Towards a Framework for Embodying Any-Body through Sensory Translation and Proprioceptive Remapping: A Pilot Study

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DOI 10.34626/xcoax.2023.11th.258

We address the problem of physical avatar embodiment and investigate the most general factors that may allow a person to "wear" another body, different from her own. A general approach is required to exploit the fact that an avatar can have any kind of body. With this pilot study we introduce a conceptual framework for the design of non-anthropomorphic embodiment, to foster immersion and user engagement. The person is interfaced with the avatar, a robot, through a system that induces a divergent internal sensorimotor mapping while controlling the avatar, to create an immersive experience. Together with the conceptual framework, we present two implementations: a prototype tested in the lab and an interactive installation exhibited to general public. These implementations consist of a wheeled robot, and control and sensory feedback systems. The control system includes mechanisms that both detect and resist the user's movement, increasing the sense of connection with the avatar; the feedback system is a virtual reality (VR) environment representing the avatar's unique perception, combining sensor and control information to generate visual cues. Data gathered from users indicate that the systems implemented following the proposed framework create a challenging and engaging experience, thus providing solid ground for further developments.

Keywords: Robot, Virtual Reality, Embodiment, Homuncular Flexibility, Non-Anthropomorphic Avatars, Non-Homologous Avatars, Research-Creation, Interactive Installation.

1. Introduction

Hugh Herr believes that during the 21st century, humans may extend their bodies into "non-anthropomorphic structures, such as wings, controlling and feeling each wing movement within the nervous system and become unrecognizable in morphology and dynamics from what we are today. Humanity will take flight and soar" (Herr 2018).

The topic concerning artificial bodies raises questions about the nature of our bodies, our identity, and what we can virtually be. Avatars play a central role in building not only our social lives, but also our identities, as they become the material out of which we embody and make ourselves real (Taylor 2002). In the dawn of virtual reality, it turned out that people could quickly learn to inhabit strange and different bodies and still interact with the virtual world. The term "homuncular flexibility" was chosen to describe the phenomenon of controlling avatars by using different degrees of freedom from the physical body (Lanier 2010; Won et al. 2015). Non-anthropomorphic avatars in virtual worlds challenge the limitations of human-centered principles and expand the potential for interaction and communication. As in the Bhagavad-Gita the deity "becomes human", becomes different through an avatar, so we can too "become non-human" through our avatars. The embodiment of the avatar can influence interactions and activate new metaphors that guide human thought and action in new ways. The use of avatars can also affect behavior, with evidence of the "Proteus effect" where people's behavior changes to match their avatar (Lugrin et al. 2016; Banakou et al. 2013; Kilteni et al. 2013; Peck et al. 2013). Citing the classic work *The Cyborg's Dilemma*: "technology that changes the appearance or affordances of the body also changes the self" (Biocca 1997). However, research in this field still lacks a systematic approach and often limits interesting possibilities (Taylor 2002; Won et al. 2016).

The aim of this paper is to introduce a novel conceptual framework for addressing any-body embodiment, which is based on the idea that the problem translates into the design of a comprehensive system that is composed of body (avatar), sensory remapping, and control scheme that alter the proprioception upon control. Virtual reality allows us to operate bodies that differ substantially from our own. However, avatars with different topology than the human shape require control schemes and interfaces that effectively translate between user and avatar (Won et al. 2016; Krekhov et al. 2019). We state that the reverse is also as important, the mapping from the body to the user, in terms of perception alteration and translation. The driving insight is that a body does not only correspond to a certain quality of movement, but also to a specific type of perception. How does a body completely different from ours perceive the world around it? Another major characteristic of our approach is the use of physical robots as the avatar bodies, which can take any physical aspect in general (Bonarini & Besio 2022) and have any possible sensing systems and abilities. From one side the interaction with the real world may impose more limitations than virtual world settings, on the other side it enables the interaction with other physical entities, such as other robots and biological beings, including humans, without them being mediated by or loosely reproduced within an artificial environment that may exclude or alter the real perception both from the physical and from the cognitive points of view.

We implemented the principal concepts of the framework in two prototypes tested in the lab and in a real exhibition. The final aim of this research is to make human subjects live the experience of having bodies possibly completely different from their own, interacting in the real world. Applications span from entertainment, to performing arts, rehabilitation, remote presence in critical situations, and many others.

The rest of the paper is structured as follows. In Section 2 we will introduce the background for embodiment, and then focus on studies on non-anthropomorphic bodies. The outline of our conceptual framework is presented in Section 3. In Section 4 the first prototype is presented, with the relative experiments and results. In Section 5 we will discuss “Connect to the Machine”, an interactive installation, based on the framework, that we designed and presented to the public. We will also discuss results obtained from questionnaires answered by the visitors. Section 6 will close the paper with the discussion and future directions.

2. Background

2.1. The Sense of Embodiment

“The Sense of Embodiment (SoE) toward a body B is the sense that emerges when B’s properties are processed as if they were the properties of one’s own biological body.” (Kilteni, Groten & Slater 2012) The term is used to refer to the set of sensations that arise in conjunction with being inside, having, and controlling a body; it is commonly studied as the compositions of three different feelings: 1) Sense of Body Ownership (SoBO), 2) Sense of Agency (SoA), and 3) Sense of Self Location (SoSL) (Kilteni, Groten & Slater 2012, Argelaguet et al. 2016).

Sense of Body Ownership: The sense of body ownership (SoBO) refers to a person’s self-perception of her body and her belief that her body is the source of her sensations (Kilteni, Groten & Slater 2012). The idea was first explored in the Rubber-Hand Illusion experiment by Botvinick and Cohen (Botvinick & Cohen 1998). Research supports the hypothesis that body ownership is a result of multisensory perception and can be influenced by sensory correlations between physical stimuli and perceived stimuli (Chancel & Ehrsson 2020, Samad et al. 2015; Ehrsson 2012; Kilteni, Groten & Slater 2012). Although our sense of body ownership typically feels inherent, stable, and unchanging, research has shown that it is highly malleable. For example, it can be influenced by the appearance of avatars (Aymerich-Franch et al. 2017; Cardinali et al. 2021; Hosa et al. 2019). Guy et al. (2022) and Krekhov et al. (2019) also showed that first person perspective positively affects SoBO.

Sense of Agency: The sense of agency (SoA) refers to the feeling that one is the one causing or generating an action; it is associated with statements like “I am in control of my actions” (Kilteni, Groten & Slater 2012). It is sensitive to the temporal relationship between the execution of a self-generated movement and the visual feedback and can be maintained in virtual reality by providing real-time or near real-time visuomotor correlations (Kilteni, Groten & Slater 2012; Franck et al. 2001). Research suggests that the sense of agency is not necessarily related to the number of degrees of freedom in control, but with the efficiency of control, and a realistic avatar representation is not necessary to induce the sense of agency (Argelaguet et al. 2016; Giroux et al. 2019).

Sense of Self Location: The Sense of Self-Location refers to the spatial experience of being inside a body (Kilteni, Groten & Slater 2012). The body space provides a reference frame for our physical body and determines the space in which body sensations are registered (de Vignemont 2011). The sense of self-location can be altered by various factors including the collocation between virtual and real body (first person perspective), synchronous visuo-proprioceptive correlations during movements, and correlated vestibular cues (Kilteni, Groten & Slater 2012; Argelaguet et al. 2016). The rubber hand illusion experiment (Botvinick & Cohen 1998) demonstrates that self-location can be changed through synchronous visuo-proprioceptive correlations between a rubber hand and a real hand.

2.2. Non Anthropomorphic Avatars

Here we discuss research that is aimed at exploring the sense of embodiment for non-anthropomorphic bodies or body parts. Due to the variety of the studies, we separate the studies based on the amount of similarity between the avatars and the human body, in terms of appearance, function, and control.

“Near-Human” Avatars: We call “near-human avatars” those bodies that are only different from the human shape visually, and which are however still following the humanoid structure and control. The results for SoBO were conflicting, with some studies indicating a preference for more realistic bodies (or body parts) (Kilteni, Groten & Slater 2012; Argelaguet et al. 2016; Kao 2019; Latoschik et al. 2017;

Tekgün et al. 2022), while others presented opposite results (Lugrin et al. 2015; Hosa et al. 2019; Krekhov et al. 2019), showing that ownership can also be felt for less morphologically similar bodies or limbs (Aymerich-Franch et al. 2017; Krekhov et al. 2019; Lugrin et al. 2015; Kilteni, Normand, Sanchez-Vives & Slater 2012; Giroux et al. 2019), possibility based on perceived functionality similarity (Cardinali et al. 2021). A growing consensus is that avatars with traits very similar to the user's are favored, but other humanoid shapes are viewed with distrust (Krekhov et al. 2019; Lugrin et al. 2015). Indeed, the biological realism of these studies may aid in user identification with an avatar, but it may also be confusing since such realism may reinforce the user's desire to move as he or she would like in the physical world (Won et al. 2015).

Minimal Humanoid Representations: This paragraph discusses the use of "minimal humanoid representations", which are still based on the humanoid structure and control but have a minimal representation. In these studies, minimal representations of the body (such as spheres tracking only the head/hands or a pose) were found to be the most recognizable by users (Wellerdiek et al. 2013) and resulted in increased exploratory behaviors and creativity without lowering the sense of embodiment (Vuarnesson et al. 2021; Laroche et al. 2021). In (Giroux et al. 2019), users also indicated SoA and SoBO for point light representations of their limbs when these were coherent with their real movements.

Morphologic Changes and Homuncular Flexibility: The section discusses studies on non-anthropomorphic avatars that are inhuman in both appearance and topology, and thus require an explicit control mapping. Control schemes were developed to include full-body humanoids with different arm and leg mapping or additional limbs (Won et al. 2015; Steptoe et al. 2013), animal avatars (Krekhov et al. 2019), and non-anthropomorphic hands (Molnar & Menguc 2022). Results showed that participants can identify themselves with, and control, avatars with different morphology and novel control mappings (Won et al. 2015); synchronous visuo-motor control was found to be a necessary and sufficient condition for Sense of Embodiment (SoE). However, strong unnatural relationships to more human-like visual cues may be detrimental for SoE and a more abstract representation of the avatar may increase the sense of ownership and performance (Won et al. 2016; Schwind et al. 2017).

2.3. Sensory Alterations

The concept of sensory substitution involves using one sense to substitute another. For example, visual information can be transformed into tactile stimuli or auditory signals can be visualized (Proulx et al. 2014). In (Bach-y-Rita & Kercel 2003) a sensory substitution device (SSD) was developed to convert visual images into tactile stimuli, allowing blind individuals to perceive visual information through touch. The authors found that extended experience with the SSD leads to changes in body image and greater control over the device.

The Reality Helmet (Waterworth & Fallman 2003) is instead an example of altered embodiment where technology becomes a part of the body and changes the form of perception. We assume that the world appears as we normally perceive it, even though we are aware that our senses are different from other animals and thus their perception of the world is different from our own. By utilizing the technical methods that define altered embodiment, we have the ability to choose different forms of perception and hence, change our understanding of the world.

3. Framework

We introduce our conceptual framework for any-body embodiment, which aims to create a system that can immerse a user into a new body while eliciting a high sense of embodiment (SoE). The framework consists of three principles:

1. A system cannot transfer a human into a new body by only acting on a subset of components.

2. The user's perception system should be a sensory translation system (ST) of the avatar's perception.

3. The system should provide a mechanism to remap the user's perception away from their own body and towards the avatar's.

Moreover, we decided to focus on robotic bodies as the avatars (Toet et al. 2020).

In the following sections we will discuss in more detail our conception of the avatar body, control system and sensory translation, with ideas about guiding principles for design and possible research dimensions for future studies.

3.1. The Robot Avatar

Since with ST we translate data from sensors into signals that the user can understand, it is interesting to keep the source of that information as unmediated as possible; this can be done with real robots, which offer both the possibility of making a wide range of different bodies, and the possibility to be deployed in real world, interacting with real, physical environments, objects, and people.

The shape of the robot should not be bio-inspired, but instead should explore new possibilities for embodiment. The robot can be in a fixed location or be able to move in space, can have parts that move and change configurations, and its size influences the type of interactions it can have. The robot can perceive its environment through various sensors such as object detection and recognition, relative position, sound, touch, and proprioceptive signals.

3.2. The Control System

The design of the control system requires a mapping between user's and avatar's movements, or, in general, actuators. One of our contributions is to separate the control system into components, by introducing the concept of PROC (Proprioception Remapping on Control) as the second component beside the mapping itself.

3.3. Proprioception Remapping on Control

With the insight that operating a non-human avatar is similar to operating a marionette (Molnar & Menguc 2022), we worked with puppeteer and artist Marta Cuscunà, to understand the principles behind puppet control. Our collaboration led to the concept of PROC, where passive feedback is associated with the user's actions to create a sense of effort and control. PROC is different from force feedback, which aims to transmit the avatar's haptic sensation to the user (Toet et al. 2020). Instead, PROC provides haptic cues based solely on the user's control signals, creating a remapping of proprioception. The goal is to immerse the user in this remapping and other sensory stimulus to create an experience of a new body. By changing proprioception, this reduces the expectation of a human body and movement, leading to a total and immersive experience.

In the design of the control system, we follow these guidelines:

Engaging Control Mappings: One of our main aims is to foster a new use of the user's body. As such, the control needs to involve the body in novel ways, for example by requiring the use of body DOFs not usually used (e.g., a tail (Steptoe et al. 2013)) or remapping existing ones (Won et al. 2015) or imposing unconventional postures and movements (Krekhov et al. 2019).

Flexible Remappings: In early design stages, some users preferred more natural mappings (e.g., forward motion to control forward motion of the avatar) while others found it more interesting, challenging and in the end more immersive to explore new dimensions. Steptoe et al. (2013) and Won et al. (2015) showed that objectives increase the SoE, which could mean that users that chose the more challenging mappings felt more immersed by the implicit challenge of these control choices.

3.4. Sensory Translation

As Sutherland states in his classic *The Ultimate Reality*: "There is no reason why the objects displayed by a computer have to follow the ordinary rules of physical reality with which we are familiar" (Sutherland 1965).

When aiming at fully experiencing the world through a radically different body, we argue that simply placing a camera in the place of the avatar's eyes (Krekhov et al. 2019; Won et al. 2015; Vuarnesson et al. 2021) is not sufficient, as the unique perception and body shape of the avatar also play a crucial role in determining the experience. Thus, one of the main elements of our framework is Sensory Translation (ST). We use this term to represent the system that gathers the data from the avatar's perception (the robot sensors, in our case) and translates them into information that can be perceived by the user, for example, translating the information from distance sensors into visual cues about the position of virtual objects in VR. In the design of the representation of the avatar's sensor information, the interface may exploit the interaction channels available to the subject; the main ones include point of view (first person view is preferred (Kilteni, Groten & Slater 2012; Argelaguet et al. 2016)), vision (preferably through a VR headset for immersion), sound, touch (haptic sensations). We also emphasize the importance of synchronous representation of control signals, to provide the user with a sense of agency and motor learning (Section 2.1). It is crucial to create a system that provides the user with as many congruent stimuli as possible, such as visual, auditory, and haptic feedback, to infer a common cause for the sensations and create a unified source of body ownership (Hosa et al. 2019; Samad et al. 2015; Shneiderman et al. 2016). Minimal representations can also be useful, as studies have shown that these can provide more relevant information (Wellerdiek et al. 2013) or foster experimentation (Vuarnesson et al. 2021). For these reasons we always remove the possibility to communicate verbally, to induce experimentation on different channels and emergent behaviors.

4. The First Prototype

Based on the conceptual ideas presented in Section 3, we conducted our pilot study with a first prototype in which a specific robot body, control and sensory feedback systems are implemented. In all the experiments we worked with the same robot body and sensory feedback, and explored different interfaces to control it, testing this prototype with 17 users with the aim to investigate both the general ideas of the framework and quality of the specific implementations.

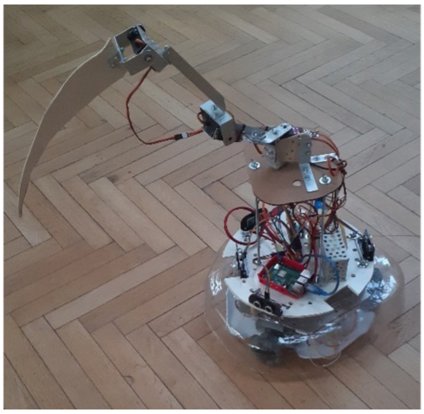
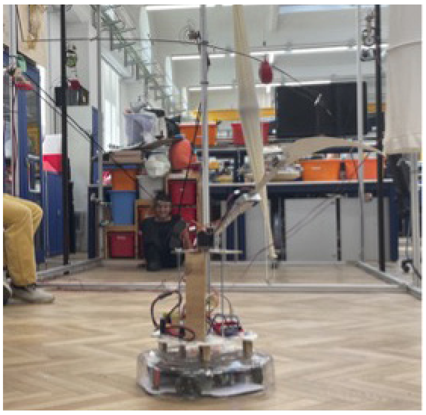


Figure 1: Claw, the robot used as avatar in the experiments of the first prototype.



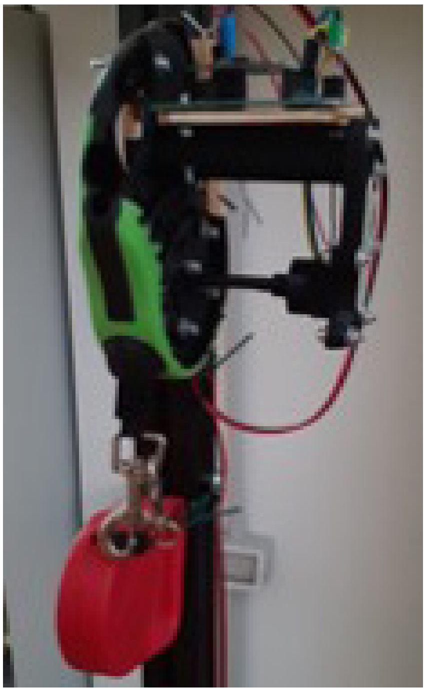


Figure 2: Above is the structure we used in the experiments to attach the leashes of *Strings*, while actress and puppeteer Marta Cuscunà is using the system to guide the robot. Below, details of the connection between the leash wheel and the rotary encoder.

4.1. Implementation

The Robot Body: The Claw robot has 3 DOF on omni-wheels and a 3 DOF arm with a curved pointed element that has been interpreted as a sickle, beak, or claw. The robot has only 3 sonar sensors in front and 1 on the back detecting the distance from any reflecting target in a range of 3.5 meters each. The conceptual characteristics of the avatar are small size, single arm that moves on wheels, and limited sensors. The purpose of this design was to explore movement in space and non-trivial interfaces, with a generic avatar that can be interpreted differently by different users (see Figure 1). We were interested in testing our system with an avatar that could be as generic as possible, far from the human shape but also from any specific creature. We achieved this objective since different users interpreted the few aesthetic elements of the robot quite differently from each other.

The Control System: We implemented two different control systems, with both a remapping logic and a PROC mechanism.

Strings: The first control interface implemented is called Strings (Figure 2), inspired by Whimsichord (Meckin et al. 2012). It consists of dog leash strings providing spring-resistant connections with fixed points on the structure surrounding the user. Each leash controls one degree of freedom of the robot and can control the robot's wheels or servo arm, depending on the setup. The speed of each DOF is directly related to the speed of pull or release of the associated leash.

Limitations of *Strings* include that it can run out of leash before reaching a target position for DOFs with large spans and separating control actions becomes difficult as the number of controlled DOFs increases.

JoyGlo: A sensorized glove (Figure 3) that was intended to be more portable, offer a more flexible control logic, and overcome the limitations of Strings. Each finger on the glove is linked to a separate degree of freedom (DOF) of the robot, allowing for more precise and independent control. The glove detects each finger's position with a linear potentiometer and provides two types of feedback (force and vibration) based on the finger position. The glove has two modes of control: "speed control" in which the DOF is controlled by the speed of the finger movement, and "position-type" in which the signal is translated into a setpoint based on the finger position. In practice, the movement of the ring finger was found to be influenced by the other two fingers for many subjects, so in experiments only the index, middle and little fingers were used for control. The control mapping is flexible and can be configured by each user.

Figure 3: The two *JoyGlo* prototypes. Sensorised gloves, with strings connections from the fingertips to the linear potentiometers. Springs add mechanical resistance while vibromotors on the tips provide additional feedback on the control action.

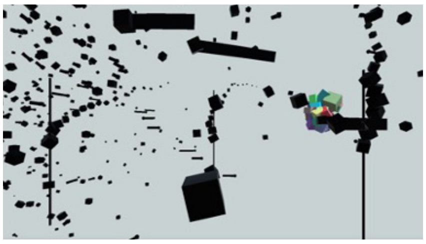


Figure 4: The VR environment representing the "avatar's perception", with the black cubes being related to the controls exerted by the user, and one of the colored blocks representing the signal coming from one of the sonars, getting closer or further from the user based on the real sensor readings. When colored blocks are invisible, it means that the corresponding sonar is not perceiving any signal.

Sensory Translation System: The purpose of this system is to convert the state of the avatar into information that can be experienced by the user. The state of the robot at any given moment is represented by 10 numerical values, which consist of 6 control signals and 4 sonar values. To achieve this, we developed a VR app in Unity and deployed it on Oculus Quest 2 (Figure 4). The app takes the user into a virtual environment where each of the 10 values has a corresponding visual effect. To enhance understanding, the environment is kept simple with only elements related to the robot's state, and control signals are separated from sensor data using color. The cube shapes were used to provide a sense of coherence and simplicity in the environment.

— wheelbase control signals were represented with black particle systems.
— servo control signals changed the rotation of three black shapes in front of the user.
— data from sonar sensors was represented with coloured shapes approaching or moving away from the user.

The design presented a challenge in balancing realism and abstraction. For the servo controls, signals were represented as separate objects instead of linking them mechanically as they were on the robot, whereas for the sonar signals, we opted for realism by matching the visual representations to the actual meaning of the signal. This duality aimed to stay closer to the robot's perspective while still providing a good user experience. Crucially, in the VR environment users can only "see" the sonar and control data, and they need to find a connection between their own movements and the visualizations.

4.2. Experiments

Our aim was to assess the sense of embodiment that this system would elicit on the users, and we focused on three specific aspects in this pilot study: the control and sensory translation systems, to test our implementations, and the effect of giving a task: while in (Vuarnesson et al. 2021; Laroche et al. 2021) they argued that giving no objectives fostered exploratory behaviors, (Steptoe et al. 2013; Won et al. 2015) showed that the presence of a task increases SoE. Since we are interested in both aspects, we tested both situations.

To test the control system, participants have been presented with one of the three following configurations:

— *Two Gloves*. One *JoyGlo* controls the wheeled-base movements and the other controls the head servos.
— *Hybrid 1*. A *JoyGlo* controls the three arm servos, and three *Strings* leashes control the wheel base.

— *Hybrid 2*. A *JoyGlo* controls the wheeled base, and three *Strings* leashes control the three arm servos.

To test the other aspects, all participants went through three consecutive phases:

1. Free exploration with VR headset on, no objective. Duration: 2-3 minutes.
2. Introduction of a simple goal: avoid obstacles. Duration: 2-5 minutes.
3. The VR headset is removed, and a task is given to be accomplished by the robot: touching an object with the tip of the arm. At this point users could see the robot, themselves, the real environment, and the effects of their movement on the robot's.

Volunteers signed an informed consent and agreement to participate in anonymous form, for a total of 17 subjects, aged from 21 to 29, 5 females and 12 males. After the experience, each subject compiled a questionnaire including some of the questions proposed as part of a standard questionnaire for evaluating embodiment with VR avatars (Peck & Gonzalez-Franco 2021), repeated for each of the three phases, and custom questions related to our specific systems. Subjects were also presented with open-ended questions to be able to better articulate their experience, and to give ideas and suggestions.

The questionnaire, all the answers and the plots of the aggregated results are available for download at http://airlab.deib.polimi.it/wp-content/uploads/2023/06/prototype.zip.

4.3. Results

In this section, we discuss the most relevant results we obtained.

"Controlling the Robot as if it Was My Own Body": Users had mostly positive responses when asked about their sense of control over a robot as if it was their own body. The level of positivity increased in phase 2 (VR with an objective), which corresponded to a decrease in "feeling out of one's body". This trend aligns with previous research on agency and synchronous vasomotor control synchrony (Section 2.1). A clear objective improved the sense of embodiment (SoE) (Steptoe et al. 2013; Won et al. 2015), though movement and creativity was reported to be enhanced in phase 1 without explicit instructions or goals (Vuarnesson et al. 2021; Laroche et al. 2021). Controlling the robot in a VR environment, even abstractly, led to a better sense of bodily connection compared to seeing the robot in phase 3, suggesting non-anthropomorphic sensory translation systems can benefit embodiment and avatar manipulation.

"Understanding What Is Happening": As expected, scores for the understanding of such an abstract environment were in general low. However, values were higher for the second phase as the participants were co-located with the robot and the task-oriented approach allowed users to obtain more synchronous stimulation across more sensory channels. This suggests that designing artificial perception systems that focus more on the avatar's own affordances, rather than mimicking human perception, may increase the sense of embodiment.

PROC Systems: Subjects reported the vibration on the gloves to be crucial for the feeling of connection to the avatar but noted that the prototypes sometimes failed to deliver the signal appropriately. Similarly, subjects enjoyed the physical sensations provided by the elastic forces and said that the constant tension they induced was important to force the body to focus on the movement they were generating. The problem they highlighted in this case was actually that these elastic forces were too weak. Overall, subjects have been positive about the systems, but did not report them as essential; however, they related the limits specifically to the inability of our devices to deliver the intended sensations consistently, encouraging us to design more reliable systems based on the same concepts.

"The Importance of the Robot's Sounds": The study found that the sound produced by the robot's motors was important for the user experience as it provided additional feedback and helped the user understand their influence on the robot's movement. Hearing was a sense for which we did not design any active system, so the presence of a sound feedback provided an unexpected multisensory experience (see Section 2.1) and feedback (Shneiderman et al. 2016), factors that are known to be crucial in the literature (Section 3.4).

5. Connect to the Machine: An Interactive Installation

In this section we present our installation *Connect to the Machine*, which we showed in November 2022 at the Milano Digital Week, and which is the natural evolution of the Claw prototype. As in (Vuarnesson et al. 2021), we structured the installation in the form of a laboratory experiment, allowing us to collect post-experience subjective reports.

5.1. The Installation

The interactive installation is composed of two experiences in parallel. Visitors could try one experience at a time but were unaware of the relationship between the two. Each experience lasted between 3 and 5 minutes.

Figure 5: The robot interaction section of our installation. Above are users observing the robot trying to understand its environment. Below is the robot Siid, the robotic avatar of our installation. The outer shell of petals can be opened or closed, revealing the hidden soft head.

In the first space, visitors interacted with an autonomous robot, and they were told only that it was "learning to interact with humans" (Figure 5). The subject in the second space was linked to a VR headset and four Strings (see Section 4.1) and was given the objective to understand and manipulate the abstract environment (Figure 6).

In fact, the second subject was controlling the robot in the other room, and what he or she perceives as abstract representations in VR were the results of the human-robot interaction in the other space: the two participants were actually interacting with each other through the system.

The Robot: Siid is a flower-shaped robot with three DOF on omni wheels and a single servo motor controlling its petals opening mechanism. The bulb on its inside hides an LED and the digital eye's pupil can also move within an eye-like screen (Figure 5). It has 4 sonar sensors like the robot Claw (see Section 4.1), and an infrared temperature sensor on the head between the eye and the bulb, used to detect the presence of a human hand. The intended objective was to invite humans to interact with Siid and to caress it, obtained with the stark contrast between the rigid shell and the soft head within, negotiated by the opening and closing movement of the petals.

The Control System: To control Siid, 4 Strings were used, 3 for the wheelbase and one for the petal movement, and they were chosen over JoyGlo for being more agnostic to users, and for eliciting more exploration in bodily use (Figure 6). The trigger button of the VR headset's controller regulates the light of Siid's bulb, and the position of the headset controls the position of Siid's digital pupil, transmitting the sensation of "looking around".

Sensory Translation: Many components of the ST were kept the same as in the prototype (Section 4.1).

However, the petal's servo was represented more realistically, with virtual petals opening and closing around the user. The biggest variation was related to the temperature sensors. The environment was made red and heavy but would turn clear and peaceful if the temperature sensor was triggered by petting the robot. Subjects in the VR room were only told about the possibility of turning the sky blue and had to figure out the combination of movements to do so (see Figure 6).

5.2. Results

Every visitor tried both experiences independently, and then were informed about how they were connected. At the end we asked them to complete a voluntary questionnaire, like that presented in the first experience, modified accordingly.

The questionnaire, all the answers the table with the aggregated results are available for download at http://airlab.deib.polimi.it/wp-content/uploads/2023/06/connect-to-the-machine-2022-installation.zip. Here we report the main results.

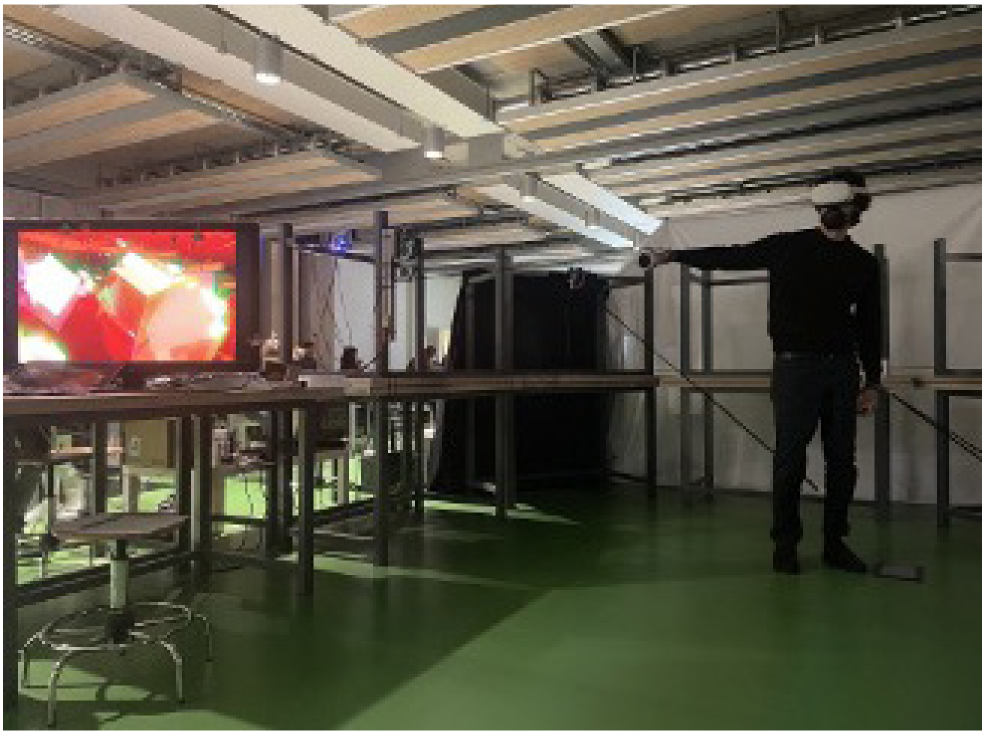


Figure 6: The immersive section of our installation. The subject is attached to 4 Strings and uses them to navigate and understand the virtual environment representing the perception of the robot in the other space. A red sky with colored cubes nearby indicates that the robot is in front of obstacles, but it's not being caressed. A screen was set up to show the visitors what the subject was seeing in real time.

For the robot interaction part, users reported liking the robot appearance and having tried to help it to learn. Users also felt that the robot was reacting to their actions. However, scores on perceived robot autonomy were quite low.

For the VR experience, subjects didn't feel like they could always understand or control what was happening. However, they consistently reported the importance of the elastic resistance of the strings to feel connection to the virtual environment.

When asked how they would improve the system, subjects talked about the difficulty of the task in VR, and of the unsatisfactory interaction of the robot. Indeed, the two are linked, as if the subject controlling the robot cannot understand how to complete the task, the robot itself will not behave in an interesting way, and also its perceived autonomy will decrease. To solve this problem, it will be important to design the control and ST systems so that the robot's abilities are easier to exploit and allow the user to "feel part of the environment, even if you feel lost in it". They also felt that sound was missing, as they could not hear the robot.

When asked what they enjoyed the most, they consistently talked about the VR experience of perceptual change, with expressions such as "challenging", "mind-blowing" and "an experience that really made me think". Users were also thrilled by the discovery of the robot and the VR system being connected. These feelings were also confirmed by the high score obtained for the question on overall enjoyment (over 80% of the 35 answers were between 4 and 5 in a 5-points scale).

Overall, these findings underline the importance of finding a compromise between the stimulating abstraction and the necessary intelligibility of the environment, and confirm the quality of the system in its ability to challenge, engage and surprise users, which are in our opinion the great possibilities that come from entering a body that is truly different from ourselves.

6. Conclusions

6.1. Discussion

With this paper, we presented a conceptual framework aimed at achieving full immersion in physical avatars with any shape, to promote exploratory behaviors from users while maintaining a sense of embodiment. The design is intended to induce a change in the user's perception of their own body, creating the illusion of being directly connected to the avatar they are controlling. The idea of altered embodiment is already present in the literature (Waterworth & Fallman 2003; Won et al. 2015; Krekhov et al. 2019), but has not yet been explored to the same extent in a comprehensive body-sensorimotor and perception framework. Our contribution is not only the combination of its components, but also illustrates the need to consider the setting as a single interconnected system.

We presented two systems that implement this framework: a laboratory prototype and an interactive installation presented at the Milano Digital Week in 2022 under the name *Connect to the Machine*. The systems consist of a robot, mechanisms to control its movements, and a virtual environment that translates the avatar's unique perception to the user. Results were highly encouraging, proving that we were successful in our main goal to make the users feel engaged, immersed in the new body and challenged to test the possibilities of their own bodies and to understand this newly perceived world, while also feeling like their own bodies and the avatar's were connected, and moving as one. However, they also expressed a desire for more effective and consistent transmission of the PROC. Despite the initial difficulty in using the system, users reported high engagement and satisfaction; indeed, as game design practices suggest, engagement and challenge are linked, and finding a balance between challenge and reward can even elicit greater immersion; this is also valid for non-anthropomorphic avatar embodiment where more unfamiliar settings actually induced more SoE, satisfaction and task performance (Vuarnesson et al. 2021; Krekhov et al. 2019; Wellerdiek et al. 2013). The system fostered self-play, and all participants were surprised by the perspective shift it showed them.

Overall, in designing altered embodiments, the possibilities are almost endless — but we do not yet know much about what will work best for which purpose, or about possible longer-term effects on the subjects.

6.2. Future Directions

Studying the possibilities for physical embodiment with an avatar with generic shape opens a wide range of opportunities. The present paper is meant to be a pilot study, opening a novel direction for this kind of research, however, already from the initial implementations we are starting several parallel explorations, to develop in detail each of the subsystems, either by improvement of the current solutions, or with new explorations.

Avatar Body: The presented avatar body implementations were designed mainly as test devices for the control and feedback systems. In future works, the focus will be on improving the quality of movement, perception, and affordances of the body, with the ultimate goal of creating wearable bodies that can support meaningful interaction by allowing the user to express themselves through movement, gesture, sound, and perceive the intentions and emotions of others.

Feedback to The User: We aim at improving the quality of movement and perception in the avatar's body to enable meaningful interaction. The perception system is currently a direct visualization of signals but may be too limiting. There is a trade-off between direct feedback based on sensor values and more high-level feedback that resembles living beings' perception. To explore this, a comprehensive study of the avatar's shape and sensor connections is necessary, also by exploring the possibilities of using multiple senses to enhance the experience by going beyond visual cues.

Measures: The results of our experiments came from questionnaires, however in future works we will introduce new measures for a deeper and more robust understanding of our framework in terms of embodiment and of user behavior, e.g., perceived position, physiological markers, users' reaction (Steptoe et al. 2013), and collection and analysis of real-time kinetic data (Vuarnesson et al. 2021; Laroche et al. 2021).

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