lacks the nuanced feedback of more advanced systems, it offers a reliable starting point for understanding and testing the impact of force feedback on user immersion and interaction.

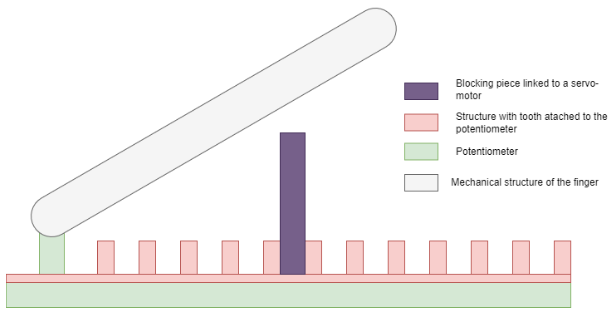


Figure 3.4: Diagram showing how a part linked to a servo motor will block a structure with teeth to immobilize the potentiometer and therefore the whole structure of the ExoTouch

3.3.3 Control board

The control board for the ExoTouch V1 is designed with compatibility in mind, based mainly on the existing Lucid Glove control architecture. This design decision ensures seamless integration with the OpenGlove solution, allowing for compatibility with various existing software and providing a robust platform for development. The control board includes an ESP-32 microcontroller, chosen for its wireless capabilities and ease of use. It is essential for communicating hand-tracking data and force-feedback commands to the VR system. This approach leverages existing, well-tested hardware and facilitates the development process by enabling interoperability and simplifying the transition from earlier prototypes to more advanced versions.

3.4 ExoTouch V2 prototype

Based on the findings from the development of ExoTouch V1, a second version was created to address several identified issues. The exoskeleton design was refined to reduce the footprint on the back of the hand, enhancing both ergonomics and usability. A new approach to force feedback was implemented, transitioning from a binary to a continuous force feedback mechanism for more nuanced interaction. Furthermore, the motherboard was redesigned as a fully functional printed circuit board (PCB) to improve the reliability and integration of the system's components.

3.4.1 Exoskeleton

For ExoTouch V2, the exoskeleton was redesigned, drawing inspiration from the work of Nick_Iacobbo [35]. The new design features a modular approach with individual components for each phalanx, enabling each segment to pull or push the adjacent one. This solution offers a balance between a wire-based design and a fully end-to-end exoskeleton, resulting in a more compact overall 3D footprint. Although the modules are slightly bulkier around the fingers, the reduced overall footprint allows the exoskeleton to conform more closely to the user's hand, making it more effective for interactions that require the use of both hands, such as holding a two-handed sword. The redesign also focused on making the structure lighter, incorporating a thumb module, and integrating the linear potentiometers directly into the structure to enhance the functionality and usability of the exoskeleton.

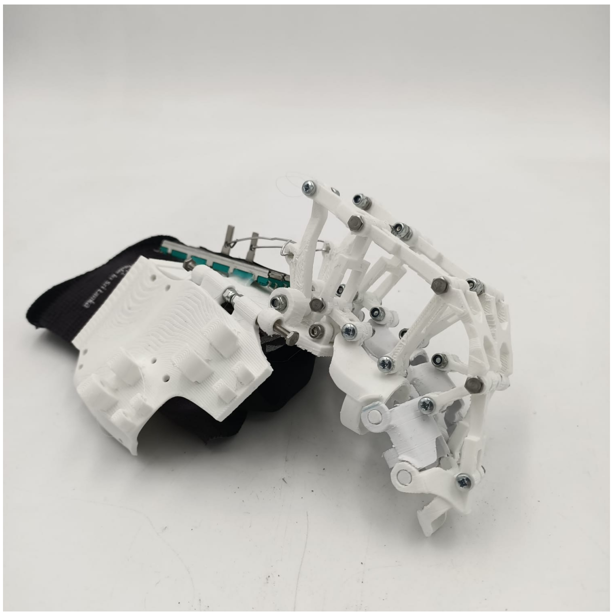


Figure 3.5: Two fingers of the ExoTouchV2 skeleton mounted.

3.4.2 Force-feedback

The force feedback system was redesigned to employ a mechanism similar to bicycle brakes. This new approach involves pressing two brake plates against the moving part of the potentiometer, thereby generating a friction force that restricts finger movement. A rubber coating was applied to the brake plates to enhance the restraining force, providing improved grip and stability. This method offers a more controlled and gradual application of resistance, contributing to a more realistic and immersive virtual reality experience.

In this method, the servomotors do not directly block the finger but instead, pull a string that adjusts the position of the brake plate relative to the moving part. A spring mechanism releases the plates when the servo stops pulling. Regarding bulkiness, the brake system requires some space;

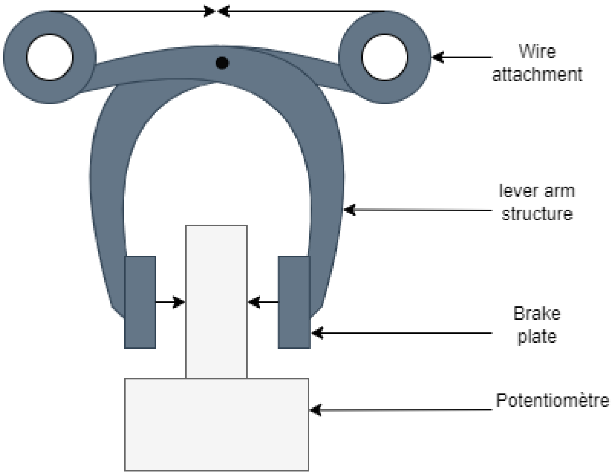


Figure 3.6: ExoTouchV2 brake diagram.

however, the servos, which can produce vibrations and cause unintended haptic sensations, can be mounted further away from the fingertips, such as on the forearm. This design choice helps reduce the exoskeleton's overall bulkiness while maintaining effective force feedback.

3.4.3 Control board

The control board was redesigned to enhance robustness and minimize size. It continues to utilize an ESP Wroom 32 microcontroller and features five dedicated connectors for potentiometers and five for servomotors. Additionally, the board includes an integrated power management circuit, allowing it to be powered by any 5V power bank. This redesign ensures improved durability and ease of use while maintaining compatibility with the existing hardware components.

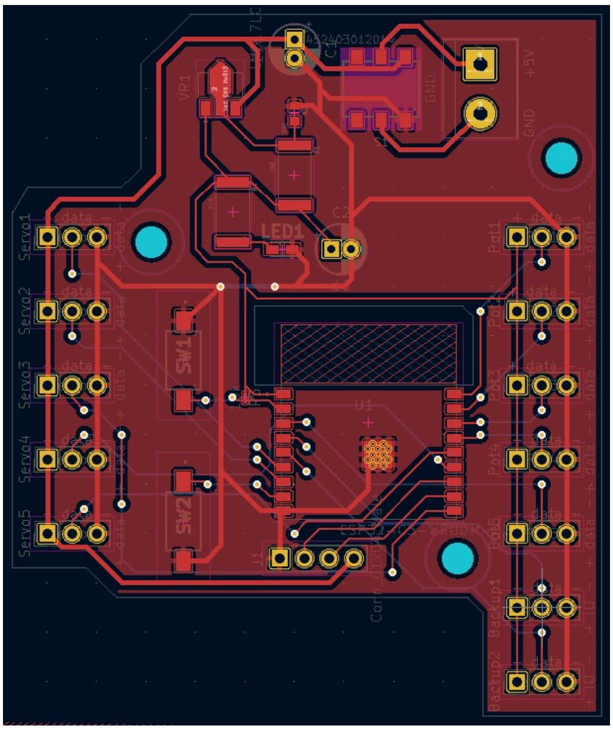


Figure 3.7: ExoTouchV2 PCB diagram.

3.5 Metrics

We will now discuss three critical aspects of the ExoTouch V2: the weight of the exoskeleton, the noise present in the input data, and the force generated by the force feedback system. These factors are essential to evaluate the overall performance and usability of the device, as they directly influence the user's experience, comfort, and the quality of the haptic feedback.

3.5.1 Weight Analysis of ExoTouch Gloves in Comparison to Existing Haptic Devices

The ExoTouch gloves weigh between 200 and 300 grams (240g for the V1, 290 for the V2). For comparison, the Lucid Glove weighs approximately 290 grams, while an exoskeleton utilizing MR brakes [8] weighs over 600 grams, and Dexmo [6] weighs less than 270 grams. Given these comparisons, ExoTouch V1 and V2 weights can be considered within an acceptable range when assessed against the current state of the art. However, it is important to acknowledge that wearing 300 grams on each hand for an extended period can lead to user fatigue, which remains a consideration in further refining the exoskeleton design.

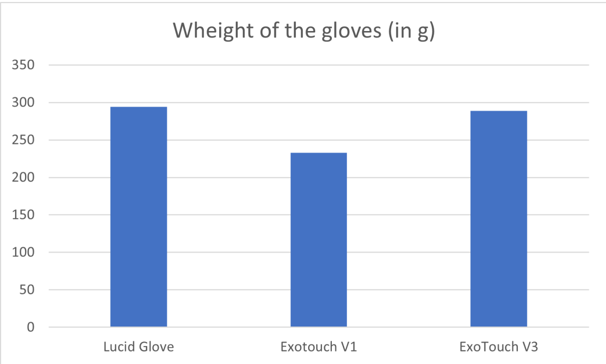


Figure 3.8: The weight of the gloves

3.5.2 Noise Evaluation in Potentiometer Data for Haptic Gloves

We introduce this metric to evaluate the impact of noise in the potentiometer data, which is a critical concern for ensuring smooth and realistic hand representation in VR. Excessive noise can lead to visual instability, causing the virtual hand to shake or necessitating significant signal filtering, increasing system latency.

To assess the noise levels, the gloves were placed on a flat table, and data was collected using the Arduino IDE's serial plotter. The deviation of the analog value was recorded to quantify the extent of the noise.

The ExoTouch gloves utilize an ESP32 microcontroller, which translates analog input using the *AnalogRead()* function into a value between 0 and 4095. For the Lucid Glove, the measured fluctuation was +/- 70, resulting in a noise range of 140, corresponding to 3.5% noise. In comparison, ExoTouch V2 fluctuated +/- 150, leading to a noise range of 300, or 7.5% noise.

Considering that a human fingertip typically moves through an angle of 180°, the noise level in the Lucid Glove corresponds to an angular deviation of 6.3°, while that of ExoTouch V2 corresponds to 13.5°. Such noise levels are sufficient to reduce the user's sense of immersion and can trigger false positives when detecting whether the user is interacting with an object. Consequently, it will be necessary to implement some form of signal filtering. However, given that the noise level is not excessively high, a light filtering approach can mitigate the noise without introducing significant latency.

3.5.3 Force Feedback Performance Analysis of Haptic Gloves

We assessed the force produced by the Lucid Glove and ExoTouch V2 for feedback. For the Lucid Glove, the force was calculated by multiplying the torque generated by the servo motors with the lever arm length. In the case of ExoTouch V2, we constructed a test stand to activate the feedback system. We then suspended various weights to determine the maximum load that the system could support.

Figure 3.9: The test stand for the force feedback of ExoTouch V2, with a servo motor and the haptic device

The results are as follows:

- LucidGlove: 1 Newton per finger
- ExoTouch V3: 2.3 Newton per finger

It can be observed that the ExoTouch V2 provides more substantial force feedback than the Lucid Glove. Additionally, unlike the Lucid Glove, which offers only binary (on/off) force feedback, the ExoTouch V2 can adapt the force feedback continuously within a range of 0 to 2.3 Newtons. This adaptability allows for a more nuanced interaction experience. It should also be noted that while ExoTouch V1 is equipped with a force feedback mechanism, it was not feasible to measure the force accurately, as it is dependent on the inherent rigidity of the plastic used in constructing the glove rather than a motorized system.

It is important to contextualize these figures. The average bending force of human fingers is approximately 70 Newtons, indicating that while these haptic gloves can provide force feedback, they are still far from delivering hyper-realistic sensations. Although effective for basic interaction, the force levels generated by these devices still need to achieve the strength required to replicate real-world object manipulation's tactile experiences fully.

3.6 Limitations and Future Enhancements of the ExoTouch V2 System

The ExoTouch V2 system exhibits several limitations that warrant further attention and potential improvement. One of the primary limitations lies in the strength of the force feedback, which may not be as powerful as desired. This limitation can significantly impact the overall immersion and realism of the haptic experience, especially when simulating interactions with objects that require a higher level of resistance.

Another notable limitation is the necessity of placing the controller on the back of the hand for hand tracking in space, which may be uncomfortable or impractical for some users. The additional bulk of the gloves also presents a challenge, potentially restricting the range of motion and making prolonged use cumbersome.

To address these challenges, several potential areas for improvement have been identified:

First, developing more powerful force feedback systems is critical for enhancing the user experience. This may involve exploring new types of actuators or control mechanisms capable of providing more substantial and precise feedback. Refining the material used for the brake plate, such as employing a silicone coating to increase friction, could also contribute to a more effective feedback mechanism.

The design of the glove itself presents another avenue for enhancement. By reducing the size and weight of the glove and investigating alternative form factors, it may be possible to create a more comfortable and ergonomic device suitable for extended use. Such improvements would likely contribute to a more immersive and user-friendly experience.

Additionally, exploring alternative tracking mechanisms that do not necessitate placing the VR controller on the back of the hand could further improve usability. Wrist-mounted or finger-mounted trackers, for instance, could help reduce the device's overall weight and make it more accessible to a broader range of users. reduce the overall weight of the device and make it more accessible to a broader range of users.

Finally, further user studies could provide valuable insights into the preferences and requirements of different user groups. Such evaluations would guide future development efforts and ensure the haptic gloves are optimized for their intended applications. Understanding user needs is crucial for refining design choices and enhancing the effectiveness of various features, ultimately leading to a more tailored and impactful haptic experience.

3.7 Conclusion

Our research on kinesthetic feedback through developing the ExoTouch haptic exoskeleton has demonstrated the potential for creating a more immersive virtual reality experience. The ExoTouch system helps bridge the gap between the real and virtual worlds, enhancing user interaction and immersion by providing users with a sense of resistance and movement. While the current implementation still has limitations, such as the force feedback strength and the overall bulkiness of the glove, these areas offer opportunities for future improvement. Moving forward, we plan to explore other forms of haptic feedback, specifically thermal feedback, to enrich the sensory experience of virtual reality environments.

Thermal Haptics in Virtual Reality | 4

In this chapter, we will focus on a second aspect of haptics: thermal feedback. Providing thermal sensations consistent with the virtual environment adds credibility and coherence to the user's experience. A virtual world set in the Arctic or in a scorching desert will not have the same impact if the user does not perceive a corresponding change in temperature.

Our research will focus on providing a global or environmental thermal feedback. Unlike much of the existing work, which primarily focuses on gloves that deliver localized thermal feedback on specific materials, our aim is to create thermal sensations that encompass the entire body. This approach will enhance the sense of immersion by simulating temperature changes that align with the user's environment in a more holistic manner. The work presented here is based on Peltier technology, which allows for precise and compact temperature control, effectively providing both heating and cooling capabilities.

4.1 Thermal System Design of the Mobile Cryo Capsule

To become familiar with Peltier technology, we developed a prototype of a novel type of "freezer". This project is a contribution to Solimán López's artistic initiative: Manifesto Terricola [36]. The concept of this project is to keep a block of ice frozen while maximizing the visible surface area. To achieve this, we designed a base with a cooling module beneath a double glass dome, which ensures thermal insulation of the structure. The Peltier technology was chosen to reduce both the size and noise levels, as traditional compressors produce significant noise and vibrations.

4.1.1 Principles and Characteristics of Peltier Modules

A Peltier module, also known as a thermoelectric cooler (TEC), is a thermoelectric device that operates based on the Peltier effect. The Peltier effect is a phenomenon where a temperature difference is created across a junction of two different conductive materials when an electric current passes through the junction. This effect results in one side of the module absorbing heat (cooling) and the other side releasing heat (heating). By reversing the direction of the electric current, the heating and cooling sides can be swapped, allowing for precise temperature control.

A Peltier module typically consists of multiple pairs of p-type and n-type semiconductor materials arranged between two ceramic plates. When an electric current is applied, electrons move through the semiconductor junctions, transferring heat from one side to the other. This

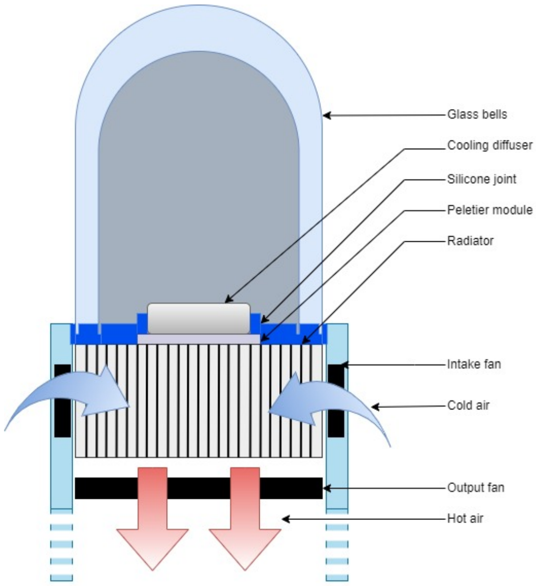


Figure 4.1: Working schematic of the the mobile cryo capsule

process makes Peltier modules highly effective for localized cooling or heating applications. The key advantages of Peltier modules include their compact size, lack of moving parts, and ability to provide both heating and cooling in a single device. However, they are generally less efficient compared to traditional refrigeration systems, as they require a significant amount of electrical power to achieve large temperature differentials.

4.1.2 Efficient Cooling Solutions with Peltier Modules

Understanding the operation of Peltier modules, the primary challenge in achieving effective cooling is reducing the temperature of the hot side. To address this, we opted for an air-cooling system inspired by computer heatsinks. The Peltier module is connected to a cylindrical heatsink using thermal paste to ensure good thermal conductivity. Surrounding this heatsink are eight small fans, each with a diameter of 4 cm, which push air from the outside towards the heatsink. The air then passes through the heatsink, cooling it in the process. Additionally, a 10 cm fan located beneath the heatsink extracts the air. This forced intake and exhaust system allows for efficient control of airflow.

We choose the peltier module TEC1-12715, a 12V 127W thermoelectric cooler. Its maximum temperature difference between the hot and cold face it advertised to be 67°C

4.1.3 Thermal Containment and Insulation Strategies

The next challenge in this project was managing the containment of the ice core. To ensure thermal insulation, two glass domes were used, one nested within the other. These domes were sealed with a molded silicone piece around their bases to prevent any air exchange. Additionally, the pressure between the domes was reduced to minimize convective heat transfer.

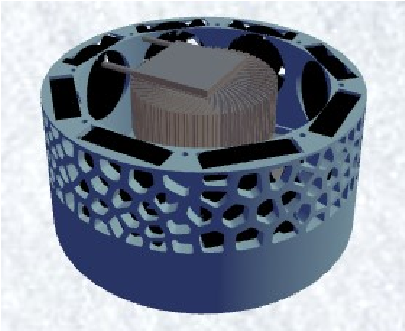


Figure 4.2: 3D render of the cooling base of the mobile cryo capsule

To achieve better thermal insulation and greater resistance to ice expansion, the glass domes were replaced with translucent acrylic domes. To ensure effective containment of the ice, an aluminum block was attached to the cold side of the Peltier module using water-resistant thermal paste. This allows for more efficient thermal energy collection from the ice, due to the increased surface area.

4.1.4 Design and Validation of the Cryo Capsule for Thermal Management

This structure allows us to maintain an ice block in a frozen state as long as power is supplied. The entire system is encapsulated within a light blue 3D-printed structure reminiscent of ice. The air intakes were camouflaged with a Voronoi pattern to create a more "natural" appearance.

Figure 4.3: Photograph of the mobile cryo capsule

To validate the functionality of the system, we first measured the temperatures of both sides of the Peltier module in a controlled environment.

The entire structure was assembled, and temperature probes were placed to monitor performance. One probe was positioned at the center of the heatsink, as close as possible to the hot side of the Peltier module, while another probe was placed on the cold side, in an atmosphere isolated from the external environment by the two domes.

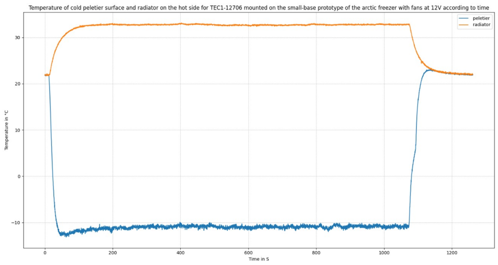


Figure 4.4: Temperature of cold and hot surface of a peltier module TEC1-12715 of the mobile cryo capsule

We observed that the temperature of the cold side rapidly dropped to -10°C (in approximately 30 seconds) and stabilized at that temperature throughout the experiment. The hot side took longer to reach its nominal temperature of 33°C. Thus, under normal operation, the temperature difference between the two sides of the thermoelectric module was 43°C. The difference between the theoretical 67°C temperature differential of the module and the measured difference can be explained in several ways. First, variations may exist between individual Peltier modules, as the uncertainty of the nominal temperature difference is not specified. Additionally, the temperature probe on the hot side was not directly attached to the hot surface; the heat had to pass through the thermal paste and a portion of the heatsink.

As a final test, we used the system to freeze water, a task that requires significantly more energy than maintaining ice at a sub-zero temperature. We successfully froze 100 mL of water at 22°C in 2 hours, demonstrating that our system effectively removes more energy from the environment within the dome than is introduced through external losses.

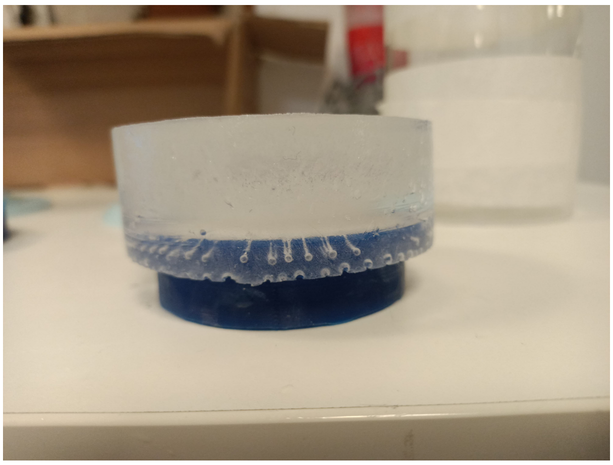


Figure 4.5: Ice cylinder produced by the mobile cryo capsule

4.2 Development and Implementation of the Thermal Haptic Vest

Building on the knowledge gained from the Mobile Cryo Capsule project, this initiative aims to develop a prototype for providing environmental thermal feedback. The objective is not to create abrupt temperature changes, but rather to recreate the ambient temperature values of the environment in a holistic manner. If the user is in a snowy environment, the goal is to provide a sensation of cold, while in a desert environment, the goal is to generate a sensation of heat.

4.2.1 Modular Thermal Module Design for Haptic Vest

To realize this project, we adopted a modular approach. Each temperature module must be independently controlled and powered to ensure interchangeability. In this section, we will discuss the thermal module that will be replicated to create the haptic vest.

At the core of our thermal module is a Peltier element. Specifically, we selected the 12V DC TEC1-12706 Peltier module, which has a power rating of 51.4W. This module offers a good balance between power and safety; a module that is too powerful could potentially harm the user in the event of a control failure. To drive this module, we used an L298N dual H-bridge driver. This driver supports a voltage range from 5 to 35V, which makes it suitable for our 12V requirements. The maximum current per channel of the driver is 2 amperes, so we connected both channels of the driver to a single Peltier element to achieve the required 50W power. Each Peltier element is controlled by a dedicated L298N driver, which allows precise control over the power supplied to the Peltier element as well as the direction of the current, enabling both heating and cooling of the user-facing side of the module. Each thermal module is equipped with an Arduino Nano to control the L298N driver.

To provide a quick visual indication of the module's status, four colored LEDs were added. The yellow LED illuminates when the module is powered. The green LED lights up when the module is idle, meaning that it is neither heating nor cooling (this may occur when the module is at the target temperature within a tolerance of one degree, or when no command has been given). The red LED is activated when the module is heating, indicating that the target temperature is higher than the current temperature of the module. Finally, the blue LED lights up when the module is cooling, indicating that the target temperature is lower than the current temperature of the module.

To maintain a constant temperature on the reference side of the module (i.e., the side not in contact with the user), we initially used a small heatsink and a 4 cm x 4 cm fan. This solution allowed for a truly modular system, with only the power supply shared across the modules. However, these small fans were not powerful enough and produced excessive parasitic vibrations, which could negatively affect the user's haptic experience.

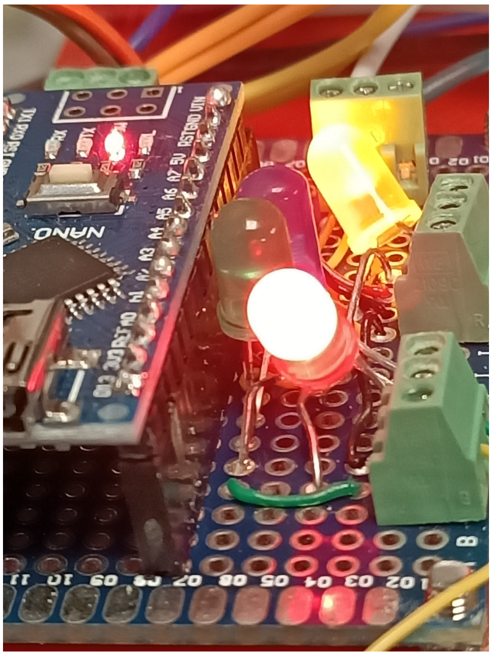


Figure 4.6: Activity LED indicator of the thermal haptic suit

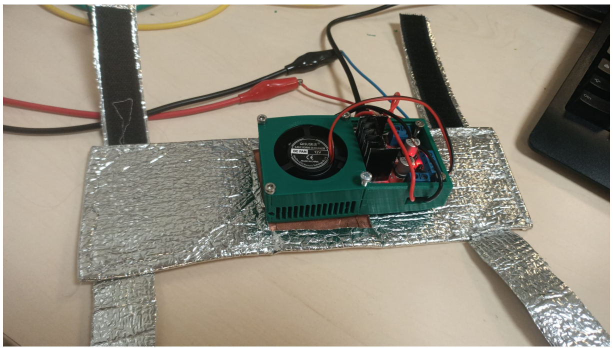


Figure 4.7: First full version of a thermal module of the thermal haptic suit with integrated fan cooling

Consequently, we decided to delegate the cooling to a single large heatsink, equipped with three 120 mm fans mounted on the back of the vest. These large fans operate at lower speeds, allowing them to dissipate a substantial amount of heat while minimizing noise and vibrations. To connect the thermal modules to the back-mounted heatsink, we chose a water-cooled thermal bridge. The use of flexible tubing and a circulating water flow enables efficient heat transfer from the thermal modules to the central heatsink without significantly restricting the user's range of motion. Although the pump used for circulating the water inevitably generates some vibrations, efforts were made to mitigate these effects by using foam dampeners and placing the pump in the back of the vest, thus reducing any adverse impact on the user.

On the user-facing side, we opted to diffuse the cooling or heating through a copper strip covered with a copper-infused fabric. The copper strip serves to distribute the desired temperature quickly over a larger area than the 4 cm x 4 cm surface of the Peltier module. The copper-infused fabric provides protection to the user, preventing cuts or discomfort that could arise from prolonged contact with semi-rigid metal surfaces.

Figure 4.8: Back radiator of the thermal haptic suit

To achieve the desired temperature, a simple proportional control was implemented. As long as the temperature difference exceeds 10°C, the Peltier module operates at full power. When the temperature difference is smaller, the power supplied to the Peltier module is reduced. Once the Peltier module reaches the target temperature, it is maintained at 30% of its power to slow down any heating or cooling. The system's response time is sufficiently slow, resulting in an average overshoot of approximately 2°C.

4.2.2 Communication and Control Architecture

To manage all the thermal modules, we developed a modular solution that allows for adding or removing modules without modifying the code. Within the vest, all modules are connected in an I2C network, controlled by an ESP32 microcontroller acting as the network master. Each module functions as a slave with its own unique address. During the initialization of the vest, the master ESP32 establishes the I2C network and identifies all the connected slave modules. The master ESP32 then continuously queries each slave to retrieve its temperature. When a temperature command is received, the master ESP32 communicates the corresponding command to the appropriate module.

For communication between the user's computer and the vest, we implemented a WiFi bridge between the ESP32 in the vest and another ESP32 connected to the PC via USB. The application on the computer communicates via USB serial with the ESP32, referred to as the base station. The base station generates a private WiFi network to which the vest connects. Each ESP32 hosts an HTTP server to handle HTTP requests. The base station receives requests regarding the temperature settings for the modules, while the vest receives commands to adjust the temperature of the modules accordingly.

The choice of a WiFi bridge between the two ESP32 devices ensures reliable and stable communication. We opted for a wireless solution to reduce the number of cables connected to the vest, thereby enhancing user comfort and mobility.

4.2.3 Performance and Safety Evaluation of Thermal Modules

To evaluate the capabilities of the vest, we constructed two thermal modules. The Peltier element, at full power, is capable of reaching temperatures as low as 0°C and as high as 50°C. To ensure user safety, a software limitation has been implemented to prevent the temperature from dropping below 10°C or exceeding 40°C. Even if a higher command is given, the modules will not allow the temperature to go beyond the safe limits. In the event that the temperature does exceed these boundaries for any reason, the ESP microcontroller in the vest enters a safety mode and halts all operations except for the water cooling system.

Regardless of the command given to the modules, all of them are able to reach their target temperature within a tolerance of ±1°C in under 30 seconds. The greater the initial temperature difference, the longer it will take for the module to reach the desired temperature.

Now that our solution has been validated with two modules, the next steps involve fabricating the remaining modules and integrating the vest into a virtual reality application. This will allow us to assess the vest's ability to enhance the immersive experience by providing thermal feedback that corresponds to the virtual environment. Future work will also include optimizing the ergonomic design of the vest to ensure comfort during extended use. We will also investigate the integration of more advanced control algorithms to improve the responsiveness and stability of the thermal modules, potentially incorporating adaptive feedback mechanisms that respond dynamically to user interactions within the virtual environment.

4.3 Conclusion

In conclusion, this chapter has explored the design and development of a thermal haptic vest aimed at enhancing user immersion through environmental thermal feedback. By leveraging Peltier technology, we successfully created a modular solution capable of generating temperature sensations that reflect virtual environments, whether they be cold, like a snowy landscape, or warm, like a desert. Our work has validated the feasibility of providing localized temperature modulation in a wearable format, allowing users to experience a deeper sense of presence within virtual settings. We also addressed critical aspects such as safety measures, control system integration, and the scalability of the thermal modules.

Looking ahead, our future efforts will focus on refining the vest's ergonomic design and conducting extensive user studies to assess the effectiveness of thermal feedback in enhancing VR experiences. The next chapter will shift focus to another aspect of haptics: vibro-tactile feedback. Specifically, we will explore how music can be transformed into haptic feedback, providing a unique way to feel sound through the use of wearable devices. This new approach aims to further expand the sensory dimensions of virtual environments, allowing users to not only see and hear but also feel the rhythm and vibrations of music.

Music to haptic | 5

In the previous chapters, we saw different methods for producing haptic feedback to the user. Now, we will reflect on the creation of haptic content. Just as the screen is useless without the image we want to display on it, our haptic devices need a signal to provide feedback to the user. Here, we will focus on creating a haptic signal for music haptization to provide a sensory experience when listening to music. We will experiment using Actronika's Skinetic vest [22] as haptic hardware.

Hearing sound while feeling associated with haptic feedback is a common sensation during concerts (either loud pop concerts or more calm ones) [37]. Sometimes, the haptic sensations are very weak, and sometimes, rock kicks blast through the bones, but this haptic component is always a great part of the concert experience compared to listening to music with headphones.
We will propose a processing pipeline to transform simple stereo music into a haptic experience, allowing users to feel the music even with headphones.

5.1 Constraints and Advantages of Haptic Signals

Like every other communication channel, haptics need a signal to give information to the user. In this context, a signal refers to a temporal sequence of one or more values that vary over time, which may be discrete or continuous. These values convey the information or message the device intends to communicate to the user.
One good example is the sound signal, represented by one continuous value oscillating and thus forming the sound we hear. We can also think of the RAW image format; this signal has multiple values, one for each picture's pixel.

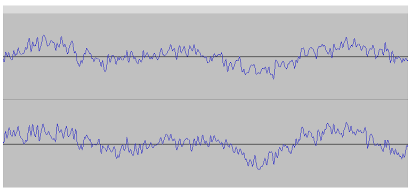


Figure 5.1: Screenshot of the Audacity software, representing an extract of the waveform of the music "BladeRunner" by Beast In Black

We will focus our research on vibrotactile haptics, as there can be multiple haptic vectors. Different methods are available to provide vibrotactile feedback; here is a non-exhaustive list:

- The electrodynamic vibrating actuators: The speaker is a typical example of an electrodynamic actuator. A permanent magnet interacts with a coil, which transfers its movement to a diaphragm. This diaphragm creates mechanical vibrations and, as a result, sound waves by changing the pressure of the surrounding air. If the diaphragm has a certain weight, any object touching it will perceive the mechanical vibration.

- Piezoelectric Actuators: Piezoelectric materials are relatively recent and continuously evolving. They are available in ceramic or polymer materials and have the property of deforming when an electric field is applied.
- Eccentric Mass Motors: This type of actuator rotates a mass whose center of gravity is offset from the center of rotation, producing a rotational acceleration around the axis of rotation.

Every feedback-providing method has its advantages and defaults. It can be feedback strength issues, power consumption, signal precision...
We need to provide precise haptic feedback for our work here, but not necessarily a strong one. The hardware proposed is a vest composed of 20 electrodynamic vibrating actuators placed on the user's torso. The signal is a 20-channel audio signal on the norm PCM16 to drive these actuators. This uncompressed format represents the amplitude values on a 16-bit depth, the standard bit depth for CD audio. The sample rate we used is 48KHz.

5.2 AI and Signal Processing for Music-Driven Haptic Feedback

Just as sound with images helps the user understand what is shown to him, haptic can improve the user's perception of the music. In the rhythmic aspect of music, haptics reduces the minimum difference required for two distinct rhythms to be differentiated [38]. Some experiments have been made to augment audio notifications (such as when pressing a key on a smartphone) and music with haptics on phones. Users tend to prefer having haptic feedback with the audio and are less demanding on the audio quality [39, 40].
On our hardware (the Skinetic vest), some work has been released for real-time audio to haptics, taking the sound input, filtering it and playing the filtered version on the vest [41]. However, this algorithm does not spatialize the audio on the vest; every actuator plays the same signal.

Our work here will focus on separating the music's sources (different groups of instruments), finding the best filters for each group of instruments, and spatializing the haptic on the vest.

The program has three main parts. First is the track separation: because each component of a song doesn't need the same processing, we separate the music into four different tracks (drums need sharp and powerful haptics, whereas vocals need something more soft for example). Then, each stereo pair of tracks (bass left and bass right, for example) goes through a series of filtering and signal processing fine-tuned for each track. Finally, we merge our four haptized tracks into one 20-channel audio file, where the tracks are played in channels corresponding to their spatialization on the torsoe.

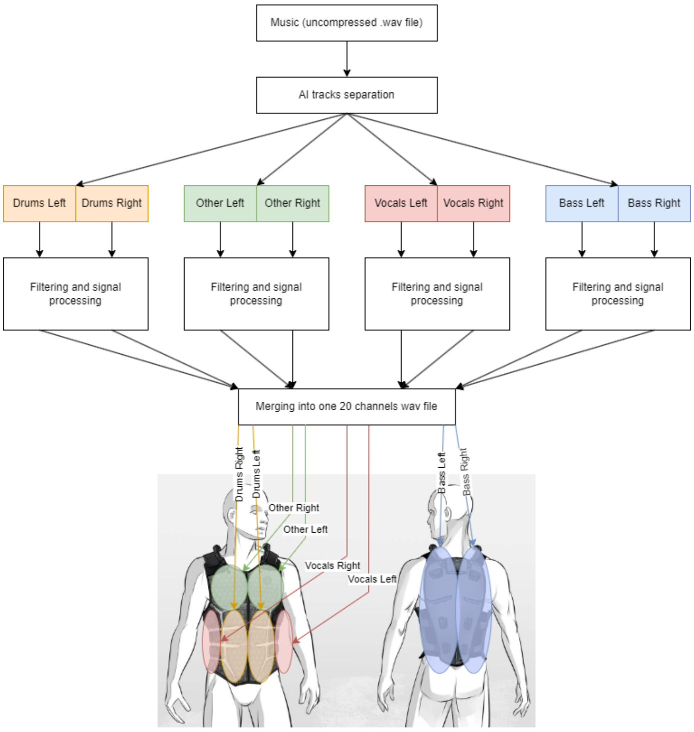


Figure 5.2: Processing pipeline of a Music to Haptics programm.

5.2.1 Tracks separation

The first step of our processing pipeline is to separate tracks. Music comprises different groups of tracks; the most standard ones are drums, bass, vocals and lead. The need for track separation comes from the fact that haptic feedback should not feel the same between discrete and continuous signals or signals of different frequencies.
To separate the tracks, we used an implementation of the Demucs music source separation AI by Facebook-research [42, 43] with the latest model Demucs (v4).

5.2.2 Filters

To translate the music into haptics, we used a series of filters. The main challenge of this process was to extract all the interesting features of the sound, even if they are on the low or high range of frequencies, and translate them into low-frequency signals with less audible components possible. The theoretical lowest frequency the human can hear is 20Hz, but in reality, we can go higher in frequencies without disturbing the user's experience. Here, we will describe each filter and then specify which ones were used on each track.

- The most basic filters used were *high-pass* filters and *low-pass* filters. These filters are used to cut off unwanted frequencies in the signal. As their names say, the high-pass filter cut low frequencies, and the low-pass filter cut high frequencies. These two filters have the same parameters: the cut-off frequency (the frequency at which the filter starts taking action) and the order (the higher the order, the more sharp the filter is).
- We then have band-pass filters that can be seen as merging a low-pass and a high-pass filter. These filters have three parameters: the

low cut-off, the high cut-off and the order.

- We also have a transient shaping filter. This filter is used to manipulate the transient components of an audio signal independently from its sustained elements. Transients are the initial peaks or sudden changes in a sound, such as the attack of a drum hit, the pluck of a string, or the consonants in speech. The principal step of this filter is to detect the attacks (where the amplitude of the sound rapidly increases from silence -or a low level- to its peak level). We first determine the attack samples by sampling the audio into small chunks of a certain time, allowing us to determine if there is an attack in this time window. We then use a high-pass filter to detect sharp transients.
  After that, we calculate the envelope where the volume is higher on the attack and lower on the rest. We then apply a gain based on the envelope max value and the filter's intensity.
  With these steps, the audio tracks have amplified attacks and attenuated sustain.
- We then have a pitch-shift effect, shifting down or up the signal frequencies.
- At last, we have a Hilbert envelope calculation to extract the signal's envelope using the analytical signal. The analytical signal is a complex signal composed of the original real signal and its Hilbert Transform as the imaginary part. The envelope represents the instantaneous amplitude (magnitude) of the signal over time, which can be obtained by taking the magnitude of the analytical signal:

$$Envelope(t) = ||AnalyticalSignal|| = \sqrt{x(t) + (HilbertTransform(x(t)))}$$

These filters were applied in different orders and with different parameters for each of the four pairs of tracks.

The bass track was first processed into a low-pass filter with a cut-off frequency of 80Hz and an order of 5. This first filter removes all artifacts from the track extractions and gives us a clean bass track. We then apply a transient-shaper with an intensity of 4 and an attack sample time of 4ms. This processing allows amplifying bass changes, making them more perceptible and increasing the track's clarity in the case of plucked bass. We then apply a second low-pass filter with a cut-off frequency of 150Hz and an order of 7. This removes all potential artifacts created by the transient shaping filter.

The drums are first filtered into two sub-tracks. We filter once with a band-pass filter between 10Hz and 100Hz with an order of 4 to select the kicks. We then filtered the main track again with a band-pass filter between 200Hz and 1100Hz, with order 4 to select the snares. These two sub-tracks are then merged into one track by simple addition. We then apply a transient-shaper with an intensity of 8 and an attack of 3ms. We then apply a pitch shift of -12 steps (an octave) to bring back more frequencies into the haptic field (high snares and high hats). Finally, we applied a low-pass filter with a cut-off frequency of 150Hz and an order of 7 to remove the audible component of the track.

For the vocals processing, we started by shifting the pitch of -24 steps (2 octaves) to get the frequencies closer to the haptic field. We then apply a band-pass filter between 80Hz and 200Hz to select only the non-audible part of the track. Finally, we enhance the audio data dynamics by calculating the track's envelope using a Hilbert transform. The envelope is then multiplied by an intensity. The track is then multiplied by the boosted envelope. The result is a track where differences between loud and silent parts are greatly increased.

For the remaining track, the lead, we first apply a pitch-shifting of -12 steps (-1 octave). Then, we apply a band-pass filter between 10Hz and 300Hz with an order of 4 to select only events that can be felt through haptics; we then apply the envelope multiplication using the Hilbert transform, just as in the vocal processing. We finish with a low-pass filter with a cut-off frequency of 200Hz and an order 7 to remove any audible artifacts.

After processing all these tracks, an amplification is applied. The value of this amplification is not the same for each track and can be changed depending on whether we want a track louder or not (it's a fine-tuning option for the end-user).

5.2.3 Spatial Mapping

After processing the four pairs of tracks, we need to merge this into a single 20-channel wav file. The torsoe is quite a sensitive zone for haptics. With a spatial acuity of 3 to 1cm and it's position close to the nervous system [44], we can create very distinguishable zones for each tracks. The different body parts and their particularities do not respond the same way to haptic stimuli [45]. While soft body-parts such as the abdomen tend to resonate ans enhancing sharp haptic feedbacks, providing haptic stimuli near bones will propagate the vibration along the skeleton. The first spatial discrimination was stereo placement, tracks coming from the left-ear audio will be placed on the left of the user, same for the right-ear audio. Then, we will place the haptics feedback corresponding to their normal audio frequencies: Bass have a low frequency, their haptics will be placed on the bottom of the vest, the lead instruments are often high frequencies, their haptics will be placed on the top of the vest. Because unlike the music, all haptic tracks have mostly the same frequencies (the frequency panel of haptics before going into audible frequencies is very small), this second discrimination helps the user understand which haptics comes from wich part of the music. We then choose to spatialise the tracks like that:

- Drums: the drums were placed on the abdomen (left and right corresponding to the music's left and right tracks). Drums are discrete and sharp haptics. Placing this type of haptics on a soft body area make the kicks resonate, increasing the strength of the feedback. Also, in concerts with big kicks such as rock or electronic music, the kick feels like it strikes from the scene, it comes from forward.
- Bass: the haptics from the bass are placed on the back. Bass are the

root of the music, placing it on ther back allows the vibration to spread into the body through the spinal column. In concerts, bass haptics often comes through the ground, spreading in the body through the bones.

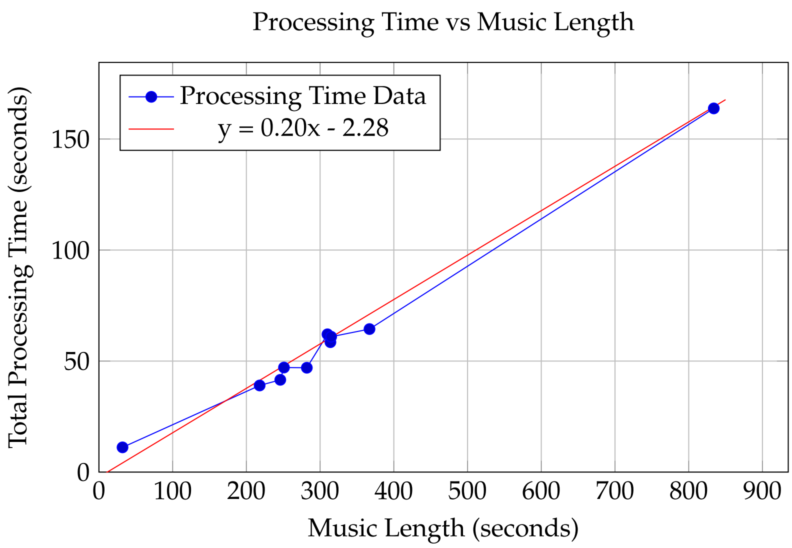
- Vocals: vocals haptics are the most modified haptic tracks. Because some music can have no vocals or moments with no vocals, we choose to place this tracks on the side of the torso, under the arms. This place do not feel empty when no vocals are played, but is very distinguishable when there are vocals in the music. With this location, the system works as great for instrumental musics as for musics with singers.
- Other: The remaining haptic tracks is places on the chest. Grouping all the different instruments that are on the middle to high-range frequencies of the music, this tracks are placed on the top of the vest. The rib cage spread a bit the vibrations, filling the space while making the link between the high-frequency drums and the kicks, and the lead instruments with the bass.

5.2.4 Evaluation Metrics

We have a few metrics we can analyse to determine the quality of our solution. We will first see the execution time of the pipeline and the incidence of each step in the overall time. Then we will analyse the quality of the solution with a frequency analysis, a Signal-to-Noise Ratio analysis, a Total Harmonic Distortion analysis and a dynamic range analysis.

To analyse the execution time of the program, we processed a few music files (n=10) of an average of 310.9 seconds. The shortest file was 32 seconds long, the longest one was 834 seconds long (STD: 192.74).
The processing was done on the same computer for all the musics. The machine was composed of a AMD Ryzen 7 2700 Eight-Core Processor at 3.42GHz, accelerated by an RTX 2080, 32G0 of ram at 1600MHz and completed by an SSD.

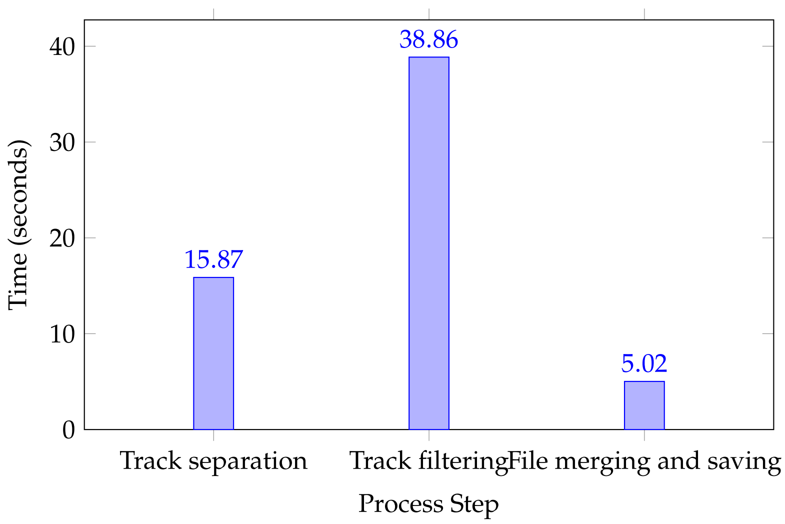
First we will look at the execution time related to the length of the audio file.



We can see that the processing time seems distributed proportionally to the music length. By using a linear regression we can deduce a model of the processing time:

$$\text{processing time} = 0.20 \times \text{music length} - 2.28$$

The three main steps of the processing pipeline (Tracks separation, Tracks filtering, Tracks merging and file saving) have different processing times.



We can see that the track processing is the heaviest step in the pipeline with an average of 38.86 seconds (STD: 27.08), followed by the track separation with an average of 15.87 seconds (STD: 6.87) and then the File merging and saving with an average of 5.02 seconds (STD: 3.97)

In the frequency analysis of the haptic spectrum, it is evident that the signal is predominantly concentrated in the lower end of the spectrum.

Frequencies above 300Hz show a volume lower than -51dB, which means that these higher frequencies are not effectively rendered by the haptic actuator. This suggests that the haptic feedback primarily operates in the bass or sub-bass frequency ranges, focusing on deep, low-frequency vibrations.

In contrast, the spectrum of the music is much more evenly distributed, with energy spread across a wide frequency range, from approximately 3Hz to 18kHz. The music spectrum covers the entire audible range, from the low frequencies that can be felt as vibrations, up to the high frequencies which are mostly perceived by the ear. Unlike the haptic spectrum, the music spectrum preserves the balance across all frequencies, allowing for a richer and more complete auditory experience.

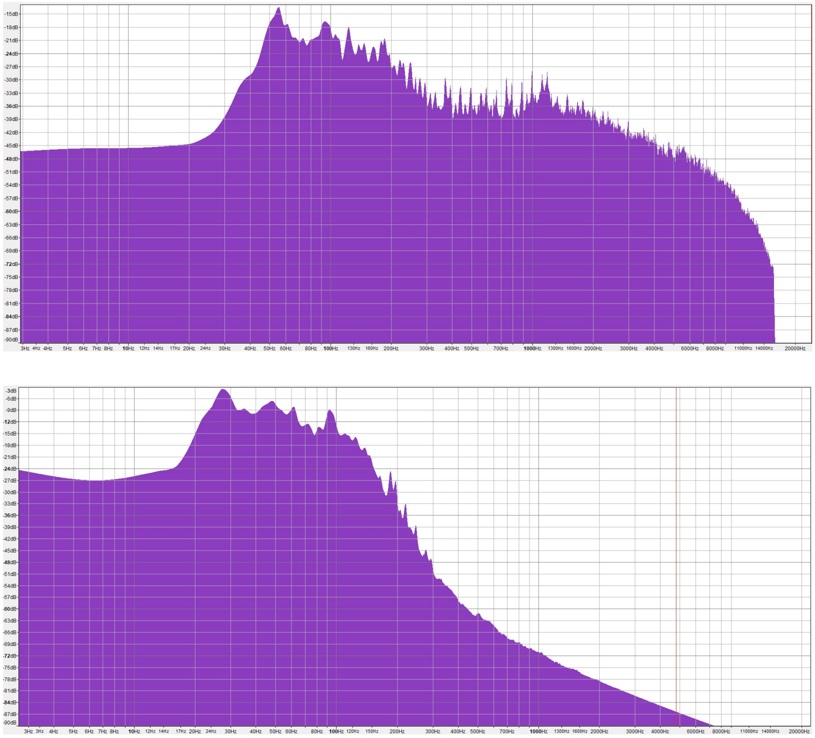


Figure 5.5: Audio Spectrum of the haptic track

5.3 Discussion and Future Work

The proposed solution processes audio files to generate haptic feedback through the application of track separation and specialized filtering methods. However, several limitations are evident in the current system. The primary area for improvement is processing time, as a non-real-time solution significantly reduces the system's adaptability by requiring the entire recording to be completed before processing can begin. While filtering can be performed nearly in real time, similar to many music production software applications, the main challenge lies in developing a track separation algorithm that operates with minimal latency. Recent advancements in artificial intelligence have introduced models capable of real-time processing [46], which could enhance the functionality and responsiveness of this pipeline.

Moreover, although this research primarily targets entertainment applications, the underlying technology holds potential for promoting inclusion in artistic events [47]. By providing an additional sensory modality, haptic feedback can enhance the experience for individuals with sensory impairments, such as those with hearing or visual disabilities, thereby increasing their immersion and engagement in artistic performances.

6 conclusion et discu

This thesis aimed to enhance the immersive experience of various digital interactions by exploring and integrating three forms of haptic feedback: kinesthetic, thermal, and vibrotactile. The overarching goal was to bridge the gap between the physical and digital worlds, making these experiences more engaging and lifelike by incorporating touch sensations. By focusing on different haptic modalities and leveraging state-of-the-art technologies, we developed a series of prototypes and systems that contributed to richer, more interactive environments.

The research began with kinesthetic feedback, exploring how force feedback could enhance the user's perception of physical properties, such as weight, force, and resistance, in virtual environments. Through the development of the ExoTouch haptic glove, we aimed to create an accessible and versatile solution for force feedback in VR. The iterative design process resulted in improvements from the Lucid Glove prototype to ExoTouch V2, addressing limitations such as feedback strength, weight, and usability. The ExoTouch V2 demonstrated the potential for creating an immersive kinesthetic experience, allowing users to physically interact with virtual objects and feel a sense of presence in the virtual world.

The focus then shifted to thermal feedback, investigating the role of temperature sensations in enhancing VR immersion. We developed a thermal vest, leveraging Peltier technology, to provide localized heating and cooling that corresponds to virtual environments. This approach allowed for the simulation of environmental temperatures, such as the cold of a snowy landscape or the heat of a desert, thereby enhancing the user's sense of presence and connection with the virtual environment. The thermal vest prototype was designed with modularity and safety in mind, ensuring effective temperature regulation while minimizing risks to the user. Future work will continue to refine the vest's ergonomic design and explore advanced control systems for more responsive and adaptive temperature feedback.

Finally, we explored vibrotactile feedback through the concept of "music to haptics." This project aimed to create a haptic experience that allows users to feel the music through a vibrotactile vest. By using AI-based track separation and filtering techniques, we successfully transformed music into haptic signals that could be spatially mapped onto the user's torso. The resulting system provided a unique multisensory experience, combining auditory and tactile sensations to enhance the user's engagement with music. While the current implementation has limitations, such as processing time and real-time capabilities, the approach demonstrates significant potential for applications in entertainment and accessibility, offering a new way to experience music for users with sensory impairments.

Throughout this work, we encountered challenges in designing and implementing the various haptic technologies, from the strength and precision of force feedback to the responsiveness of thermal control systems and the quality of vibrotactile feedback. Despite these challenges, the prototypes developed in this research have provided valuable insights into the potential of haptic feedback to enhance VR and flat screen experiences. Each modality contributes uniquely to the overall sense of immersion, highlighting the importance of multisensory integration in creating convincing and engaging virtual environments.

Haptic technology is increasingly transitioning from entertainment-focused applications to practical, real-world implementations. This trend is particularly evident in the automotive industry, where haptic feedback is integrated into steering wheels and seats to enhance driver awareness of their surroundings. Furthermore, initial work is being conducted to incorporate haptics into spacesuit designs [48]. Building on this trajectory, the next step for this field is to identify new applications for haptic technologies beyond entertainment. This shift will present new challenges, particularly in the seamless integration of these technologies into diverse practical contexts.

In conclusion, this thesis has demonstrated that haptic feedback, encompassing kinesthetic, thermal, and vibrotactile modalities, has the potential to significantly enhance the user's experience in virtual environments. By integrating touch sensations into VR, we bring the virtual closer to the real, providing users with a more holistic and immersive experience. As VR technology continues to advance, the inclusion of rich haptic feedback will be crucial in creating truly convincing virtual experiences that fully engage the user's senses and emotions.

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