Haptic Interfaces for Embodiment in Virtual Environments

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Abstract— **The convergence of haptic technology with the understanding of human perception is opening new possibilities for immersive virtual experiences. This work addresses the role of haptics in the design of systems for supporting embodiment in virtual and real environments. The paper presents haptic interfaces for embodiment by analyzing them in terms of the three main feedback types: proprioceptive, kinesthetic and tactile. Each category is discussed by first analyzing embodiment requirements and then the available haptic technology. This review is closed by some considerations in the domain of capturing and encoding for covering the whole embodiment pipeline.**

I. INTRODUCTION

Since its inception Virtual Reality (VR) has pushed the possibility of interacting with virtual objects and in general to move user's experience into a virtual world with increasing levels of participation. This interaction calls into action all the senses and in particular the introduction of the sense of touch has greatly improved the possibility of manipulating virtual objects [39]. It is well known how research on haptic interfaces started from tele-operation for the purpose of manipulating distant environments and then become fundamental in the realm of virtual environments [48], [19]. Haptic interfaces allow to perceive and transmit motion and forces to real or virtual entities stimulating the somatosensory system, and indeed the participation of the user in the Virtual Environment (VE) is elicited by the combination of the different modalities. In general such participation has been addressed by the extensive research in the domain of presence. In this work we are looking at a deeper level of interaction and participation taking the virtual experience to a higher level by means of embodiment.

Embodiment literally means personification or incarnation, that is the integration of the presence of a body on the mind. Following the embodied cognition paradigm our own body shapes the way the mind is structured [13], [38]. A striking example of the embodiment is the extended perception of our body by means of tools that we use frequently in a skillful way or the extension provided even by cloths.

In the context of human-machine interaction and VEs, embodiment describes the possibility of perceiving an external entity as part of his own body, or a complete replacement for the body. Biocca [7] introduced the concept of *progressive embodiment* for describing the technological and theoretical evolution of virtual environment systems toward full embodiment. Even basic interfaces for VE provide some sort of embodiment but since the beginning of research on VE it was clear how visual and audio channels are not sufficient for embodiment although their dominant role in multimodal perception. The point with perception of touch is that it involves multiple body parts and it is fundamental in many practical tasks.

The research challenge that is behind this work is the role and the possibilities of the haptic modality for supporting embodiment in partial and full sense. The specific challenge is to take advantage of the characteristics of the perceptual system for supporting the technological requirements for the haptic interfaces. An important assumption in the embodiment concept presented here is that it is based on a non-invasive approach avoiding other possibilities like electrical stimulation or implants that could produce virtual stimuli at the level of the nervous system.

In the following section the principles of an embodiment system will be discussed for issuing the major requirements and then the perceptual and haptic technology will be discussed addressing the different aspects of haptic feedback.

II. PRINCIPLES AND ARCHITECTURE OF EMBODIMENT SYSTEM

In an embodiment system for advanced virtual and real interaction we can identify two key roles: the *participant* and the *avatar*, The participant is the human subject that is going to experience the avatar world by means of the body of the avatar. For the objective of subject stimulation, following the approach presented in the VERE Project [45], we should consider two different conditions with different challenges: the *moving participant condition* (MP) , in which subject motion is reflected on the avatar world and limited by the physical constraints of the avatar world, and the *inert participant condition* (IP) in which motion is absent due to limitations of subject physical abilities or by design. Figure 1 sketches these two conditions on the left side.

From the point of view of the avatar we can identify two types of scenarios: *virtual* and *physical*. In the virtual case the avatar is a virtual body that interacts in a totally virtual environment generating perceptual stimuli from the virtual model. In the physical case the avatar is a physical body like a human purposely instrumented or a robot. In terms of application the physical avatar in the form of a robot allows the participant to actively interact with the avatar environment. The robotic case can be considered as an advanced case of tele-operation in which the information sent over the connection is full bodied. The Robonaut [2] humanoid robot for teleoperated space operation is an example of application. Figure 1 sketches these two conditions on the left side.

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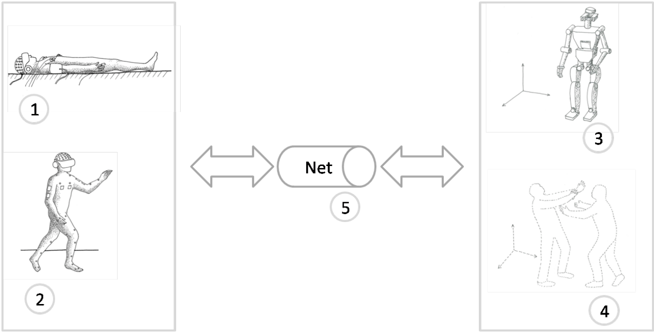


Fig. 1. Sketch of the possible embodiment configurations. On the left side the participant is depicted in the two inert and moving condition. In these two participant conditions the haptic interface is not depicted, but in the moving condition it could be as complex as a full body exoskeleton. On the right side the avatar is depicted as a robot interacting in the real world or as a virtual human. In the middle the network connection is the medium. The numbers are used in the text for presenting the challenges.

Both in the real and virtual scenario the participant should be able to perform a set of actions in the avatar environment by means of the avatar. The main actions performed in the real and virtual environment are navigation, object manipulation and human-to-human interaction. From these actions it is possible to identify some physical interaction elements that have to be supported by the system, guiding the investigation of the required haptic technologies:

- perception of inertia of own moving body and the objects being manipulated
- contact with objects in the environment
- perception of weight of objects being lifted or held [50]
- walking sensation comprising body motion and step perception
- human hand-shaking

From the above action we can derive the research and technological challenges for capturing, modeling and rendering interaction. We refer to these challenges using the numbering in Figure 1 reporting, over applicable, recent works on the topic:

1) inert participant
    - intention of motion
    - perception of motion
    - perception of touch
    - vestibular effects
2) moving participant
    - virtual walking
    - force scaling
    - kinematic adaptation [36]
3) robotic avatar
    - touch sensing
    - haptic modeling
4) virtual avatar
    - force modeling
5) network
    - haptic encoding and compression [16], [47]
    - delay management [54]
    - participant and avatar based adaptation

In the robotic avatar scenario, for example, the challenge is in the mapping between the human kinematic to the robot kinematic and in the sensing of interaction forces, while in the virtual avatar scenario the main challenge is in the synthesis of the interaction forces over the participant.

A. *Measuring Embodiment*

Embodiment can be measured at large by means of presence evaluation [59], but it can be more specifically assessed by measuring the ownership of the virtual body parts [34], [28], [52]. In addition other haptic quality measure should be adopted for assessing the presence of instability and the realism of the force feedback whenever it is applicable.

B. *Components*

Before entering into the role of haptics in the embodiment it is worth considering the main characteristics of the embodiment system. On the participant site we have an ”‘embodiment station”’ that comprises multi sensorial feedback components providing visual, audio and haptic stimuli. While in the moving participant case we should take into account the motion acquisition, in the inert participant the motion and behavior intent has to be acquired by means of physiological measurements like EEG, ECG and EMG, taking advantage of the research in domain of Brain Computer Interfaces (BCI) [37].

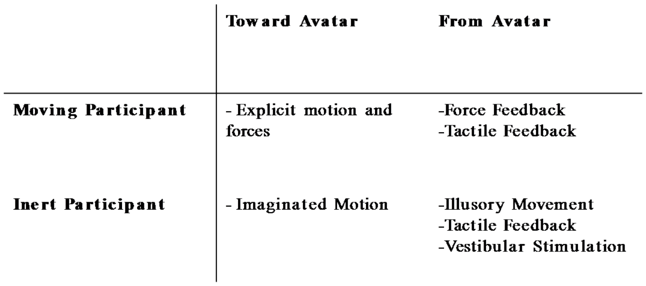
III. HAPTICS FOR EMBODIMENT

The role of the haptic feedback component is to provide the physical interaction spanning from basic contact to complex interactions. We can identify several elements that contribute to the overall haptic feedback starting from the haptic perceptual system [26]:

- proprioceptive feedback: information about the position of our body parts and their movements
- kinesthetic feedback: information about the forces applied to the body
- tactile feedback: information covering the touch with surfaces
- vestibular feedback: perception of the gravity vector

The first two elements are mutually exclusive of one of the participant conditions. In particular proprioceptive stimulation will be fundamental for compensating the lack of motion in the inert scenario, while in the moving scenario kinesthetic feedback will provide responses to the exploration of the avatar environment. The resulting exchange of information and feedback between participant and avatar can be synthesized in figure 2.

The discussion will continue by presenting in the following Sections the principles of stimulation in each feedback dimensionality, addressing the findings from neuroscience that allow to reduce the technological requirements for providing the feedback itself. An example of support from neuroscience is the study of the Visual Enhancement of Touch (VET) effect in which touch perception is improved by a vision of a body part associated to its own body [31]. In



	Toward Avatar	From Avatar
Moving Participant	- Explicit motion and forces	-Force Feedback -Tactile Feedback
Inert Participant	- Imaginated Motion	-Illusory Movement -Tactile Feedback -Vestibular Stimulation

Fig. 2. Information and feedback flow between participant and avatar

this case it would be fundamental to understand in the robotic avatar if it is still valid in the case in which the participant see himself as a robot.

IV. PROPRIOCEPTIVE FEEDBACK

In the inert participant condition (IP) the challenge is to stimulate the body in a way to elicit virtual proprioceptive signals by means of kinesthetic illusions. In the neuroscientific domain this fundamental assumption has been studied by performing experiments in which muscles spindles are activated by mechanical stimulation producing illusions of motion of the associated limbs where the effectiveness of this stimulation depends on spindles' density.

In these experiments the subject, blindfolded and ear plugged, received vibrations on different part of the arm [23]. The result of the stimulation is measured both objectively by means of fMRI, PET or even EEG, both subjectively asking the subject to report the timing of the induced virtual motion, to represent the perceived motion with the other free limb, and in general to express subjective measures of the illusion by expressing it in psychological terms of *continuance, vividness and strength*. While physiological measurements can provide information about the formation of an illusion it is also important to measure the absence of real motion by means of EMG analysis. In these experiments the vibration actuator is placed on the skin above muscle's tendon with variable vibration rate and amplitude with the objective of identifying the most effective pair for inducing an illusion.

In the reference work by Naito et al. [33] vibrations in the range 10-240Hz and amplitude 0.2-3mm identified in the 70-80Hz range the most effective vibration rate. The desired motion induced by the vibration is not the only effect of the stimulation, in particular when adopting long stimulation sessions (30-60s) When the vibration ceases an *aftereffect* illusory motion is produced in a direction opposite to the one generated by the stimulus [23].

Following this initial promising result several experiments have been performed in literature, firstly addressing if multi-directional movements can be elicited, like in Calvin et al. [8] in which flexor and abductor of the wrist have been stimulated to produce 2D patterns.

More recent work by Albert et al. [1] investigated illusions of complex trajectories by first recording the type Ia afferent messages by means of microneurographic recording of imposed motions over the ankle representing alphabetical letters. The recorded pattern of the 5 ankle's tendons have been averaged and then provided to the corresponding actuator around subject's ankle. This stimulation induces motion that are being recognized by the subject symbolically and visually reproduced by writing. The stimulation of multiple tendons not only allows to reproduce complex motions but also to increase the perceived velocity of the motions if two tendons of the same muscle are stimulated [60].

Neuroscientific research has shown the feasibility of the generation of illusion. It is now necessary to identify a technology that allows to provide the required patterns in multiple body parts for the embodiment system. Most of experiments adopted bulky actuators that cannot be easily deployed or integrated in the full body, like the Mini-shake 480 used in [33] providing a force peak of 10N with a diameter of 76mm. From the findings of Roll et al. [40] it can be also understood how vibrators should be placed in a way to cover all the muscles that affect a given motion and their positioning should be tailored to maximize the illusion. The other requirement of the actuators is their ability to vary the frequency of stimulation for reproducing the type Ia activation patterns.

The application of this approach for the embodiment requires to create stimuli associated to a specific motion to be induced. Recent work by Thyrion et al. [49] is aimed specifically at this: from the functional properties of muscular spindles they derived a prediction method of the firing patterns of given 2D/3D motion, then they provided these patterns to subjects by means of vibrotactile stimulation and compared the resulting movements.

In terms of technology the low cost requirement brings to the adoption of DC vibrator motors with an unbalanced mass that have the side effect of coupling frequency with amplitude of the generated vibration. This is partially a limitation due to the fact that different levels amplitudes have shown to produce illusions. An example of such types of actuator has been used in the preliminary work of Celik et al [9]. In their work the vibrator motor was packed into a casing connected to an elastic band attached to the arm. The alternative to vibrating DC motors are voice coils actuators that provide good force to dimension ratio and can generate vibrations along a single direction with the possibility of varying both frequency and amplitude. Niwa et al. [35] compared these two types of actuator for induction of illusions obtaining that they are equivalent for duration of stimulus longer than 200ms, while for shorter stimuli DC motors were not able to induce the illusion.

Research in illusory movements has focused on arm-forearm, wrist and ankles, but it could be extended to other joints like knees, although shoulders and thigh pose a challenge to this approach because tendons are covered by muscular tissue.

V. KINESTHETIC FEEDBACK

Kinesthetic feedback enters into action during the exchange of forces between the user and the virtual environment. Most of haptic interfaces are designed to provide this type of feedback because it is involved in many tasks. For the purpose of embodiment the haptic interface should be capable of affecting the whole body allowing to perceive forces at different body parts, simulate different terrains, or the weight of lifted objects. When looking at kinesthetic haptic interfaces we can organize them along four dimensionalities:

- metaphor: tool, encounter, direct
- portability: grounded, wearable
- interface: external, cable suspension, exoskeleton
- body part: hand, finger, torso, full body

Most of known haptic interfaces like the Phantom [51] are tool-based, grounded and external because in this way they are nearer to the application cases and they provide less limitations in the selection of the actuators and components. The tool metaphor is quite useful for several applications but it provides a reduced embodiment because of the single contact point with participant's body.

For providing a higher level of embodiment by means of multiple points of interactions researchers have investigated haptic exoskeletons [5] applied to hands [11], arms and legs, mostly for the purpose of rehabilitation [12]. Body exoskeletons have been also developed for supporting elderly in daily life [24] or for allowing performing demanding tasks like power augmentation [21]. A body exoskeleton for embodiment presents some reduced requirements with respect to the ones for power augmentation because, by definition, it interacts only with the participant body and it does not need to generate external forces [30]. For this type of systems there are anyway major challenges for the transmission of force to the different joints in particular under the requirement of improving transparency of the interaction [6].

A different level of interface and embodiment is provided by grounded and direct interfaces that are attached to the torso of the user allowing to modify the perception of gravity and perceived slope during walking [17]. Virtual walking is a general topic of Virtual Environments that has been addressed both to simulate a large walking space in a small real environment by means of moving platforms or re-orientation techniques, and also to simulate different terrain types like in Visell et al. [56].

VI. TACTILE FEEDBACK

Tactile feedback focuses on the aspect of the somatosensory system that allows humans to perceive contact over the skin, surface roughness and other surface properties without the exchange of forces. In terms of devices we can describe them along three dimensionalities:

- avatar body part: limb, hand, finger or torso
- perceived stimulus: roughness, impact, shape
- stimulation: pressure, vibration, stretch, pinning

Stretch and pinning type interface have been developed for providing perception of surface properties on the fingertip [14] or arm [58], or eventually display gravity information [3]. In many haptic application tactile feedback is integrated with kinesthetic feedback for improving the quality of contact [20].

For the purpose of embodied perception and immersivity some research has been performed on tactile vest that provides contact information with virtual objects by means of vibrotactile elements [27], [55] or by pushing solenoids. Starting from the characterization of the somatosensory system it is possible to derive some technical requirement for tactile interfaces [15]. For example regarding human pressure sensors it is necessary to take into account minimum spatial and temporal distances of stimulation, minimum level of pressure activation and JND variations [44].

The integration of tactile with kinesthetic feedback is still a challenging topic because of the complexity in the integration of technologies and in the overlapping of stimulations. Wagner et al. [57] presented a robotic arm with a pin based tactile array integrated by means of a common FEM simulation, while Kim et al. [22] performed a similar approach with a Phantom and pneumatic tactile actuation. The result of the integration has shown to improve some tasks like shape discrimination [42].

VII. VESTIBULAR FEEDBACK

The perception of body acceleration is important in many tasks, and it should be a general element provided by the embodiment system. The vestibular system is indeed important for proprioception and it can provide an important contribution for the embodiment supported by haptic interfaces. This system provides indication about orientation of the body with respect to the gravity vector and it is quite important in standing motion. There have been also some neuroscientific finding like Lopez et al. [29] regarding the effect of altered vestibular stimulation and body ownership.

For a discussion about the vestibular system and some implication in virtual environments see [25]. The typical approach for vestibular stimulation is the adoption of a moving platform that induces accelerations over the human body, while simplified acceleration models can be obtained by means of tilting table that exploit the decomposition of the gravity vector. Tyler et al. [53] adopted a sensorial substitution mechanism for providing missing vestibular information by means of a tactile stimulator that was integrated with a head mounted accelerometer.

VIII. HAPTIC CAPTURING AND MODELING

Previous sections focused on the haptic interfaces required for producing a given stimulus while this section briefly deals with the other aspect for the purpose of an overall embodiment system: the capturing, modeling and encoding of the haptic information.

A. Robotic Avatar

In the *robotic avatar* condition the avatar system should be able to acquire kinesthetic and tactile information of the surrounding world. The acquisition of exchanged forces is anyway not sufficient for providing the full embodiment.

In the discussion so far we have assumed that the robotic avatar is humanoid in a sense that it has a body schema with an equivalent topology. This is anyway not sufficient to guarantee a mapping of the proprioception of the robot with the one of the human, that is transmitting the robot body schema to the human, because other factors are involved like joint length. Morphology is only a part of the problem of the body schema and indeed we have to take into account inertia and joint compliance. In particular most of existing robots are stiff and it has to be clarified how and if the stiffness of the robot has to be transmitted to the human on the network and then rendered by means, for example, of an exoskeleton.

Tactile sensing for robotics has instead received most of the attention for providing tactile sensors on the fingertip for grasping and object manipulation [32]. In particular Dahiya et al. [10] presented the available tactile technologies while Argall et al. [4] discussed the different applications of robot sensing for interaction with humans. A recent example of modular tactile sensing is RoboSkin by Cannata et al. [43].

B. Virtual Avatar

The major difference between the robotic and virtual avatar condition is in the way haptic information is generated. While in the robotic condition the focus is in the real world sensing and encoding, in the virtual condition haptic information has to be generated from haptic models of the environments that can be used to synthesize feedback directly on participant site. This is specifically the role of Haptic Rendering [41] that computes the haptic feedback in response of the interaction with the user. This computation is a specialized form of physical simulation that produce high frequency response required by the haptic perceptual system. Some of the haptic properties can be totally synthetic like basic friction and stiffness, while more complex properties have to be captured from the real world and synthesized as in the haptic data rendering approach [18]. Tactile interaction with full avatars have been partially explored, and the work by Spanlang et al. [46] is an example.

IX. CONCLUSIONS

The final goal of a full haptic embodiment station poses several challenges both in terms of haptic interface technology and in stimuli generation, but it provides great opportunities for providing interaction with avatar environments or for allowing impaired people to perform virtual experiences. In this work we presented an overview of the haptic technologies that can be combined to provide full body embodiment.

What emerges from this review is the number of challenges and open points for the final goal. Some issues are more technological, like the actuation for proprioceptive illusions and body exoskeleton actuation. Other issues are instead connected to our understanding of the perception of embodiment and the effect on our sensorimotor system of illusions and perceived compliance of the avatar system.

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