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Executive Summary of the Thesis

Haptic Feedback and Embodiment in the Physical Metaverse: Exploring Proprioception and Body Ownership

Laurea Magistrale in Computer Science and Engineering - Ingegneria Informatica

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1. Introduction

In the dynamic landscape of the 21st century, the emergence of the Physical Metaverse signifies a transformative blend of digital and physical realities. Departing from the traditional Metaverse, this paradigm shift introduces non-humanoid physical avatars, prompting an exploration into the realm of non-verbal communication. The study's focal points encompass embodiment, haptic feedback, and non-verbal communication as key drivers. Embodiment [1] research into the seamless integration of a user's physical self with their digital presence, fundamentally altering the experience of virtual reality. Simultaneously, the investigation into haptic feedback devices seeks to enhance immersion by simulating tactile sensations, crucial for engaging the sense of touch in virtual environments. Non-verbal communication takes center stage, emphasizing its foundational role in interactions within the Physical metaverse, where entities may diverge from traditional human modes of expression. We focused on designing devices tailored for embedded haptic feedback, with the ultimate goal of making users perceive external objects as extensions of their own bodies. The research adopts a holistic approach, combining theoretical and philosophical exploration with practical and experimental design, ultimately contributing to our understanding of how embodiment, haptic feedback, and non-verbal communication converge to shape this novel frontier. The central objective involves designing an innovative device framework that induces users to perceive their non-humanoid avatars as integral to their own bodies, fostering heightened body awareness and a profound sense of involvement. In particular, this thesis focuses on an avatar that is radically non-humanoid: *the Room*. A Visitor subject enters and interacts with an animated space in VR which is itself the avatar of the Controller subject, the one embodying and animating *the Room*. Such body structurally perceives reality in a distributed way, thus making *touch* the most suitable means of perception for the Controller. The challenges of integrating modules in haptic feedback devices are discussed, along with the exploration of "The Room" as a character with social objectives. The social interaction in The Room revolves around the manipulation of soft components, conveying comfort or discomfort to the Controller in response to actions of the Visitor.

2. Background and related works

During the development of this project, we closely examine some key concepts that we've learned from existing research, with a main focus on the body, awareness, how we sense our bodies, and the sense of touch. This exploration is based on findings from studies that examine how the physical and virtual worlds interact, especially in the context of the Physical Metaverse [2]. We considered important aspects like knowing where our body is, our personal perspective, and feeling like we own our bodies, emphasizing the role of the brain in these processes. To understand how visual and touch cues work together to shape our sense of owning a body, we'll use the Rubber Hand Illusion as a model [4]. In our exploration, we took into account the concept of Homuncular Flexibility, shedding light on how the brain could adapt its model to various body types. We also presented a framework for embodying a variety of avatars, underscoring the significance of swift real-time processing. These insights formed the basis for comprehending how the brain perceives and adjusts to different bodies, laying the groundwork for a thorough examination of touch feedback in immersive virtual environments

3. Research and inspirations

By summarising the concepts from the theoretical and experimental background we develop innovative haptic feedback devices, and we embark on a multidisciplinary exploration, drawing inspiration from nature, instinctive behaviors, and various philosophical realms. In exploring human movements and expressions, we went through into foundational philosophical questions. These include motivations driving physical actions, essential needs, the evolution of body communicative ability, body ownership, sensory engagement, primal needs. Drawing on Schopenhauer's [5] insights our perception of physicality, the dual role of the body as a manifestation and vessel of the Will, and the distinction between living entities' intentional mastery of their bodies and the machine intelligence's potential for remarkable feats. Perception, inherent in living organisms, is influenced by genetically embedded needs, leading to the concept of "body affordance" as a foundational principle and a surmountable challenge. Introducing an embodiment framework, we adopted modular design principles, emphasizing comprehensive user involvement, sensory system translation, and proprioception remapping. The developed system includes two main modules. Sensory Translation, a pivotal module, delves into the nuanced conversion of sensory information, while the Human Translation component focuses on representing human-derived signals in virtual reality. Then our focus converges on the significance of body senses, movements, and physiological responses, highlighting the pivotal role of the somatosensory system in proprioception. A transformative shift in research focus is unveiled, emphasizing the elicitation of expressive sensations through haptic feedback [3]. This redefined approach seeks to establish a profound connection between individuals and technology, not only within physical environments but also in the immersive landscapes of the Metaverse.

4. Haptic feedback devices

Beginning with the concept of conveying sensations, our objective was to establish a means of communication solely through haptic feedback, minimizing reliance on verbal or visual modes of communication.

We explored deeply into the development of mechatronic systems, specifically concentrating on crafting a servo suit as an innovative alternative to conventional vibration-based haptic suits. In this process, we implemented both a replica of an existing haptic suit based on vibration motors and an entirely new servo suit, incorporating servo motors as a different type of actuator. Additionally, we designed various other haptic feedback devices. The creation of each haptic feedback device involved a thoughtful process, where we identified meaningful sensations for the experiment through a comprehensive study, considering the embodiment of a non-human-shaped avatar in the virtual world.

4.1. Haptic feedback Vest

As we embarked on implementing both vests, our initial focus was on prioritizing the optimal placement of motors on the human torso, ensuring spatial organization, and maintaining symmetry in hosting modules to achieve a consistent and precise sensory evaluation. Thorough testing played a crucial role in determining the best orientation for each actuator, and we designed specialized hosting modules to accommodate both types of motors seamlessly. Each haptic feedback vest is equipped with 16 motors arranged in a 4x4 matrix, with independent control facilitated by microcontrollers (ESP32 for Vibro, PCA9685, and ESP32 for Servo). The ServoVest employs servo motors featuring anchor-shaped plastic components, delivering tactile sensations akin to a pinch. Our cable management approach is optimized, consolidating ground and source cables to enhance operational efficiency and ensure streamlined organization in both vests. The final product are presented in Figure 1

Figure 1: Servo and Vibro suit.

All the modules described below share the same PCA9685 and ESP32 for the controlling part.

4.2. Tightening: Servo-Driven Feedback Module

The tightening haptic module in Figure 2 integrates a servo motor with a cylindrical component featuring a central fence. A cylinder perforated along the rotational axis is crucial, with tape threaded through it and securely fixed. As the servo motor rotates, the tape coils around the cylinder, creating a palpable tightening sensation on the user's arm or leg. This dynamic engagement provides a tactile experience resembling pressure and constriction, enhancing the haptic interaction for a versatile and immersive experience.

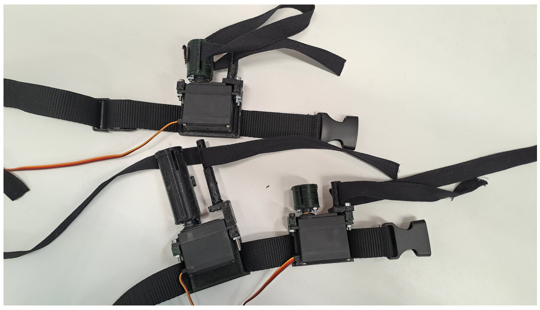

Figure 2: Servo-Driven Feedback Module.

4.3. Slider device

The slider haptic feedback device in Figure 3 is an arm-mounted system designed to transmit a wide range of tactile sensations to the user. It incorporates a continuously rotating motor, specifically the AR3606HB, allowing for sensations over a large surface. Challenges arise in real-time position tracking due to the motor's speed-controlled characteristics. A 180-degree servo motor, connected to the continuous rotation motor, enables the transmission of two distinct sensations through a carefully designed mechanical structure. Two fabric types, soft and coarse, are chosen to differentiate positive and negative tactile experiences.

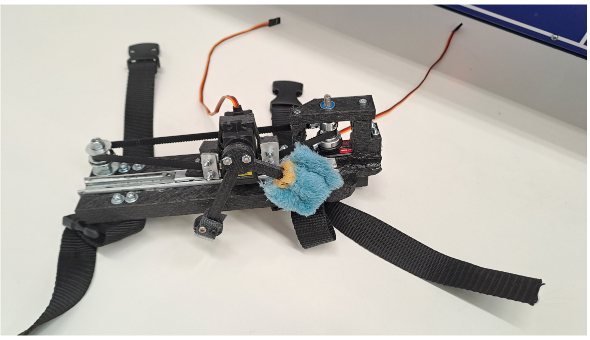

Figure 3: Slider device.

4.4. Lever-Driven Tactile Sensation

The pressure haptic feedback module in Figure 4 features a servo motor integrated with a lever mechanism, simulating the motion of a diaphragm for controlled pressure on the user's skin. A thin layer enhances precision, concentrating tactile feedback to a localized area for a realistic and immersive experience. The module attaches securely to the body using tape.

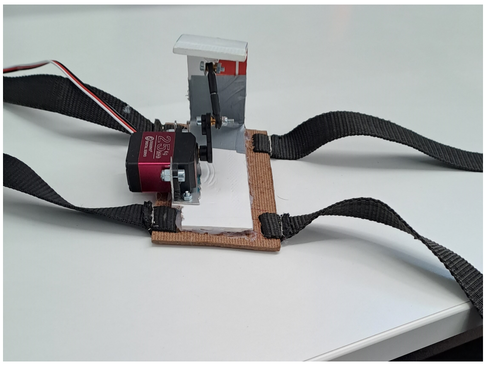

Figure 4: Lever-Driven Tactile Sensation .

5. Programming and communication

In developing the devices discussed, we used the C++ language, along with the Arduino IDE and VSCode software. As previously illustrated, the haptic devices developed with this thesis are experienced by the Controller subject as he controls its Room avatar. The Controller perceives the environment visually through a minimalistic digital environment created in Unity and deployed on an Oculus Quest 2 VR headset. This app acts as the centralised controller of all the logic, and is crucially also responsible for controlling all the haptic devices. During this design phase we explored various aspects, with particular attention to communication, as it is fundamental to achieving system reliability and real-time reactivity. These considerations are integral to our overall goal of creating a seamless and instant user experience. To achieve this, we experimented with various communication protocols, including MQTT, TCP, and UDP, to select the most suitable for our purposes. After thorough testing, we concluded that, for its simplicity and speed, the UDP communication protocol was the optimal choice for our system. Furthermore, initially, we considered a setup where the Oculus communicates with a single ESP32 (the master) via UDP protocol, then this ESP32 using the ESPNOW protocol as an ad hoc solution to transmit messages to each microcontroller(the slave) connected directly to the haptic devices. However, we found that this approach added complexity to the system pipeline and introduced latency.

6. Experiments

Centered on the primary goal of our project, we present the experiments conducted to assess various haptic feedback devices, encompassing both theoretical and practical dimensions. Our main emphasis lies in gathering feedback from subjects to garner comprehensive insights for potential enhancements. The research questions guiding our investigation delve into the perceived naturalness of haptic feedback, its usability, engagement, and impact on embodiment. Our study analyzes fundamental concepts such as body awareness, embodiment, quality of experience, non-verbal communication and nuanced aspects of controllability. The aim is to contribute to a deeper understanding of haptic feedback within the experimental context of "The Room". "The Room" is a virtual space where a Visitor subject interacts with dynamic elements like shape-shifting columns and a blooming flower. A second participant, the Controller, plays a pivotal role in manipulating the virtual environment and providing feedback to the Visitor. The Controller receives haptic feedback through dedicated devices and visual stimuli via the Oculus headset, capturing actions from both the controller and the visitor within the virtual world. This interactive system seamlessly blends virtual reality and haptic feedback, creating a collaborative adventure. The setup poses a unique challenge in redefining social interaction within a non-human experience, emphasizing the exploration of how an actuated space can embody social characteristics. The Room's social objective centers around the flowers, where the controller guides the visitor to interact, conveying sensations and emphasizing the importance of care in handling them. To broaden the scope, we introduced the "Whale simulator" scenario, chosen for its realistic and specific nature in contrast to the abstract and communication-based nature of "The Room". Sensory patterns observed in "The Whale" showcase a continuous low-frequency distribution, emphasizing slower yet recognizable dynamics compared to the brief and irregular touch patterns of "The Room". This observation underscores the significance of focusing on the sense of touch to discern meaningful elements, providing valuable insights into the dynamics of haptic communication in diverse contexts. Furthermore, with the "The Whale" we seek to evaluate the operational efficacy of haptic suits, particularly through UDP communication and ensuring code correctness for embedded motors. This adds another layer to the experimental exploration, enriching our understanding of haptic technology and its practical applications.

6.1. Whale Embodiment: experiment definition

In the "Whale Simulator" experiment centered around the immersive experience of embodying a whale within a Unity-based simulator. Participants in figure 5 navigate the vast ocean as a virtual whale, with the simulator replicating authentic whale movements to create a lifelike encounter. Two distinct experimental setups involve participants actively controlling the virtual whale through interactive gameplay and experiencing predetermined movements without control. These setups aim to evaluate the functionality, usability, and experiential dimensions of haptic feedback devices. Results from this first experiment reveal the significant enhancement of the whale control experience through haptic feedback. The study also explores participants' ability to embody the virtual whale, indicating an intensified sensation of being in the ocean. Detailed findings from questionnaire responses highlight nuances in participants' experiences, including directional challenges, synchronization observations, and suggestions for improvement. Notably, participants with visual references reported a smoother connection between perceived sensations and visual stimuli.

Figure 5: The whale experience.

6.2. Room Embodiment: experiment definition

In "the Room", the Controller embodies the room avatar with an abstract visual perception while the Visitor enters the digital space, creating a lifelike encounter for participants within a Unity-based VR environment. The experimental setup in Figure 6 involves the Controller wearing one of two suits, animating a virtual space featuring spheres and a flower bud. The interactive game-play setup requires the Visitor to navigate and explore the digital room, generating haptic and visual responses on the Controller side without direct communication channels. Results from the experiment reveal insights into participants' experiences, emphasizing the comfort and positive effects of the haptic feedback devices. The haptic feedback contributes to the overall experience, enhancing engagement and interaction within the virtual environment.

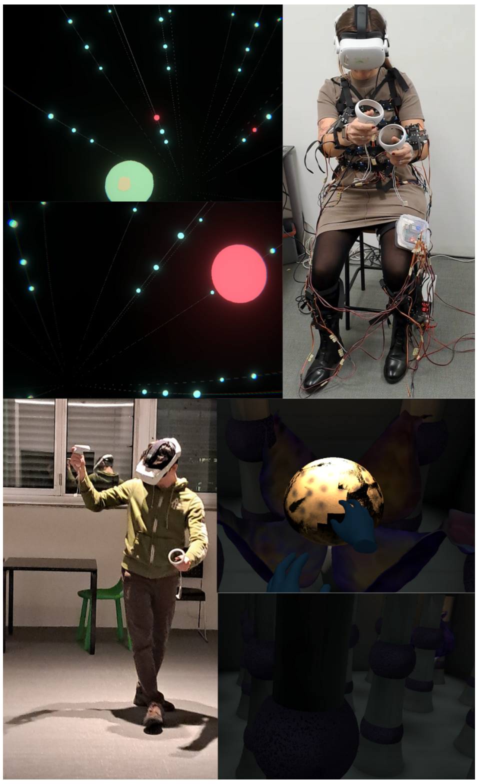

Figure 6: The Room experience, the two subjects communicating through their VR environments. On the upper part the Controller and the corresponding view. In the lower the Visitor with the corresponding view.

From the result we capture diverse facets of the experience. The study highlights both positive aspects and challenges. One notable challenge is the difficulty of establishing effective communication with such an unfamiliar non-humanoid entity using only non-verbal cues. The diverse range of experiences and preferences among participants highlight the subjective nature of individual responses to VR environments. Overall, the experiments offered valuable insights about user experiences with different haptic feedback suits in virtual reality.

7. Conclusion

The exploration of embodiment and haptic feedback in technology aims to bridge the gap between digital and physical worlds, with embodiment being a key factor in creating immersive experiences. Haptic feedback technology, designed to replicate tactile sensations in virtual environments, plays a crucial role in enhancing the feeling of embodiment. The study delves into various haptic feedback devices, emphasizing their potential to create a strong sense of presence in virtual spaces. A groundbreaking experiment on room embodiment reveals challenges in mapping sensations from different devices to the body and highlights the impact of device usage frequency. The experiment focuses on assigning tasks to devices in "The Room" setup, outlining challenges in communication and feedback due to non-responsive dynamics. Real-time feedback issues arise, and the experiment underscores the importance of combining suits and feedback devices for a more enriched virtual reality experience. However, limitations are acknowledged, as certain haptic devices may not be universally suitable for every experience. The subjective nature of user responses and the need for a tailored approach to virtual reality design are emphasized, considering individual preferences and cognitive nuances.

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