

THÈSE

Pour obtenir le grade de
Docteur

Délivré par l'UNIVERSITÉ MONTPELLIER

Préparée au sein de l'école doctorale **I2S**
Et de l'unité de recherche **LIRMM / CNRS-AIST JRL**

Spécialité: **SYAM**

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**Analysis of sensory
requirement and control
framework for whole body
embodiment into a humanoid
robot for interaction with the
environment and self**

Soutenue le 14 Décembre 2015 devant le jury composé de

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Acknowledgements

First of all, I thank Pr. Abderrahmane Kheddar to have given me the opportunity to work on such an interesting topic, as well as for his guidance all along this thesis.

I would like to thank my supervisors, Andrea Cherubini and Laura Aymerich-Franch for their precious advices. And I thank Ganesh Gowrishankar for his help and support.

I thank the members of my jury to have accepted to review my work and to have given me useful comments that improved this manuscript, Peter Ford Dominey, Gerard Bailly, Pr. Laurence Devillers.

I would like to thank Nicolas Serrurier for his help in the administrative matters and Tokiko Uga that made my stay in Japan a lot easier and enjoyable. Many thanks to Eiichi Yoshida for his help setting up in the laboratory and his constant support for the different experiments presented in this work.

I thank Pierre Gergondet, Thomas Moulard and Francois Keith for their advices and their technical skills in computer science and robotics. A special thanks to Kenji Kaneko and his precious support solving the problems encountered with the humanoid robot.

Finally I am grateful for my friends, members of the JRL and LIRMM, for their friendship that made my days in the laboratories very pleasant: Stan, Airi, Herve, Amandine, Benjamin, Giovanni, Antonio, Joris, Rafa, Joven, Hoa, Julie, Adrien, Jovana, Vincent, David, Aurelie, Antoine, Manu, Karim, Kevin.

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Introduction

The emergence of humanoid robotics opens new opportunities in assistive robotics for frail persons. Their integration in social environment would allow them to assist elderly or physically disabled people in daily tasks. Indeed, humanoid robots are, by design, best suited to evolve and interact in a human environment. Indeed, their deployment won't require a complete restructuring of human environment, such as houses and their implements. Unfortunately the current level of ground robotics technologies, such as in artificial intelligence and visual perception, do not allow humanoid robots to interact physically and socially autonomously and intuitively with humans. Recent tools of programming and conveying human intentions are much close to teleoperation tasks. Of course, the humanoid robots, whatever sophistications they reach, must be embedded by capabilities of learning through acquiring knowledge using: (i) web services, or by (ii) demonstration or (iii) imitation. When necessary skills are acquired, one needs to instruct the robot with the desired tasks to be achieved. This is done through instruction interfaces such as speech or gestures. Speech recognition have reached a considerable level of achievement but transforming human verbal/language instructions into robotic actions is a challenging open issue. Gestures, when possible by the user, have limited semantics and you may certainly agree that it is difficult to express most of our daily tasks only by body or hand gestures. There is a clear need for more intuitive and easy-to-instruct interfaces. Note that current agreed trends in robot telerobotics are based on shared-autonomy and task space control. Indeed, it is not necessary to specify the tasks at the trajectory level or even at the intrinsic constraints level. For example, the user won't instruct the robot by specifying which actuators have to move and by how much; s/he also does not need to say to the humanoid to keep balance and not collide... as these are handled by the part of the embedded autonomy. It is worth noting that instructional process is not unilateral. Indeed, recent studies show that during such teleoperation, the humanoid robot also affects the operator's behaviors and feeling [98]. But whatever interface used, the human-robot interface synergy and intuitiveness of use is best reached when a high level of embodiment can be achieved.

This work is supported by the European Union FP7 integrated project VERE (Virtual Embodiment and Robotics re-Embodiment)¹. The aim of this project is to develop a platform that allows a human participant to control a virtual or a robotic entity, called surrogate, that

¹www.vereproject.eu

they feel as their own. This feeling is called embodiment. Special attention is given to instruct the surrogate through a brain-computer interface (BCI), which allows the user to control the surrogate by thought, eventually enhanced with physiological interfaces, while remaining still at a remote location. Though-based control, would ideally allow overcoming current technologies drawbacks.

The feeling of embodiment goes beyond what is known up-to-now in teleoperation. The difference between teleoperation and embodiment lies in the feeling of ownership felt towards the controlled system. In a perfect embodiment scenario, a user would experience the same feeling as if s/he was the surrogate. In this work we study the feeling of embodiment of a user toward a robotic avatar in a scenario where one interacts with one's self.

Elderly or physically disabled people would be able to regain a certain level of physical and social autonomy with the use of a surrogate. In an ideal scenario they would be able to fetch themselves a dinner or a drink, shower themselves, or even carrying themselves to bed through the surrogate that they control.

The realization of such a complex endeavor faces the following challenges in terms of embodiment.

1. Surrogate aspect

Recent advances in humanoid robotics technology allow to “replicate” a person in a form of an android without the ability to walk, namely a Geminoid. On the other hand, some humanoid robots have walking ability, but they lack human close resemblance, e.g. “human-like” skin or facial features. The humanoid robotic surrogate used in this ideal scenario would have a different aspect from the user. Most of the current studies on embodiment toward a surrogate use “human-like” features. In our work we are interested in the embodiment into a robotic “looking” humanoid robot surrogate.

2. Embodiment toward a walking surrogate without feedback

In the above-mentioned ideal assistive robotic scenario, elderly or patients with mobility impairment would (re-)gain the feeling of mobility by means of the surrogate they embody. In order to reach this goal, several issues must be faced in terms of controllability. In telerobotics, an inherent latency occurs between the command of the operator and the realization of the task by the robot. In our work we are interested in how this latency affects the embodiment of the subject controlling a walking humanoid robot. Another problem is the appropriate control input to pilot the humanoid robot so that the user remains embodied in the surrogate even s/he cannot use gestural motions as commands (e.g. mobility impairments). In our work we investigate the embodiment felt by the subject while steering the robot without somato-sensory feedback equipment, instead, only visuo-auditory feedback is used.

3. Interaction with oneself

Most of the studies on embodiment use a fake limb or mannequin as a surrogate. Therefore, little is known about the feeling experienced by the user while the surrogate controlled by the user interacts with one's self. Several technological and physiological aspects are raised in this scenario. In case of successful embodiment, several

studies show that the feeling of touch can be experienced by the user without haptic displays, when the surrogate is touched. But what would be the experienced feeling if the surrogate would touch the user instead? In such case, does the embodiment of the user towards the surrogate stay or break? In order to study this question we developed a framework where one is able to control a surrogate via BCI to realize two scenarios. In one scenario the subject is able to control the robot to grasp a can, to walk toward one's self and to present the can to one's self in order to take a sip. In the second scenario the user is able to control the robot to come toward one's self and to manipulate one's own arm. Due to the limitation of BCI system for controlling a robotic arm, a scenario of gesture motion control was developed to especially study the feeling of touched experienced during an embodiment scenario when the surrogate touches the user and when the user touches the surrogate.

In this work we study and make progress over those challenges as follows.

In the first chapter we introduce the concept of embodiment. First, we define the feeling of embodiment which is believed to be composed of three components: self-location, ownership, agency. We present key experiments to explain the requirements for obtaining this feeling toward an artificial limb. We then show through different works in the literature how this feeling of embodiment can be extended to a whole body. All along the presentations of the state of the art, the different challenges to obtain a feeling of embodiment via a humanoid robot instead of other surrogates such as virtual avatar or mannequin are discussed. Finally we show the different applications from the knowledge learned from the study of embodiment in engineering as well as in medicine.

In the second chapter we present the framework developed to realize a self-interaction experiment. The framework is designed to be used in various scenarios in order to expand the knowledge of the embodiment. In this work we chose a scenario that explores the feeling of embodiment where one's interacts with oneself. In this scenario a user controls the humanoid robot to either bring her/himself a drink or manipulate her/his own arm. We first present the main components of the overall system composed of a user interface, vision components and control. Each of these components used in the experiment are then detailed. We then present an assistive navigation feature that we have developed to help the user to steer the humanoid. Finally, we present and discussed the results of this prototype. The prototype revealed two main issues when one interacts with oneself via a surrogate that needed to be explored separately: the walking task and the interaction task.

In the third chapter we study the feeling of embodiment felt by a subject who steers a humanoid robot. For this purpose an experiment is designed where a subject controls the humanoid robot while standing with a joystick controller. When teleoperating the robot, latencies are experienced by the subject. First, we study how partial and delayed control affect the feeling of embodiment of the user. The embodiment felt by the subject is assessed through a questionnaire. We then study how the embodiment is affected by the type of control used by the subject. Indeed, with the designed framework presented in Chapter 2 the subject controls the surrogate with a BCI and an assisted navigation system. In order to study how the embodiment is affected by the type of control (joystick or BCI) the subject is asked

to achieve a trajectory, where her/his level of embodiment is assessed by a questionnaire.

In the fourth chapter we examine the feeling of interacting with the environment or one-self with an embodied robotic arm, with regard to the results obtained in the experiment presented in Chapter 2. We first present the different challenges encountered to embody a “robotic-looking” limb instead of a “human-looking” limb. The differences in terms of requirement to establish the embodiment with a “robotic-looking” arm instead of a “human-looking” arm are then discussed. We then present the set-up used to assess the embodiment felt toward the robotic limb when interacting with the environment, one’s self and the surrogate through gesture control. The results of the level of embodiment as well as the different haptic sensations felt by the user in the different conditions are then discussed.

Glossary

AR	Augmented Reality
BCI	Brain-Computer Interface
BLORT	Blocks World Robotic Vision Toolbox
BOLD	blood-oxygen-level
CAD	Computer-aided design
COM	Center of Mass
ECoG	Electrocorticography
EEG	Electroencephalography
EMG	Electromyography
ERD	Event Related De-synchronization
ERS	Event Related Synchronisation
FLANN	Fast Library for Approximate Nearest Neighbors
fMRI	functional Magnetic Resonance Imaging
FOP	Feeling Of Presence
FPFH	Fast Point Feature Histogram
FPS	Frame Per Second
FSM	Finite State Machine
HMD	Head Mounted Display
ID	Identification
IHI	Invisible Hand Illusion
IMU	Inertial Measurement Unit
JPY	Japanese yen
JRL	Joint Robotics Laboratory
NCS	Nerve Conduction Studies
NiTE	Natural Interaction Middleware
OBE	Out-of-Body Experience
PCL	Point Cloud Library
ROS	Robot Operating System
RGB-D	Red Green Blue - Depth
RHI	Rubber Hand Illusion
SAC-IA	Sample Consensus Initial Alignment

SCR	Skin Conductance Response
SD	Standard Deviation
SIFT	Scale-Invariant Feature Transforms
SLAM	Simultaneous Localization And Mapping
SoE	Sense of Embodiment
SoT	Stack of Tasks
SSVEP	Steady-State Visually-Evoked Potential
VERE	Virtual Embodiment and Robotics re-Embodiment
WPG	Walking Pattern Generator

State-of-the art

The aim of this work is to study the feeling of a user controlling a humanoid robot to realize a task with one's self. Under certain conditions, shown in this work, the users feel as they own the artificial body that they control. This feeling is called embodiment. In the first section, the embodiment is presented by means of a proof-of-concept and the description of several key experiments and their results. Then, the different challenges and the tools necessary to explore the embodiment of a humanoid robot are presented in the following ones.

1.1 Embodiment

In this section, the notion of embodiment is presented and discussed. The term *embodiment* has been used in the literature by many fields. The definition of embodiment in each field is discussed, from which we choose the one best suited to our work. A key demonstration which illustrates the notion of embodiment is first presented. This is followed by introducing the groundwork of limb embodiment and the several works toward whole body embodiment. Finally, the different challenges to embody a humanoid robot are highlighted and the necessary tools to realize and to assess the feeling of embodiment are then presented.

1.1.1 Definitions

In the literature, the term embodiment has different meanings depending on the area of usage. In philosophy, the term embodiment is used to discuss the role of the body in shaping the mind [44]. It is also used to express the feeling of having a body [88] [18]. In cognitive neuroscience, embodiment relates to the representation of the body in the brain [11] [51]. This representation can be altered under certain neurological conditions, as seen in [77] [89]. In virtual reality, the term embodiment has been discussed with regard to presence in virtual

environments [13]. From a robotic point-of-view [60], embodiment is defined as the controller and sensory system of an agent, allowing the agent to interact physically and socially with the environment as described in [61]. For example, in [115], simulation capability is embodied in a humanoid robot.

In [82], a Principal Component Analysis of the results of a set of questionnaire items shows that the feeling of embodiment is composed of three subcomponents which are, sense of self-location, sense of agency and sense of body ownership. Each of the subcomponent represents a key element of the feeling of embodiment toward an artificial body.

- **Sense of self-location:**

Self-location refers to where one feels located in space, which is different from where one perceives to be located in space [76]. In the case of out-of-body experience (OBE), these two locations are different. In this case, the person perceives her/himself from outside her/his own body.

- **Sense of agency:**

A definition of the sense of agency is given in [18] as having:

“global motor control, including the subjective experience of action, control, intention, motor selection and the conscious experience of will”

This sense can be disturbed with a difference between a movement and the visual feedback of this movement, as discussed in [129] [17] [39].

- **Sense of body ownership:**

The sense of body ownership represents the feeling that the body belongs to one's self [43]. Certain pathologies, like somatoparaphrenia, alter this feeling and can cause the patients to not recognize their own limbs as being theirs.

In the rest of this work we choose the definition of the sense of embodiment (SoE) as described in [71] to refer to:

“the ensemble of sensations that arise in conjunction with the being inside, having and controlling a body”

1.1.2 Proof-of-concept

In [20], an experimental manipulation of embodiment with a foreign limb is presented, namely the Rubber Hand Illusion (RHI). The set-up of the experiment is shown in Figure 1.1. In this experiment, the subject is seated in front of a table with one's left hand resting on it. A second hand made of rubber, with the appearance of a human hand, is placed in front of the subject near one's hand. A standing slab of cardboard is placed on the table so that it separates the rubber hand and the subject's hand. The cardboard slab is used to prevent the

subject to see one's real hand. The experimenter is facing the subject. During the experiment, the subject is asked to stay focused on the rubber hand while the experimenter strokes the rubber hand and the subject hand with a brush synchronously. After 10 *min* of synchronous stroking, the subject indicated that s/he felt the stroke of the brush on the rubber hand and not on her/his hand. According to [30] [81], the illusion can occur only after 10 *s* to 20 *s* following the synchronous visuo-tactile stimulation.



Figure 1.1: Experimental setup of the Rubber Hand Illusion (Courtesy from [55]).

In order to confirm the illusion and to obtain a quantitative measure of its strength, a follow-up experiment is devised. In this follow-up experiment, the subject is asked to perform an inter-manual reaching task before and after the stroking period. The set-up of the experiment stays the same as for the RHI with the addition of the subject's right arm asked to be placed below the table as seen in Figure 1.2.A. The inter-manual reaching task is performed by the subject eyes closed and consists in placing the hand located below the table under the hand placed above the table as shown in Figure 1.2.B. After the illusion is induced the subject positioned one's hand (below the table) near the rubber hand instead of near one's "real" hand. Further tests demonstrated that the displacement between the subject "real" hands increases with the stroking time. Moreover, when the stroking of the subject hand is asynchronous, the displacement is lower than in the synchronous case. In the literature, this displacement is called "proprioceptive drift". The drift is believed to increase with the level of embodiment. A qualitative way to measure the embodiment is to use a questionnaire at the end or during the experiment. During the questionnaire, the subject assesses or denies several statements by giving them a grade from "strongly disagree" to "strongly agree" related to her/his feeling of embodiment. In our work, we evaluate the embodiment felt by the subject with a questionnaire designed to assess each subcomponent of the embodiment.

The results of the RHI provided a first major step toward the study of embodiment of a foreign limb. The RHI experiment also showed that visuo-tactile synchronous stimulation is sufficient to induce a feeling of ownership toward an external artificial limb. In our work the visual aspect and the type of stimuli used to induce the illusion differ from the classical RHI

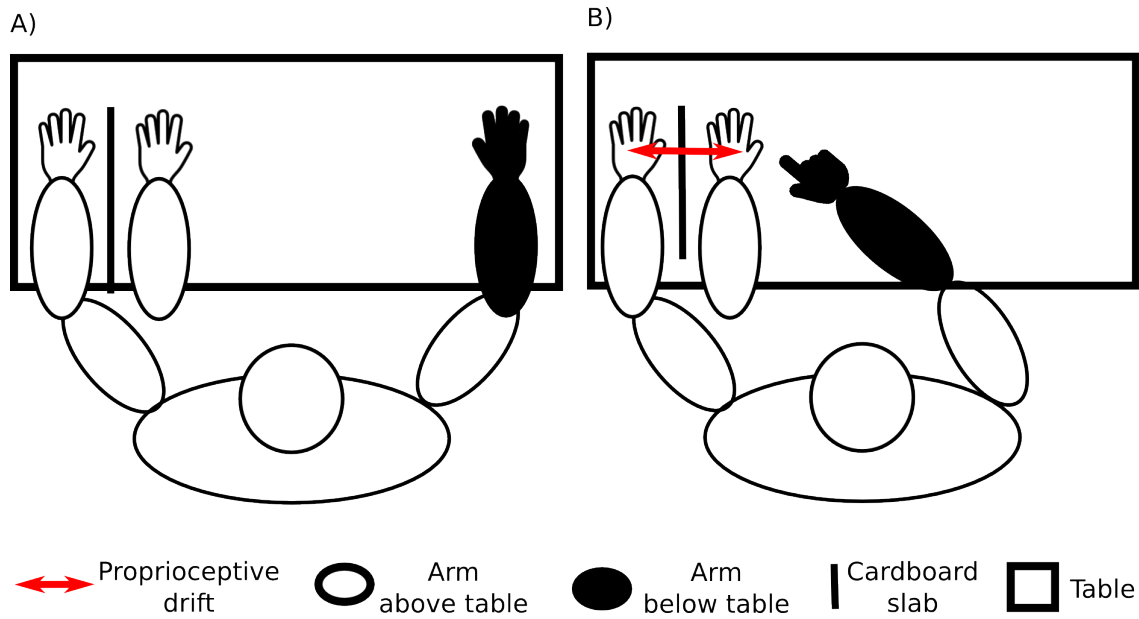


Figure 1.2: Experimental set-up of the inter-manual reaching task. A) The classic set-up of the RHI with the subject's right arm placed under the table. B) Inter-manual reaching task to determine the proprioceptive drift

experiment. In the following section, several variations of the RHI are shown to explain the different aspects of the embodiment related to the visual appearance of the artificial limb as well as the different types of stimuli used to induce the feeling of embodiment.

1.1.3 Artificial limb embodiment

In order to further understand the limb embodiment mechanism, the RHI demonstration has been replicated several times by many teams and with different variations.

1.1.3.1 Variation of stimuli

In [29], the brush used for tactile stimulation in the classic RHI has been replaced by a beam of light that produces an illusion of tactile or thermal sensation. In this experiment (see Figure 1.3), the illusion of embodiment is realized only by stroking the fake hand with the beam of light, without stimulating the real subject's hand. This experiment induced an illusion of ownership toward the rubber hand equivalent to the classic RHI in terms of strength. The subjects also reported feeling a thermal or tactile sensation associated with the light from the fake hand.

The classic RHI experiment demonstrated that the feeling of ownership can be induced in a motionless artificial limb with a synchronous visuo-tactile stimuli. However, with this set-up, the feeling of agency of the subject toward the artificial limb cannot be well assessed with a rigid rubber hand. In [67] a variation of the RHI is used to study the feeling of ownership and agency toward a moving rubber hand. In this study, the subject is able to move the right index finger of the rubber hand by moving his own right index finger as seen in Figure 1.4.A.

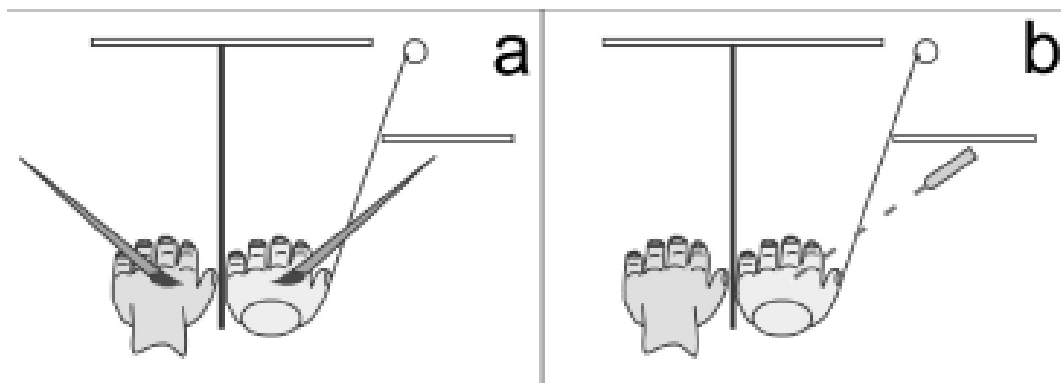


Figure 1.3: Set-up of the thermal Rubber Hand Illusion, from [29]. a) Representation of the classic RHI experimental set-up. b) Representation of the experimental set-up using a beam of light on the rubber hand instead of a brush as a stimulus.

With this set-up, a quantitative measure of the “proprioceptive drift” is also realized with the left index finger of the subject as seen in Figure 1.4.B. This study demonstrates that a visuo-motor stimuli can induce a feeling of ownership and agency toward the artificial limb. Moreover, the study shows a dissociation between the feeling of agency and ownership. Indeed, the results show that in the condition where the subject’s finger stayed still and the rubber hand’s finger moved, the agency is removed, but the ownership is kept. However, in the condition where the position of the rubber hand is different from the subject’s hand, the ownership is reduced, but the agency is kept. This finding further reinforces the idea that the embodiment is composed of the feeling of agency, ownership and self-location, as stated in [82].

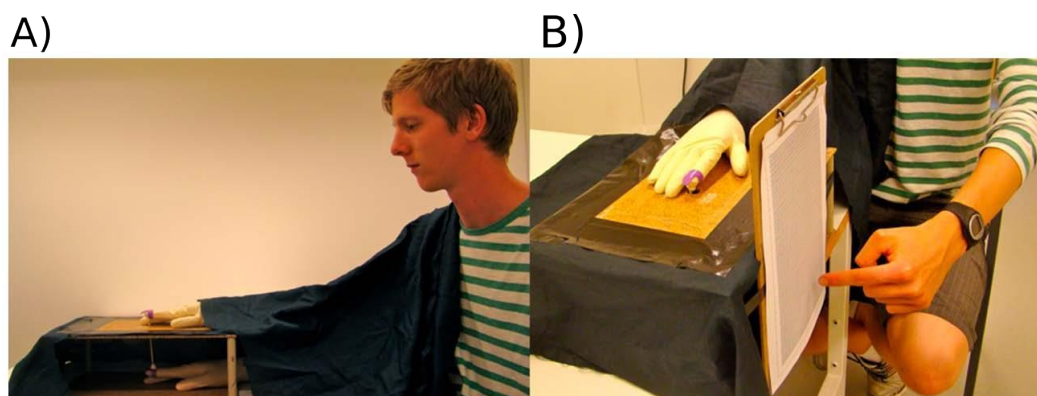


Figure 1.4: Experimental set-up of the moving RHI. A) A blanket covers the right hand of the subject and the fake hand. The real hand of the subject is placed below the fake hand which is in sight of the subject. The index fingers of the real and fake hands are rigidly linked with a rod and two plastic rings. B) The subject indicates with her/his eyes closed where s/he felt her/his right index finger was located by placing her/his left index finger to the corresponding location on a board. (courtesy from [67]).

1.1.3.2 Visual aspect

Another important question that the classic RHI set-up arouses, but does not answer, is the visual aspect of the artificial limb. How important is the visual aspect of the artificial limb, to enable the feeling of embodiment. Is a “human-looking” limb part of the minimum conditions required to elicit this feeling?

Several studies have questioned the necessity of human visual appearance of the artificial limb to create the feeling of embodiment. In [6] a variant of the RHI demonstration studied the skin conductance response (SCR) (as seen in Figure 1.5) of a subject when the rubber hand (or table) is threatened by a fake harmful action. The study mentions that the subjects felt a lesser feeling of embodiment when the rubber hand is replaced by an empty space. In those conditions, the empty space (table) and the subject’s hand are synchronously stroked (as seen in Figure 1.5.B) like in the classic RHI demonstration (as seen in Figure 1.5.A).

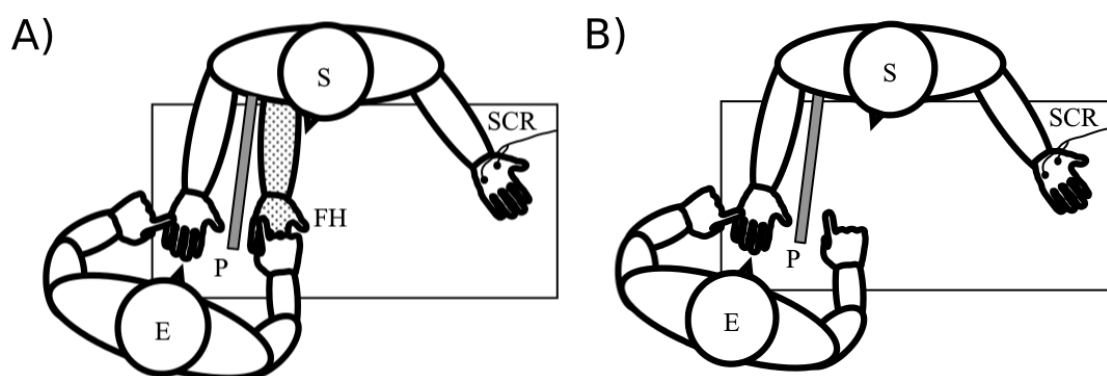


Figure 1.5: Experimental set-up of the RHI with SCR measurement. A) Classic RHI experiment set-up with SCR measurement. B) The rubber hand is replaced with empty space (in this case a table). Abbreviations: E, experimenter; S, subject; P, partition; FH, fake hand; SCR, SCR electrodes. (courtesy from [6]).

In [140], the RHI is realized with an incongruent orientation as well as with a wooden stick instead of a rubber hand to study the influence of visual aspect and orientation of the artificial limb. The study states that one of the minimum conditions to feel the rubber hand as one’s own is the human resemblance and reasonable orientation of the fake hand. The same conclusion is shown in [109]. In a recent study [54], a new experiment called the *invisible hand illusion* (IHI) further explores the question of the visual aspect and orientation of the fake limb. In this study, several behavioral and functional Magnetic Resonance Imaging (fMRI) experiments demonstrate that it is possible to induce the illusion of an invisible hand on non-amputated subjects. The different experiments replicate the RHI with a rubber hand, an empty space (Figure 1.6.A), a rubber stump (Figure 1.6.B) and a wooden block (Figure 1.6.C) as a non-corporeal object. In this study, the subjects felt the illusion with the rubber stump and the empty space. However, with the non-corporeal wooden block the subjects did not felt the illusion.

This result is also demonstrated in [139]. The results of the IHI experiment show that, to induce the feeling of ownership toward a foreign limb, the artificial limb needs to be an object

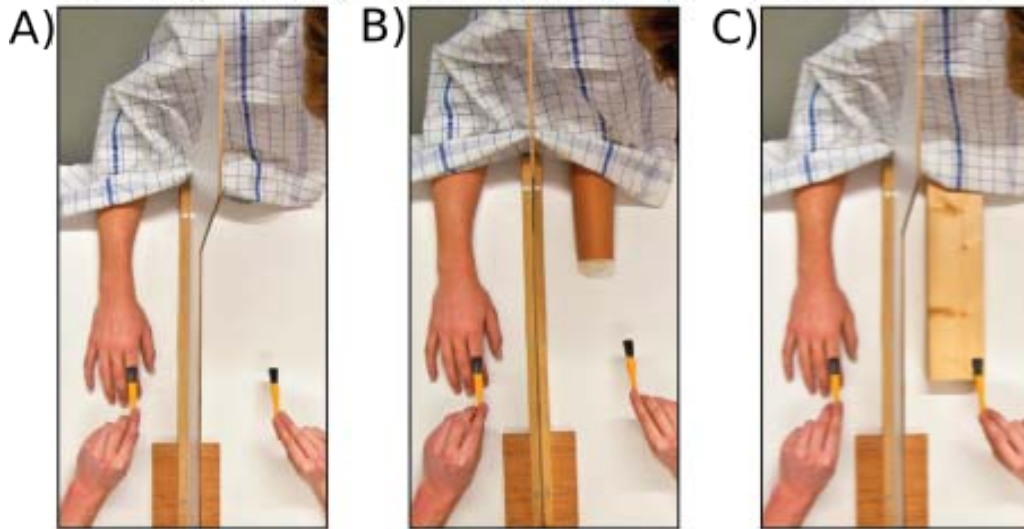


Figure 1.6: Experimental set-up of the invisible hand experiment. A) Empty space. B) Rubber stump. C) Wooden block. (courtesy from [54]).

that does not cancel the illusion and be located in the peri-personal space of the subject with a reasonable orientation. The question of the visual aspect of the artificial limb is discussed in our work as well, since we are working with a humanoid robot that has the similar geometric structure of an average human [69] without the human-like skin feature as in [70] and [98]. The “hands” of the robot are however not anthropomorphic. The IHI experiment showed that the important point of the visual aspect is to avoid a “negative effect” on the illusion. In our case the robot’s hands which are grippers, have the same function as real hands. With the results showed by the IHI experiment, we expect that the similar function between the robot hands and the human hands will avoid this “negative effect” on the illusion.

In [113] and [31], the RHI is realized with blindfolded healthy subjects. In this variant of the RHI, the subjects are asked to touch the rubber hand while the experimenter touches the subjects real arm at the same location. Interestingly, in [113] this test was also realized on blind subjects, but the illusion was not successful.

1.1.3.3 Virtual limb

Limb embodiment has also been studied using a virtual hand as the fake hand. A recent study [128], showed that subjects respond in a lifelike way, even in a virtual environment. This result means that the RHI could be experienced in a virtual environment as if it would be in reality. A first experiment, using image projection instead of virtual reality was realized in [62]. In this study, a video projection of a real subject’s hand was used as a fake hand to realize the RHI. However the results showed that the illusion of ownership was weaker with the projected hand than with the rubber hand.

In [134], the RHI was realized within a virtual environment to study the embodiment of a virtual limb instead of a projected limb. This experiment is referred as the virtual hand illusion. In this set-up, the visual informations perceived by the subject are all computer

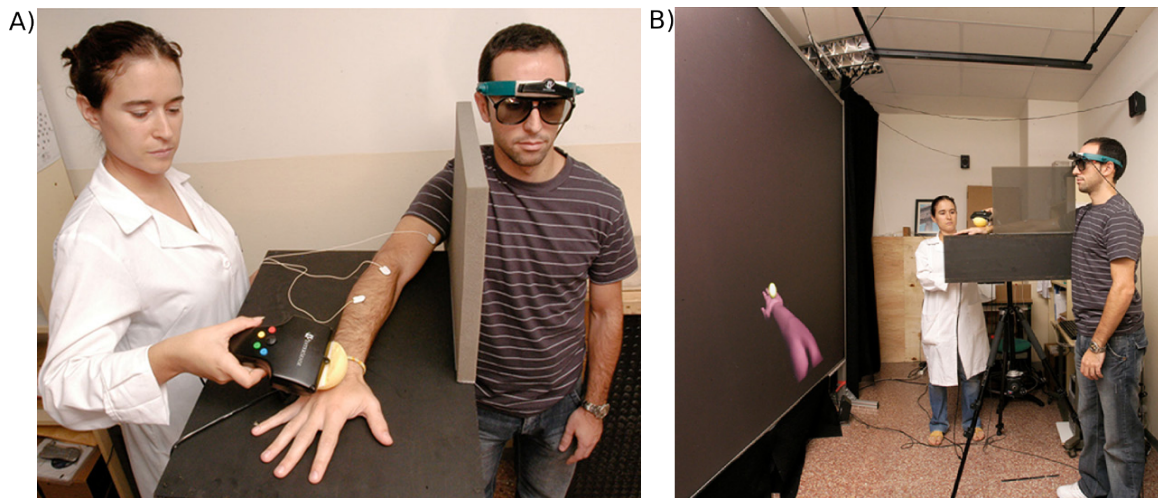


Figure 1.7: Experimental set-up of the virtual hand illusion. A) The subject wears a head tracker and a pair of passive stereo glasses. The experimenter stimulates the subject's real hand with a 6-degree freedom Wand, whose position is tracked. B) The virtual hand in the screen is seen from the subject's perspective as projecting out of her/his right shoulder. Like in the classic RHI, the subject's own hand is out of view and resting on a support. In the projection, the subject sees a sphere striking in synchrony and in the same place on the virtual hand as the touch stimuli performed to her/his own hand. (courtesy from [134]).

generated. In this experiment, the subject is head-tracked to synchronize her/his field of view with the virtual environment as seen in Figure 1.7. One of the main differences compared to the work done in [62] is that the fake hand is purely virtual instead of a projection of a real limb. The results of this experiment show that the subjects are able to feel ownership toward a virtual limb. This virtual set-up offers a new possibility to explore the embodiment that cannot be done in the real world. In particular, it is possible to modify the visual aspect of the fake hand and add a motion to it.

1.1.3.4 Multisensory integration

The different variations of the RHI, with different types of stimuli or visual aspect, converge toward the idea that the illusion is a success when there is a correlation, between stimuli. Embodiment can also be achieved via multimodal methods (gaze and speech) [99], a correlation between intention and action with Brain-Computer Interface (BCI) [4] or gesture control [100] of artificial body as detailed in section 1.1.4.3). In the case of the RHI, the illusion is successful with a correlation between visual and tactile stimuli. This was confirmed with quantitative measures using a fMRI on subjects realizing the RHI experiment. In [33], brain activity has been identified in the area associated with multisensory integration on subjects during the RHI. This result is also shown in [54]. It is also reported that the activity was stronger when the rubber hand had a correct orientation. In [33] [31], it is suggested that the neurons in this identified multisensory area, take part in the integration of the sensory and proprioceptive informations. They are believed to be responsible for the feeling of ownership toward the artificial limb.

Following the work done on limb embodiment, several studies have been conducted to obtain the feeling of embodiment toward a whole body instead of a limb alone [135]. In the following section, we present the adaptation of the work done on “single limb embodiment” to “whole body embodiment”.

1.1.4 Whole body embodiment

1.1.4.1 Out-of-body illusion

One of the major differences between the embodiment of a limb and the embodiment of a whole body is the modification of the subject’s viewpoint. Indeed, in order to embody a whole body, the subject’s viewpoint must be located on the artificial whole body (also called surrogate). In this situation, the subject would be able to see one’s self. This situation is called an out-of-body experience (OBE) and have been reported in patients suffering certain clinical conditions affecting the brain such as strokes or schizophrenia. In [7], the OBE is induced on a subject, by directly stimulating an identified area on the left temporoparietal junction with implanted electrodes. The subject reported a shadow presence with a similar posture.



Figure 1.8: Experimental set-up of the out-of-body illusion (courtesy from [30]).

In [30], an experimental set-up is designed to recreate the conditions of an OBE on a healthy subject. To do so, a subject seated still on a chair is asked to wear a head mounted display (HMD), which feeds back the video recorded by a camera placed behind the subject

as seen in Figure 1.8. In order to induce the illusion, a synchronous visuo-tactile stimulation is used (same as the RHI). In this case, the visuo-tactile stimulation consisted of a tapping motion exercised on the subject's chest. The tapping motion is also realized synchronously on the subject's chest and in front of the camera (as seen in Figure 1.8). Doing so, the subject is able to feel and see the touch at the same time, but from the camera point-of-view. In this set-up, the subject's sees one's self from the back, but think of it as a mannequin, an empty shell. The body seen in front of her/him is then disowned.

This disown phenomena is also reported toward one's real hand in [46] without the need of a fake hand. In this case, one's hand is disowned by applying an asynchronous visuo-tactile stimuli on one's real hand. However, in the case of the OBE illusion, the disownership of one's body occurs because the subject takes over an illusory body.

In [30], the OBE illusion is measured by several means along several experimental set-ups. In a preliminary experiment, the subject of the illusion is asked a set of questions relative to the embodiment like in the classical RHI with the addition of questions relative to the self-location (instead of the hand location). In this experiment, the illusion is induced after 2 *min* of stimulation. In order to confirm this result with a quantitative measure a second experiment was devised. In this second experiment, the OBE illusion is induced with the same method used in the preliminary experiment. The assessment of the strength of embodiment is done by measuring the SCR of the subject when the illusory body is threatened by a fake blow to the torso with a hammer. The measurement is done during two conditions. In one condition, the visuo-tactile stimulation is done synchronously and in the other condition the visuo-tactile stimulation is done asynchronously. The results show that in the synchronous condition the threat response of the subject is superior (as well as the embodiment questions grades) than in the asynchronous condition. This result demonstrates the success of the OBE illusion. In [53], the same set-up and measurement are used to demonstrate that the subject's real body is disowned. In this case, the threat response is measured while threatening the subject's real body instead of the illusory one.

The measurement of the response to threat has also been used in the case of the RHI [54] [55] [6] to evaluate the level of embodiment toward the artificial limb. In [34], it is also shown that the threat to the rubber hand, after inducement of the illusion, elicits a cortical anxiety response visible with fMRI.

Recently a robotic set-up [56] has been developed to self-induce a variation of the OBE illusion [19] to study the feeling of presence (FOP). The robotic set-up is represented in Figure 1.9.

As seen in Figure 1.9, the robotic system is composed of a master robot held by the subject and a slave robot placed behind the subject. During the experiment, the subject is asked to place one's index finger in the master robot. In order to induce the FOP illusion, the motion of the master robot is mapped onto the slave robot allowing the subject to tap one's own back. The robotic system allows the subject's motion to be mapped with/without a delay and with/without a somatosensory force feedback. During the experiment, the subject is blindfolded and standing. With this set-up, the FOP is induced using motor-tactile stimulus.

In the case of synchronous stimulation with force feedback, the subjects reported a self-location in front of their real body. In this case, the subjects have the sensation of touching

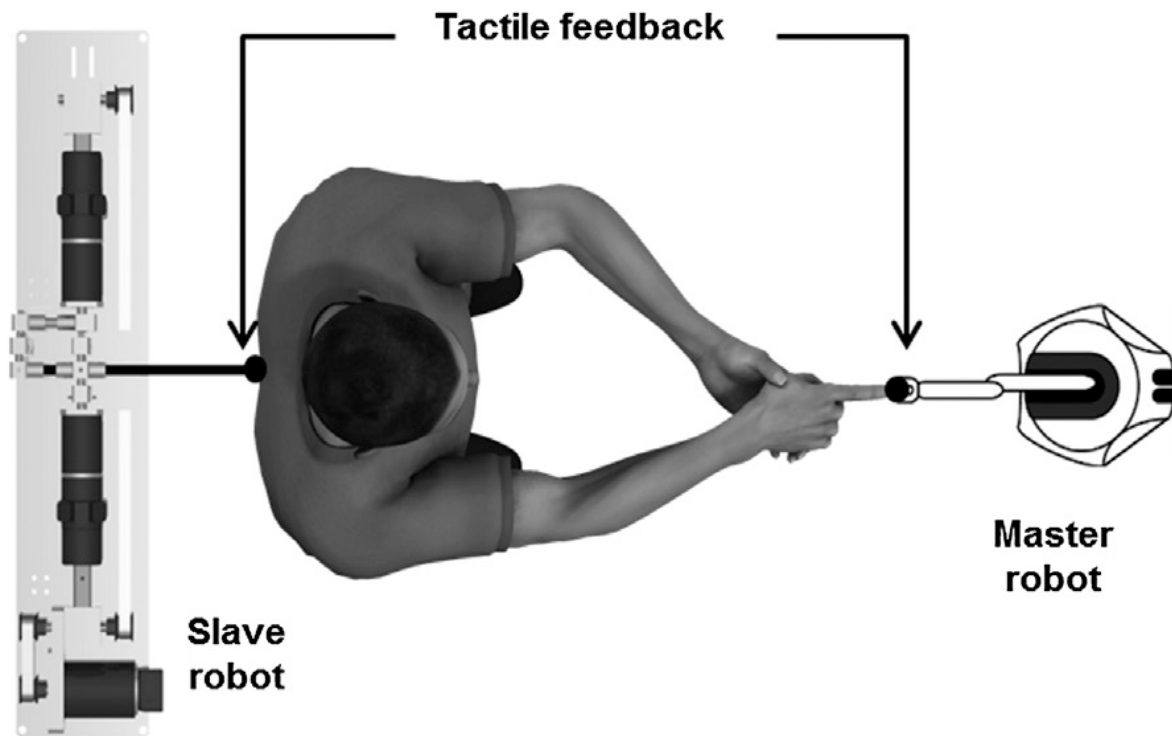


Figure 1.9: Experimental set-up of the self-induced out-of-body illusion (courtesy from [19]).

themselves. This difference between the subject’s real body location and self-location is similar to the “proprioceptive drift” experienced during the RHI and offers another means of quantifying the level of embodiment of a subject. Similar results have been found in [78] using virtual reality and visuo-tactile stimulation.

Interestingly, in the case of asynchronous stimulation, without somatosensory feedback, the subjects reported a self-location located behind their physical body. In this case, the subjects reported the feeling of a presence behind themselves. During the experiments, the neurological patients reported a stronger illusion than the healthy subjects.

The OBE illusion results show that by artificially changing the point-of-view of the subject, it is possible to disown one’s own body and take over an illusory one. The importance of the first person perspective is also demonstrated in [136], where a subject is able to own a virtual body. In the OBE illusion, the illusory body is just represented by the camera placed behind the subject. In the next section, we present the work of embodiment toward artificial body.

1.1.4.2 Body swap illusion

In [112] five experiments are conducted using the set-up shown in Figure 1.10 to explore the embodiment of artificial body using the results obtained from the OBE illusion. A first experiment is realized in order to induce the illusion of ownership toward an artificial body; in this case, a “man-like” mannequin. Like with the OBE illusion, the first-person view from

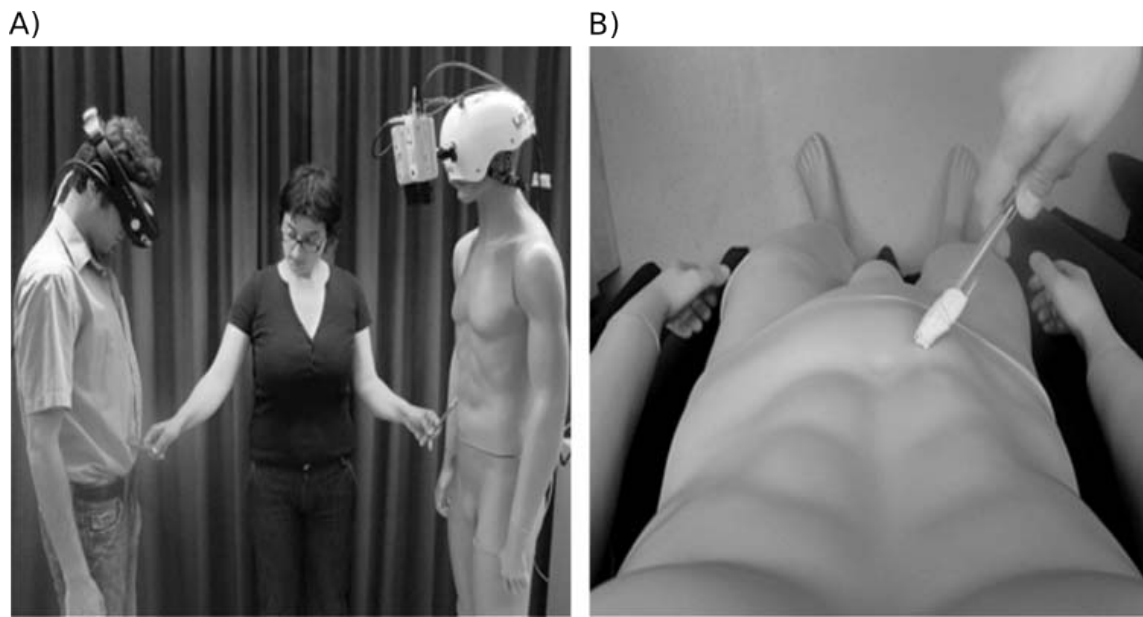


Figure 1.10: A) Experimental set-up of the body swap illusion. B) View of the mannequin head mounted camera displayed on the subject's HMD (courtesy from [112]).

the “target” is provided through a pair of stereoscopic cameras mounted on the mannequin’s head which is oriented downward as shown in Figure 1.10.A. The subject wears a HMD and is able to see the video recorded by the cameras. In this configuration, the subject sees the mannequin body as seen in Figure 1.10.B.

In the first experiment, the illusion of ownership is induced with a visuo-tactile stimulation. The experimenter touches synchronously the mannequin and participant stomach. As a control test, an asynchronous stimulation is performed as well. The feeling of embodiment is measured with a questionnaire answered by the subject. The results showed that the illusion of ownership toward the mannequin is successful in the synchronous case and unsuccessful in the asynchronous case. These results are in accordance with the results previously found with the RHI illusion.

In a second experiment, the same test is realized, but with a physiological measure. A SCR measure of a threat to the mannequin stomach is performed and confirms the finding of the first experiment.

A third experiment is used to control if the embodiment is only localized toward the stimulated part of the bodies. In this experiment, the stimulation is realized on the abdomen or the hands of the artificial and real bodies. However, the threat on the mannequin remains on the stomach. The results show that the level of anxiety is higher in the synchronous condition compared to the asynchronous control condition for both stimulation locations. This result suggests that the stimulation of one body part induces ownership for the whole body.

A fourth experiment is performed to study the impact of the visual aspect of the artificial body in whole body embodiment. Does the artificial body need to be “human-like” in order to achieve whole body embodiment? In order to answer this question, a SCR to

a threat measurement is realized on a mannequin (“human-like”) and a rectangular object (“non human-like”). The results show a successful embodiment toward the mannequin, but an unsuccessful embodiment toward the rectangular object. In view of the results, the study states that only “human-like” bodies are able to be embodied. Then the question is, what constitutes a “human-like” body in terms of visual aspect? In our work, a humanoid robot without “human-like” skin is used and the question of the visual aspect is crucial. Therefore, further investigations are made in our study concerning the impact of the “robot-like” visual aspect on the embodiment in chapters 4 and 3.



Figure 1.11: Experimental set-up used to induce the “body swap illusion” (courtesy from [112]).

The final experiment is realized to study the feeling experienced during self-interaction. The previous experiments showed the successful embodiment toward an artificial body (mannequin), but the question remains as to whether this embodiment is kept if the subject sees and interacts with her/his real body through the owned artificial body. In order to study this issue, in the final experiment, the mannequin is replaced with an experimenter as seen in Figure 1.11. The pair of cameras are then mounted on the experimenter’s head which is oriented toward the subject’s body. With this configuration, the subject is able to see her/himself from the knee to the shoulder. The subject is then asked to present one’s arm as to shake someone’s hand. In order to induce the embodiment, the subject and the experimenter are asked to squeeze each other’s hands for two minutes. In the synchronous condition the experimenter and the subject squeeze each other’s hands in synchrony. In the control condition, the experimenter squeezes the subject’s hand in an alternating rhythm in reference to the subject (no synchrony). The results of the experiment show that the embodiment is established also in this configuration. Even though the subject recognizes one’s own body, the subject believes the experimenter’s arm and body to be one’s own. Interestingly the tactile sensation felt from

the handshake is sensed by the subject from the experimenter's arm. This result is similar to the one obtained with the RHI in "limb embodiment".

This experiment showed interesting results concerning the embodiment feeling while the subject is interacting directly with her/his surrogate. In chapter 2 we present a new set-up to further explore this interaction. Indeed, in the configuration presented in [112] the subject does not have full control over her/his surrogate which, in this case, is an experimenter. In our study, we use a humanoid robot as a surrogate so that the subject is able to interact with her/himself freely either by thought or gesture control. This set-up enables us to further investigate the embodiment feeling during self-interaction.

1.1.4.3 Android embodiment

As discussed in the previous sections 1.1.3 and 1.1.4, "limb embodiment" and "whole body embodiment" studies rely heavily on "human-looking" limb and surrogate to induce the embodiment. In order to further investigate this issue, android robots have been developed [64] [70] to remove the influence of the "robotic-looking" aspect of humanoid robots such as [69]. Androids are robotic systems that are designed with a high degree of anthropomorphism in terms of visual aspect human-resemblance, as well as for their motion capabilities.

Presence



Figure 1.12: Geminoid robot HI-1.(Courtesy from [63]).

In [98] a teleoperated android is presented, namely Geminoid HI-1. Geminoid has been designed to be the duplicate of an existing human being as seen in Figure 1.12. Since the first

Geminoid HI-1, other Geminoids have been made which are based on other existing human beings. Geminoid allows the study of the relation between human and robot in depth, such as personality trait. The visual aspect is taken from an existing human being by making a silicon mask of the subject. The shape and skin of the android are designed to match the original subject. The pneumatic actuators of the Geminoid are placed in a specific configuration to offer a smooth motion capability as well as a realistic facial expression. The Geminoid is used especially for interacting with other people and is not designed to walk. Therefore, the Geminoid is seated during the interaction experiments. The actuators and speakers embedded into the Geminoid face allow the subject's facial expression and sound to be mimicked. The interaction with another person is made through an interface controlled by the subject. The interface allows the subject to speak and execute pre-recorded motions on the robot. The use of pre-recorded motions is necessary due to the complexity of the Geminoid and real-time motion generation. This also ensures the safety of the other person interacting with the Geminoid. The pre-recorded motions of the Geminoid are generated by analyzing the motions of the duplicated subject. With both appearance and motions copied from the duplicated subject the Geminoid ensured a high level of mimicry with the duplicated subject.

Geminoids were first made with the intention to study the feeling of presence, i.e. how a person perceives the human existence. Would the fact that the surrogate (in this case Geminoid) looks and moves like a human is enough to be perceived as a human existence by a third person (or the duplicated subject her/himself)? The first reaction of the duplicated subject in front of the Geminoid was that "[...] it was like looking in a mirror. However, when it began moving, it looked like somebody else, and I couldn't recognize it as myself." [98]. Another interesting result is the adaptation of the duplicated subject's motions to the Geminoid motions. The duplicated subject reported "The current Geminoid cannot move as freely as I can. I felt that, not just the Geminoid but my own body is restricted to the movements that HI-1 can make" [98]. Even if the Geminoid has been designed to mimic the duplicated subject, the generated motions are not perfect. During the control task of the Geminoid, the duplicated subject tended to reduce her/his motion capability to mimic the motion of the Geminoid. Finally, similar results to the RHI and body swap illusion were found. Indeed, when a third person touched the Geminoid, the touch was also felt by the duplicated subject. Even though the duplicated subject had only an external third-party view of the scene (not first person perspective like in the RHI or body swap illusion) and no tactile feedback. In this case, the feeling of ownership toward the Geminoid is believed to be induced by socially interacting with the third person through the Geminoid. Before the third person touched the Geminoid, the duplicated subject socially interacted with the third person through the interface which allowed to have a vocal conversation, launch pre-recorded motions such as nodding and move the Geminoid's head.

Ownership through social interaction

The influence of social interaction on ownership toward the Geminoid has been specifically studied in [99]. In this study, three parameters of a social interaction between the Geminoid and a third person (named interlocutor afterwards) are analyzed. These parameters are: the

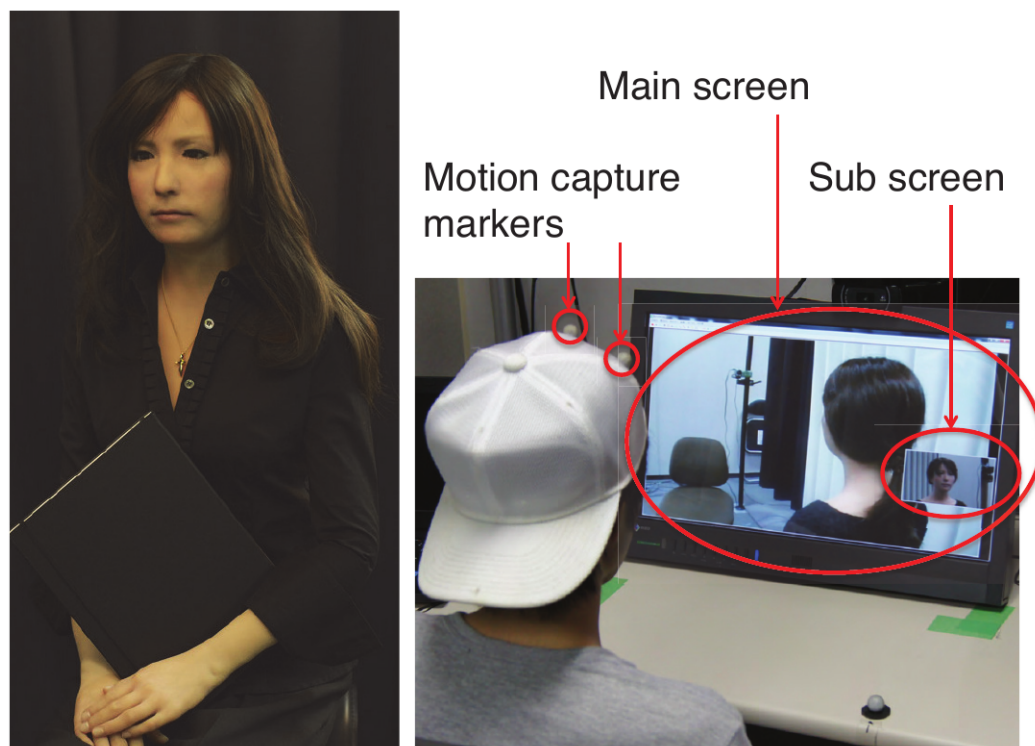


Figure 1.13: Geminoid F and its teleoperation interface (courtesy from [99]).

visual feedback of the interlocutor, the reaction of the interlocutor in reference to the social interaction and the control of the Geminoid by the teleoperator.

In this study, the Geminoid F (shown in Figure 1.13) is used due to its improved facial expression features compared to the Geminoid HI-1 which is more appropriate for manipulation tasks. The Geminoid is teleoperated through an interface allowing facial expression and voice mimicry [65]. The teleoperator is also able to hear what the Geminoid hears. The teleoperator is equipped with a motion capture marker so that her/his head motion can be mapped onto the Geminoid's head. The visual feedback available on the interface shows the interlocutor in a near person view on the main screen and the face of the Geminoid on a sub screen (shown in Figure 1.13). In this experiment, no pre-recorded motions are used, only the head motion of the Geminoid is used.

The experiment started with a practice phase where the teleoperator was instructed to move one's head in the Geminoid control condition. After the teleoperator observed the Geminoid's head moving through the interface, the experimenter touched the Geminoid. After this interaction, questions were asked to the teleoperator to evaluate her/his feelings. The questions focused on: the experienced feelings while controlling the Geminoid, if the touched was felt through the Geminoid and if the teleoperator felt located in the Geminoid's room. After this practice phase, the conversation phase started through the Geminoid with (or without depending on the condition) an interlocutor. The topic of the conversation was either common or controversial to study the evoked effect. At the end of the conversation, the experimenter touched the Geminoid and asked the questions to evaluate the teleoperator's

feeling before the beginning of the next condition.

The results showed that the sense of ownership toward the Geminoid was the highest when teleoperator was able to control the Geminoid and when the interlocutor was visible and reacted during the conversation. Interestingly the sense of ownership was improved independently of the control by the teleoperator when the interlocutor was visible in the interface compared to when the interlocutor was not visible. This result showed the importance of the social interaction in the sense of ownership. The influence of control or no control over the surrogate is further examined in our work in chapter 3 during a walking task.

In the next section, another experiment is presented with the Geminoid to explore the feeling of ownership through gesture control.

Limb ownership through gesture control

In [100] limb ownership toward the Geminoid is studied. Following the results obtained with the RHI, the Geminoid is used to examine if the feeling of ownership could be transferred to a robotic surrogate with a “human-looking” aspect through visuo-motor stimulation. In this study, the influence of the delay in the control of the Geminoid is also considered in the feeling of ownership.

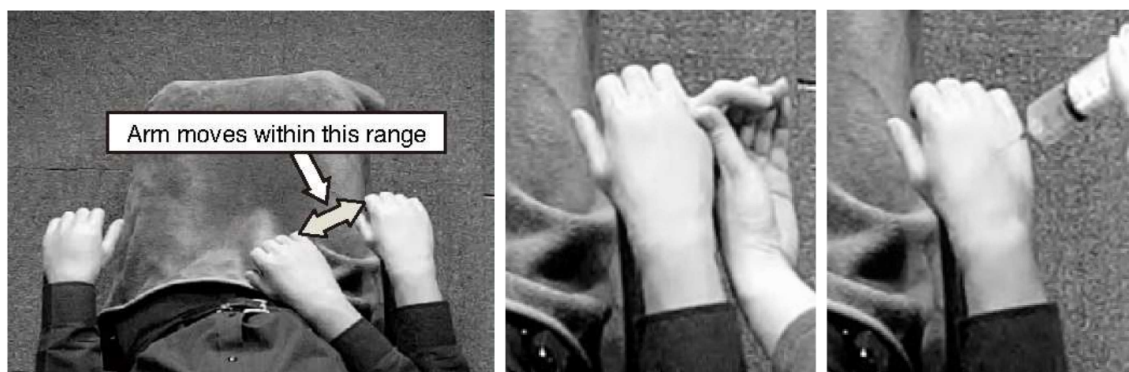


Figure 1.14: Simulated image from the Geminoid perspective showing the motion capabilities, the finger bending and the injection threats (courtesy from [100]).

Before the start of the experiment, the subjects are asked to look at the Geminoid which is highly similar to a real person in order to establish a social connection. In this experiment, the subjects are seated and are asked to look downward like the Geminoid initial pose. A motion capture marker is placed on the right hand of the subjects. The measure of the ownership feeling of the subjects is done with a questionnaire and a SCR to threat. In this experiment, the embodiment feeling is created through visuo-motor congruency when the subjects are asked to move their right hand and see the similar motion realized on their HMD from the Geminoid’s viewpoint as seen in Figure 1.14. The threat is then evoked by showing through the HMD a finger bending scene or an injection scene inflicted to the Geminoid’s hand as shown in Figure 1.14.

In this set-up, to control the time delay of the robotic system, all the video sequences showed in the HMD are not experienced in real-time but are pre-recorded from the Geminoid

viewpoint. This method is used for the “hand motion” of the Geminoid as well as the threat scenes performed on the Geminoid hand (injection and finger bending). The marker placed on the subjects right hand is used to match the subjects hand position and the Geminoid’s hand position in the video sequences.

By rendering pre-recorded image sequences in the HMD, the time delay between the subjects hand motion and Geminoid visual feedback can be manually set to create three conditions. A first condition with no delay, a second condition with a delay of 1 s, and a third condition where the Geminoid’s hand stays still despite the subjects hand motion. These three conditions are hereafter called respectively no-delay, delay and still.

The results, given by the SCR and the questionnaire, show a significant difference between the no-delay and still conditions in the case of the injection threat. This strongly suggests that the transfer of body ownership from the subject toward the robotic system is successful when there is no delay between the gesture of the subject and the visual feedback of this motion realized by the Geminoid. But this condition is not realistic. In a practical use, a teleoperated robotic system is subject to inherent latencies and delays due to the network and control in particular. Interestingly, the results show no significant difference between the delay and no-delay conditions which is different from the results found with the RHI. As we have seen before, the RHI realized with a visuo-tactile or a visuo-motor asynchronous stimuli caused the embodiment to fail [20] [6] [67] [112]. In [133] it is demonstrated that the delay of discrepancy between the stimuli should be less than 300 ms in order to induce a strong feeling of ownership toward the rubber hand. In this experiment, the fact that no significant difference between the delay (of 1 s) and no-delay conditions is found in terms of ownership suggests that the feeling of ownership toward a teleoperated robotic system might be more tolerant to a delay in the case of visuo-motor stimuli compared to a visuo-tactile stimuli like in the RHI.

In our work, this result is important since we want the subject to teleoperate a humanoid robot. In our experiment, the subject is asked to teleoperate the humanoid robot in order to realize a walking task before realizing an interaction task. In order to study the embodiment feeling during the walking task, we examine the feeling of embodiment when the subject teleoperates the robot walk with a delay in chapter 3.

Body ownership through BCI

The previous studies show that the body ownership transfer toward a “human-looking” robotic system is possible with a visuo-motor stimuli or a social interaction. In our work where we want the subject to interact with one’s self, the gesture control might not be the safest way. Indeed, with the gesture control, the subject might inadvertently touch the humanoid robot which performs the motion and might harm one’s self. In the case of self manipulation, the solution chosen in this work is to control the humanoid robot through BCI. In section 1.2 different BCI technologies are presented.

In [4] [5], the feeling of ownership toward a Geminoid which is teleoperated through BCI is studied. In the previous section 1.1.4.3, the feeling of ownership is obtained through visuo-motor stimuli, but it does not prove that the feeling of ownership would occur also

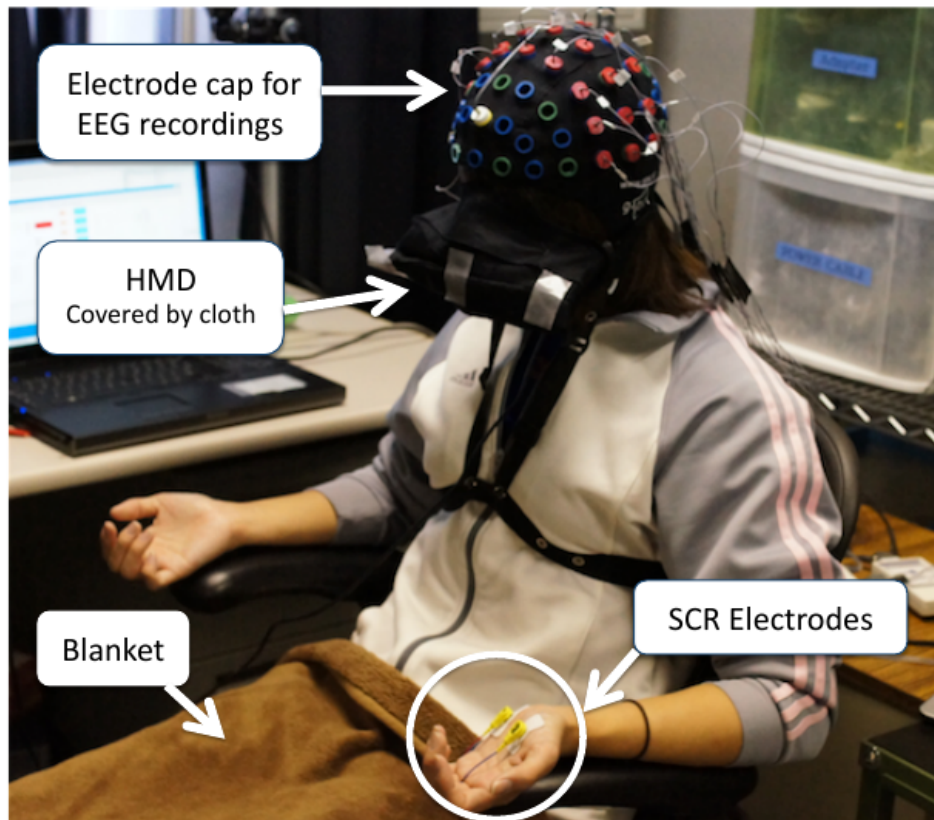


Figure 1.15: A subject wearing the experimental set-up to control the Geminoid's hand with BCI (courtesy from [5]).

if the motion is thought instead of being effectively realized by the subject. In this case, the dynamic proprioceptive feedback from the user is eliminated and only the intention of realizing the motion is left. In [110] the feeling of ownership toward a virtual hand is induced through motor imagery. This result shows that the feeling of ownership over a virtual hand is possible by imagining the motion only. However, motor imagery uses an invasive technique to extract the information from the subject's brain. In [4] a non-invasive technique is used to extract the subject's motion intention. Moreover, the results obtained between a virtual hand and robotic hand might be different like the results obtained with the rubber hand and the Geminoid as we have seen previously in section 1.1.4.3.

In [4] the motor task is extracted from the subject using the EEG signal [95]. In this experiment, the subject wears a HMD and an EEG cap (as seen in Figure 1.15) and is able to see through the Geminoid head-mounted camera which is oriented downward. In this experiment, the feeling of ownership is evaluated with a SCR and a questionnaire.

Before the experiment, the subject is trained in motor imagery task. In the experiment, the subject is asked to move the Geminoid hands. A training session, realized before the experiment, is used to determine a classifier capable of extracting the hand movement thought by the subject for the left and right hand. Only the subjects performing with a rate of success of 60-100 percent were selected to perform the main experiment.

In the main experiment, the subject is seated with the same posture as the Geminoid. A blanket is placed on the subject's knees as well as the Geminoid in order to near visual aspects. The hands of the subject are oriented like the Geminoid hands. Each of the Geminoid hands are equipped with a ball able to light up according to the experimenter's command to facilitate the imagery task of the subject. When the ball on the left/right hand is light up, the subject is asked to think of a left/right hand motion in order to launch a gripping motion around the lighted ball.

Three conditions are used in this study. The first one is, the robot stays still even when the subject succeeds the motor task (namely *Still*). The second one is, the robot's hand moves only if the motor task result corresponds to the correct lighted ball (namely *Match*). The third one is, the robot's hand moves even if the motor task result corresponds to the wrong lighted ball (namely *Raw*). The threat used after the realization or not of the motion to evaluate the ownership is an injection threat to the Geminoid hand as described previously in section 1.1.4.3.

The results of the questionnaire show that the ownership feeling is dependent of the BCI performance achieved by the subjects. The subjects who experienced the *Match* condition obtained the highest results of ownership. Subjects under the *Raw* condition with a high BCI performance also experienced a high level of ownership. However, the subjects under the *Raw* condition with a low BCI performance experienced a poor level of ownership and thought the injection occurred to another person. Interestingly, the interviews conducted after the experiment revealed that some subjects under the *Still* condition experienced a level of ownership higher than the level of ownership under the *Raw* condition. The explanation is similar to the results presented in IHI experiment in section 1.1.3.2. The explanation is that the error experienced in the *Raw* condition has a "negative effect" strong enough to destroy the feeling of ownership (Same as the wooden block in the IHI). However in the *Still* condition, the robot's motionless arm is not accounted as an error by the subjects who are still trying to imagine the motor task. Since the subjects still imagine the task, even though the robot arm does not respond, the feeling of ownership remained. The results obtained by the SCR were not significant enough. However, the difference in the questionnaire scores between the *Match* and *Still* conditions is significant which strongly suggests the transfer of ownership through brain control.

The different results obtained with the Geminoid show that the ownership of an android with a "human-looking" aspect is possible. This feeling can be induced by different means, either social interaction, synchronous visuo-motor stimuli or even through BCI control. These results however have not been confirmed with a humanoid robot that does not resemble visually to a human, such as the HRP-2 [69] used in our work. Therefore, the embodiment feeling toward a "robotic-looking" humanoid robot is extensively studied for the embodiment of limb and whole body in this work respectively in Chapters 4 and 3. The results obtained with the BCI showed in section 1.1.4.3 suggest promising results for the BCI control of humanoid robots. However, the study shows that a high performance classification is required in order to obtain the ownership transfer. In our experiment, a walking task is necessary in order for the subject to interact with the environment or with her/himself through the surrogate. In Chapter 2 we present a framework developed in this work which aimed

to assist the subject to control the humanoid robot during a walking and interaction tasks in order to keep a high level of BCI performance necessary to obtain a high level of ownership. The feeling of embodiment experienced during the walking task will be especially studied in Chapter 3.

In the next section, certain applications to the study of embodiment are presented in the engineering and medical fields.

1.1.5 Embodiment applications

1.1.5.1 Engineering

The knowledge brought by the study of the embodiment is also used to develop robotic devices, used not as a simple tool, but as an extension of our body. This is especially crucial in the area of prosthesis limb. What makes a robotic limb or leg feel as one's own limb or leg? This knowledge would improve the use of the prosthesis for the patients. The body representation knowledge learned from the embodiment can also be used to add a limb to the body, namely a supernumerary limb. In the following sections, some applications of the embodiment in the fields of prosthesis and supernumerary limb are presented.

Prosthesis



Figure 1.16: Synchronous stimulation applied to the patient stump and the rubber hand (courtesy from [32]).

In [32] the RHI is induced on an amputee patient by stimulating her/his phantom limb. On the amputee patient, specific areas of the stump correspond to the phantom fingers. When those areas are stimulated by touch, the patient feels the touch on the stump but also on a finger of the phantom limb. Therefore by stimulating the different areas of the patient

stump, the phantom fingers of the patient can be mapped onto the stump. Then, to induce the RHI, a visuo-tactile stimulation is used between the mapped areas of the stump and the corresponding fingers of the rubber hand as seen in Figure 1.16.

Most of the prosthesis hands, used by amputees, are not equipped with a sensory feedback feature. In [124], an experiment is realized to induce a sensory feedback illusion on a “robotic-looking” humanoid prosthesis hand. The illusion is induced with a visuo-tactile stimulation between the hidden stump and the robotic hand. After inducement of the illusion, the patient reported feeling the robotic hand more like a real hand. This illusion also works when the patient controls the robotic hand via the recording of her/his arm muscle activity. This results show that a patient can have a strong feeling of ownership toward a “robotic-looking” prosthesis hand.

Commercial prosthesis hands like the “i-limb quantum” from the company “touch bionics” [16] allow the patient to perform daily tasks with different types of control. For example, the i-limb quantum shown in Figure 1.17.B is controlled by the user either by gesture, proximity, mobile application, or muscle activity. Prosthesis hands can also be covered by a “human-like” silicon skin as seen in Figure 1.17.A. Unfortunately, nowadays a high-end prosthesis hand remains expensive and can cost up to 100 000\$ (USD).

Recently, the rise of the 3-D printing technology offers an alternative to high-end prosthesis hands at a cost under 1000\$ (USD). Indeed, several open-source projects, e.g. [106] or [105] offer the possibility to print and build your own robotic hand as shown in Figure 1.17.C.

In this regard, the result obtained in [124] is interesting for our work since we use a surrogate with a “robotic-looking” aspect. In our case a further study is needed since the hands of the robot are grippers as shown in Figure 1.17.D.

Supernumerary limb

In [55], the aim of the study is to give the subject the feeling of ownership toward an extra-limb, in this case, a second right arm. The feeling of ownership of the third arm is confirmed with a questionnaire and a SCR to threat. One major difference with the RHI is the lack of disownership of the real right arm. Indeed, after the embodiment is induced, the sensation of touch on the real arm is also felt on the third arm. This experiment demonstrates that an artificial supernumerary limb is able to be felt as part of one’s own body along the other “natural” limbs. Recent works are focus on the control and ownership of such limbs [96] [1].

This knowledge is also used for the design of supernumerary robotic limbs [80] [146] as seen in Figure 1.18.

1.1.5.2 Medical applications

Another application to the study of the embodiment is found in healthcare. Certain mental diseases are believed to come from a misrepresentation of the patient’s own body. For those mental illnesses (stroke, schizophrenia, Alzheimer’s diseases), no efficient treatments currently exist. Moreover due to the very high research cost and the rarity of new drugs discovery [130], the pharmaceutical industry is decreasing the development of new drugs for brain diseases [66].

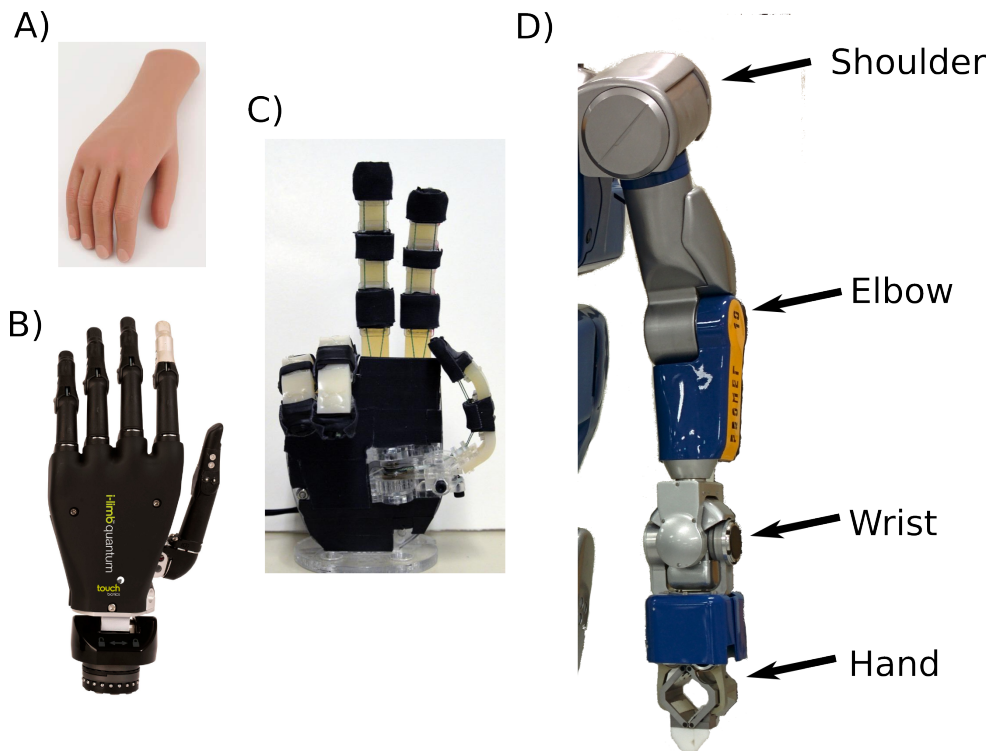


Figure 1.17: A) Human-like silicon skin for prosthesis hands from the company touch bionics (courtesy from [16]). B) High-end prosthesis hand i-limb quantum from the company touch bionics (courtesy from [16]). C) Open source bionic hand from the OpenBionics project (courtesy from [106]). D) Left arm of the humanoid HRP-2 used as surrogate in this work.

Eating disorder

Patients suffering from eating disorder are believed to have a misrepresentation of their body image. In [21], a new treatment based on virtual reality is compared to a standard cognitive behaviour therapy. In this study, the result shows that the virtual reality based treatment may improve the long-term treatment for binge eating disorder patients.

Phantom limb

After an amputation, some patients feel that their missing limb is still attached to their body. This pathology called phantom limb could benefit from a better understanding of the body's representation. New rehabilitation procedures are developed to relieve the pain of their missing limb. In [107] a mirror therapy treatment based on virtual and augmented reality allows a patient to reduce one's pain.

Schizophrenia

In the case of schizophrenia, certain patients reported to have a difficulty to make the difference between their self and their surrounding. The study of the embodiment or the feeling

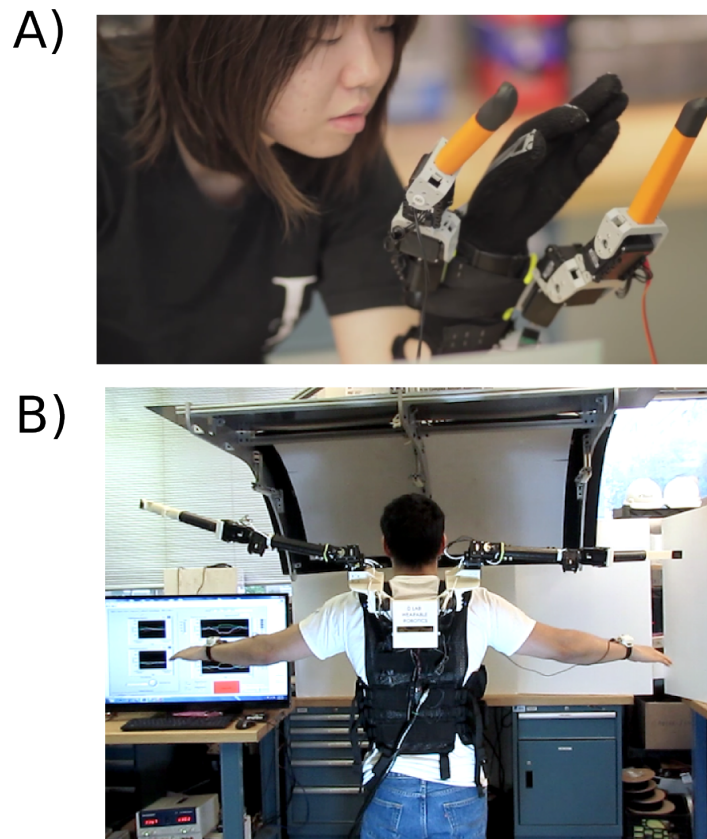


Figure 1.18: A) *Supernumerary fingers*: The two robotic fingers are worn around the wrist to enhance the grasping motion of the human hand. (courtesy from [91]) B) *Supernumerary arms*: The two robotic arms are strapped on the user and can be used to realize a two-persons task with only one user. (courtesy from [91])

of presence could give some tools and knowledges to obtain a better understanding of this feeling. New treatments based on virtual reality are already being explored [40].

1.2 Brain-computer interface

Brain Computer Interfaces (BCI) allow to bypass the usual motor pathways of communication between user and assistive devices, including robots [143]. Humanoid robot surrogates controlled by such technology [10] [47] can help users with severe motor disabilities to regain a certain level of autonomy, by being able to interact with the environment, other people and themselves.

1.2.1 Acquisition

In this section, we present non-invasive technologies used in BCI to measure the brain activity in real-time. The advantages and drawbacks of the different technologies are discussed.

1.2.1.1 fMRI

fMRI stands for functional Magnetic Resonance Imaging. The primary form of fMRI uses the blood-oxygen-level dependent (BOLD) contrast. This is a type of specialized brain and body scan used to map neural activities in the brain or spinal cord by imaging the change in the blood flow (hemodynamic response) related to the energy used by the brain cells. This technology is popular in brain research because it does not require the patient to be exposed to radiation or undergo shot. The fMRI technology has been used to control a humanoid robot [22], however the temporal resolution, inherent to this technology makes it difficult to use it.

1.2.1.2 EEG

Electroencephalography (EEG) is mostly used with non-invasive electrodes placed along the scalp but invasive electrodes have also been used in special cases. This is based on the voltage fluctuations resulting from ionic current within the neurons of the brain [97]. EEG is often used to diagnose epilepsy, which causes abnormality in EEG readings. Before the arrival of the fMRI with its high spatial resolution imaging, it was also used to diagnose brain tumors. Indeed, EEG technology has a poor spatial resolution and low signal to noise ratio especially in its non-invasive set-up, but the temporal resolution is very high. Moreover, this technology is much cheaper and more practical to set-up than the fMRI. For these reasons EEG technology is widely used in BCI.

In the following next sections, we present two technologies based on EEG acquisition.

Motor imagery

Motor imagery is based on detecting the event related de-synchronization (ERD) and event related synchronisation (ERS) when the subject executes or imagines a movement. In [114] a 4-class classification is used on subjects to detect the imaginary motions imagined with: tongue, feet, left hand and right hand. In [42] this technology is used to control a wheelchair. However this method requires the subjects to go through a long training period to obtain a high performance.

SSVEP

In our work we chose to rely on the steady-state visually evoked potentials (SSVEPs). SSVEPs are elicited when the subject observes a flickering stimulus. Indeed, we can retrieve the frequency of the flickering stimulus in the spectrum of the brain signal acquired above the visual cortex of the brain, as seen in Figure 1.19. The method we use to extract the SSVEP from the brain signals is the minimum energy classifier introduced in [41]. It is extended to provide a zero-class implementation, which detects when the subject is not attending any stimuli. The classifier is able to operate at a high level of accuracy (above 80%) after a short training (about 6 *min*) and a new command can be provided every 200 *ms* [117]. This represents a good performance for an SSVEP-based BCI system [142].

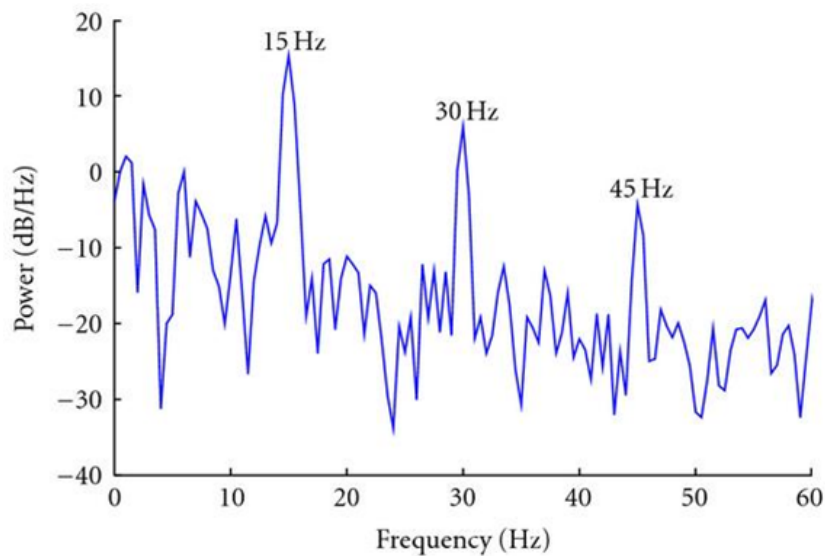


Figure 1.19: Spectrum of brain signal when attending a 15Hz visual stimulus (courtesy from [147]).

1.2.2 Applications

Decoding human motor intentions, in order to use them as an input signal for the control of a robot, is a challenging and open issue. In assistive robotics, electromyography (EMG) signals, which result from the activation of muscles, are often used since the interpretation of motor intentions is rather accurate [49]. However, in the case of patients with severe motor disabilities, EMG is not available, thus, electroencephalography-based (EEG-based) BCI are preferable. However, the decoding of motor intentions in EEG activity has not been achieved yet. Therefore it is better to perform a goal-oriented control [125] using a high-level intention recognition.

Many assistive applications have been developed using a BCI [24]. For example in [145], a complex gripper is controlled via BCI with a user interface specifically designed to realize a grasp. Many vehicles, such as a wheelchair [42] or a virtual plane [3], have also been controlled with a BCI. These different works are either specialized in navigation or in interaction with objects. Instead, in our work, we propose a vision-based semi-autonomous control framework (see Chapter 2), to realize both navigation and interaction, with a thought-controlled humanoid robot.

1.3 Self-interaction

In this section, we present two recent experiments where one subject interacts with one's self.

In [59], a subject controls a robotic arm by thought to take a bottle from a table, bring the bottle near her/his mouth to take sip from a straw, and put back the bottle on the table as seen

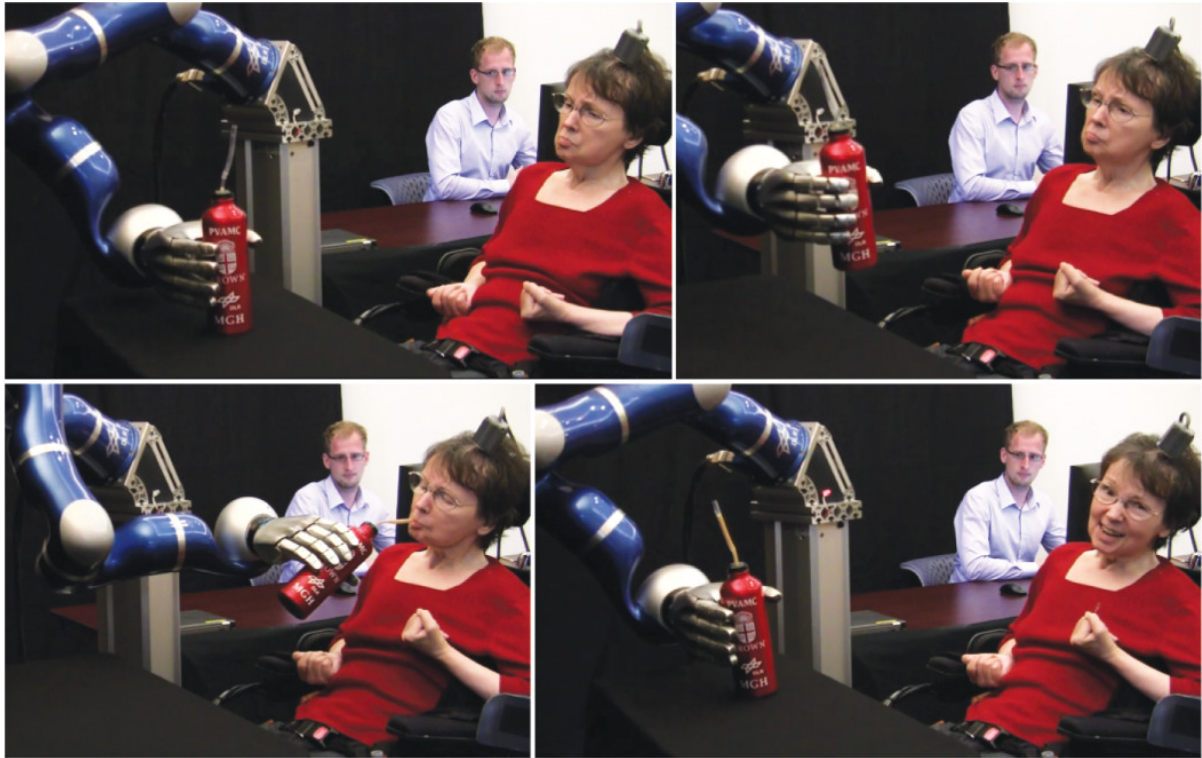


Figure 1.20: A robotic arm is thought controlled by a subject to grasp a bottle, serve herself a sip, and put back the bottle on the table (courtesy from [59])

in Figure 1.20. The BCI used in this experiment relies on the motor activity of the subject acquired through Electroencephalography (EEG). The motor activity is then interpreted into a motion input for the robotic arm. In order to help the subject, the robot hand motion is constrained in the plan of the table. The grasping of the bottle is also triggered when the robotic hand collides with the bottle. Prior to this experiment, the subject weekly practiced point and click actions with the BCI for 5 years.

More recently, a similar experiment was realized by decoding the subject intentions from the posterior parietal cortex [2]. Future researches will focus on giving the patient the illusion of tactile feedback by directly stimulating the somatosensory cortex of the subject to provide the sensation of touch.

In both experiments, the subject is required to have an extensive period of training and an invasive method of acquisition for the BCI. In our work, we present a framework which uses a non invasive method for the BCI and does not require a long period of training for the subject. Moreover the subject controls a complete humanoid robot from a first person view to walk toward a bottle and bring it to her/himself to take a sip.

1.4 Conclusion

In this chapter, the requirements to induce the feeling of embodiment toward a limb or a whole-body have been presented. More recent works even induce this feeling toward a seated “human-looking” humanoid robot. However, several issues remain unknown concerning the embodiment toward a “robotic-looking” humanoid robot capable of walking.

Most of the embodiment studies use a “human-looking” limb, mannequin or android. In our work, we study if the aspect of a “robotic-looking” humanoid without anthropomorphic hands is a suitable surrogate to be embodied.

The embodiment toward an android have been demonstrated, but the question remains if the embodiment is maintained when the surrogate is walking.

In the presented embodiment set-ups (sections 1.1.4.3 [100] 1.1.4.2 [112]), the subjects were unable to directly interact with themselves. To the best of my knowledge, the related embodiment feeling of "directly interacting with one's self", has not yet been study. In this work, an experimental framework which allows to study this feeling using a BCI without an extensive period of training is presented in the next chapter.

BCI control of Humanoid For Self-Manipulation

In the previous chapter, the requirements to establish the feeling of embodiment toward a surrogate are presented through the explanation of several key experiments. However, the different set-ups, did not allow to study the feeling of embodiment when one directly interacts with one's self. In this chapter, we present a framework designed for this purpose.

Recently, we proposed a BCI-based controller enabling the user to pilot a humanoid robot to grasp a can from a desk, and walk to a table to drop the can on it [47]. With that controller, precise positioning of the humanoid robot was impossible, due on one hand, to the coarse control interface provided by the BCI, and on the other, to the poor perception of the environment that the user had through the robot camera. Besides, the robot could only operate on rigid objects, and did not take into account the presence of the human.

In this chapter, we present a more general framework, for BCI-controlled task execution and human-robot interaction. The main novelties are the generality of the framework, that can now be used for both navigation and interaction, and the improvement in the positioning accuracy with respect to our previous work [47]. A versatile vision system has been developed, to generalize object recognition and pose detection, and include human detection and segmentation. The addition of an accurate navigation, based on Simultaneous Localization And Mapping (SLAM) and on a pose regulation controller, offers the user the choice of a semi-autonomous control mode that guarantees precise positioning. Finally, the immersion performance of the system has been greatly enhanced thanks to a HMD where the user can see through the robot's "eyes" and receives information given by the vision system. The previous framework presented in [47], displayed the video feedback from the robot's camera on a computer screen which is less immersive than a HMD. With these fundamental contributions, it is possible to perform a complex task such as allowing the user to control the robot to perform an interaction with one's self.

This chapter is organized as follows. In section 2.1, the components of the framework and their mutual interactions are presented. In sections 2.2, 2.3 and 2.4 respectively, the vision, user interface and control methods used in this work are detailed. Finally the experiments and results are presented and discussed in section 2.5.

2.1 Framework and References Introduction

In this section, we outline our framework with all the reference frames that are used.

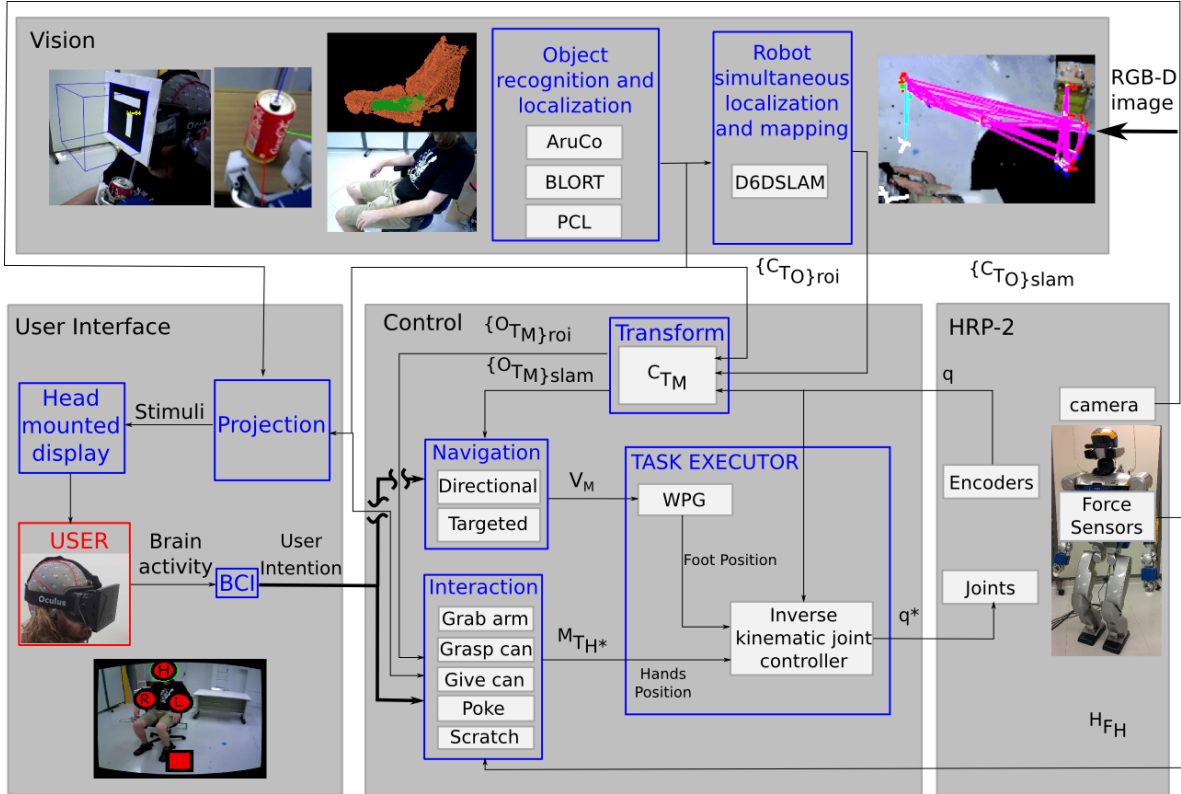


Figure 2.1: Data flow of the complete framework.

2.1.1 Framework

Our framework is outlined in Figure 2.1. In our work, the human-size humanoid robot HRP-2 presented in section A.1.1, is remotely controlled by a user equipped with an EEG cap and a HMD for visual feedback and head control. The RGB-D images acquired by the robot are processed by the Vision modules to localize the robot in the environment, and to localize relevant objects, including human body parts, in the scene. Throughout this work, we will indifferently refer to human body parts and environment objects as *objects*. Since the RGB-D camera and the HMD intrinsic parameters are known, it is straightforward to project both the robot camera view and the recognized object models in the HMD.

The `User Interface` display changes according to the current state. Transitions between different behaviors can be either initiated by the user, or automatically triggered, for example by the detection of certain objects. The recognition of the user's intention through BCI relies on the use of the well known steady-states visually-evoked potentials (SSVEPs). These potentials are triggered when the user observes a stimulus flickering at a given frequency (frequency-based VEP) or following a specific pattern (code-based VEP). The integration with the various vision modules allows us to generate these stimuli based on the environment of the robot or on the control context. For example, flickering arrows can be displayed to control the steering of the robot when no assistive scheme has been already enabled.

The user intention output by the BCI is sent to the `Control` modules, to realize the corresponding tasks (`Navigation` or `Interaction`) with the humanoid robot. Details on the `Vision` and `Control` modules, which represent two major contributions of this work, will be given in sections 2.2 and 2.4 respectively.

2.1.2 Reference Frame Definitions

The reference frames used in this work are shown in Figure 2.2. On the robot we consider: the RGB-D camera frame C , the robot center of mass (CoM) frame M (with X and Y parallel to the ground), and the robot operating hand (left or right) frame H . In the environment, O represents the frame linked to the target object. In Figure 2.2, we show three possible instances for this frame: an aluminum can, B , the user's forehead, F , or arm, A . Throughout this work, points are represented using the homogeneous representation. Coordinate frames are defined in superscript, such as $^A P$, and the homogeneous transformation matrix $^B T_A \in \mathbb{SE}(3)$ transforms points from frame A to B . The transformation $^B T_A$ is characterized by the translation $^B P_A = (^B X_A, ^B Y_A, ^B Z_A)$ and the rotation matrix $^B R_A$.

2.2 Vision

Several image processing modules have been integrated in our framework to realize the different computer vision tasks required for semi-autonomous control. In order to lower the time processing, the algorithms run only when necessary. All the image processing modules are detailed hereby.

2.2.1 Object recognition and localization

The `Object recognition and localization` module gathers the different algorithms for identifying, tracking and localizing objects seen by the RGB-D camera. This module outputs the object identity

$$O = \{O_1, O_2, \dots, O_n\} \quad (2.1)$$

and its pose in the camera frame, $^C T_O$.

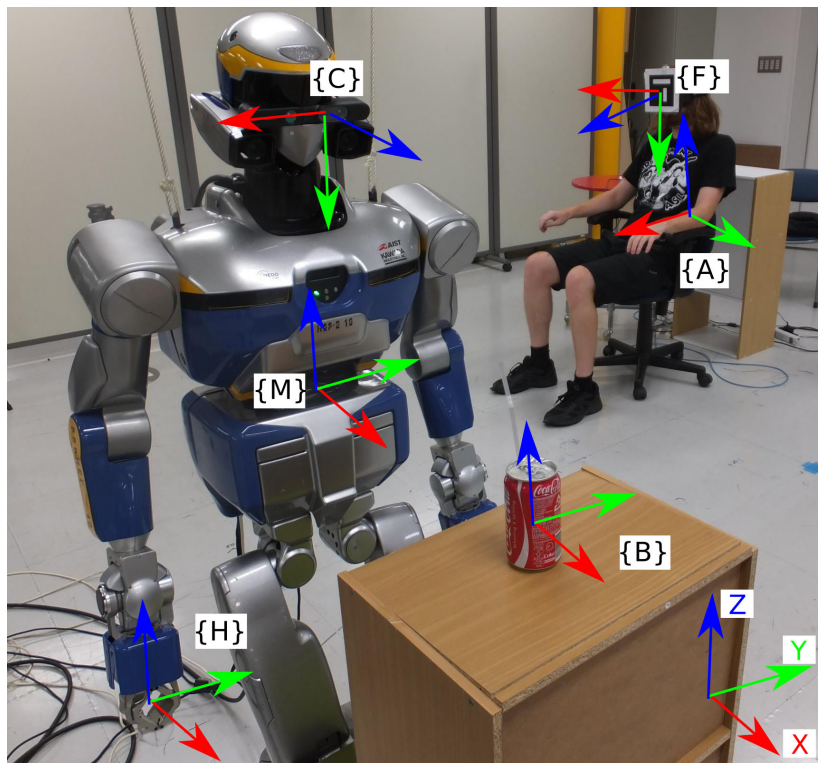


Figure 2.2: The reference frames used in this work.

Depending on the object category, three object recognition modules have been integrated: an augmented reality (AR) tracker for marked objects, a Scale-Invariant Feature Transforms (SIFT) and edge-based tracker for 3D and texture modeled objects, and a cloud-based recognizer for human body parts.

2.2.1.1 Marked objects

AR markers are used to tag certain objects in the environment. To identify and localize the markers in RGB images, we use the ArUco library¹ based on [45]. The detection algorithm provides an accurate pose estimate of multiple markers which is necessary for the tasks that require a high precision. We also used those markers in our initial approach to manipulate the user's arm. ArUco relies on printed black and white square fiducial markers shown in Figure 2.3, instead of natural textures or key points [144], to provide a very fast, robust and accurate pose estimate. The ArUco library [45] also provides a method to generate the different markers. The size as well as the number of bits which defines the marker identification (ID) can be chosen. In our work, we use three different marker ID, one to detect the HMD pose and two others to detect the user's shoulders.

The algorithm detects the square contour of the markers, then determines their poses using the pixel position of their four corners. The contour extraction is realized by image seg-

¹www.uco.es/investiga/grupos/ava/node/26

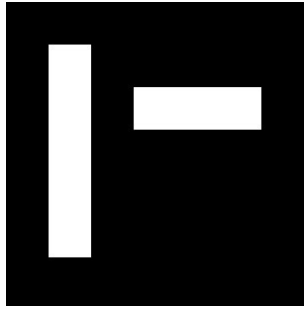


Figure 2.3: Marker used by the ArUco library.

mentation using a local adaptive threshold method instead of the well known “canny filter” in order to speed up the processing time. All the segmented image contours are then extracted using the “Suzuki and Abe” [138] algorithm. The “Douglas-Peucker” [27] algorithm is then applied to the extracted contours, to determine the contours that are approximated by a four vertex polygon since the markers are rectangular. The inner part of each detected four corners contours, which constitutes the binary code of the marker, is then analysed. This part is done by first removing the perspective projection of the contour, then by applying the “Otsu” method [101] to binarize the resulted contour’s inner image. The “Otsu” method is used to find the optimal threshold in a bimodal image, which is our case with the black and white markers. The resulted image is then divided to extract the binary code and compare it to the known dictionary, to infer the marker identity O . The intersections of the lines that form the contour of the detected marker are then used to refine their corners position. Finally, the marker pose ${}^C\mathbf{T}_O$ is estimated by iteratively minimizing the image plane projection error of the four square corners, with the “Levenberg-Marquardt” method [86].

Within our framework, ArUco is indispensable for all tasks that require a precise localization of objects that can be tagged, without excessive environment structuring. For example, we use it to derive the user head position, thanks to a marker placed on the HMD as shown in Figure 2.4..

2.2.1.2 3D and texture modelled objects

For all the objects that cannot be tagged, and that must be recognized by relying only on their natural aspect, we use the Blocks World Robotic Vision Toolbox, BLORT [92]. This toolbox provides tools to recognize and track objects using RGB images as shown in Figure 2.5. The recognition is done using a priori learned Scale-Invariant Feature Transforms (SIFT)[84] along with a 3D Computer-aided design (CAD) model of the object. At run time, the object is tracked and localized using a bootstrap filter [26] to compare the current images with the learned model. In our framework, we use BLORT to recognize and localize everyday life objects (e.g. a tool or a bottle), that must be manipulated by the humanoid robot.

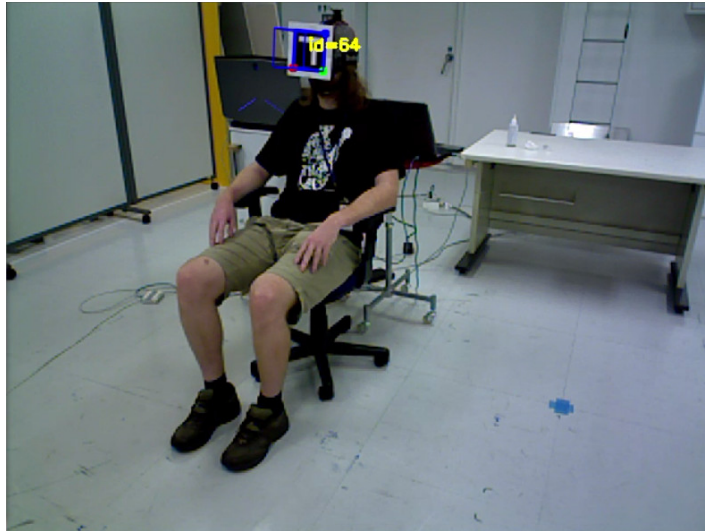


Figure 2.4: Marked HMD tracked with the ArUco library.



Figure 2.5: A can tracked by BLORT.

2.2.1.3 Human body parts

Another fundamental requirement of our framework is the capability of physical interaction between user and humanoid robot. To this end, a body part recognizer is necessary. We cannot rely on the above approaches, since neither AR markers nor special textures (i.e., clothes) can be applied on parts of the user's body. Moreover, skeleton trackers such as NITE², which requires the user to be standing fully in the camera field-of-view, cannot be used in our scenario, where these assumptions may be broken, and images are shaky, due to the camera's motion.

Thus, we have decided to use the Point Cloud Library (PCL) [127] to recognize body parts (e.g., the forearm, as in Figure 2.6) based on a pre-recorded template. First, we compute the normals to the template point cloud (organised in a kd-tree structure) with the Fast

²<https://wiki.debian.org/PrimeSenseNite>

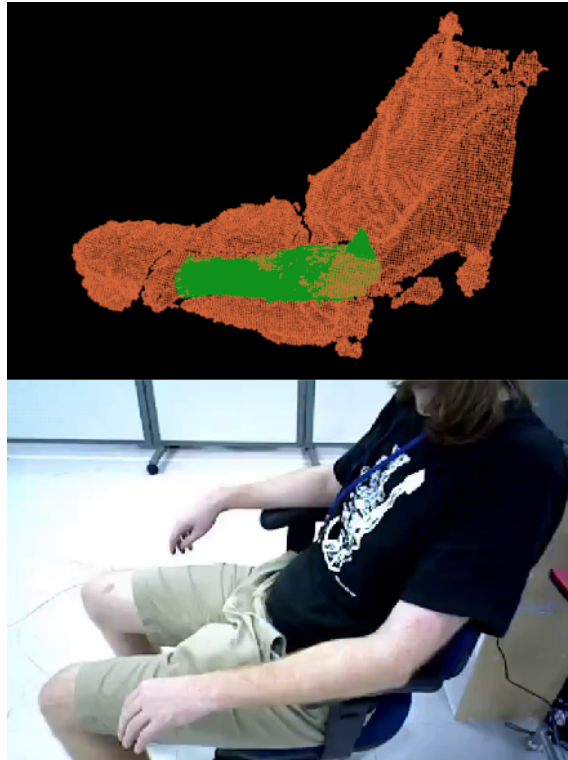


Figure 2.6: Forearm detected by the body part tracker.

Library for Approximate Nearest Neighbors (FLANN)³, then the surface curvature variations with a Fast Point Feature Histogram (FPFH) [126]. The body part pose is then estimated by the Sample Consensus Initial Alignment (SAC-IA) algorithm [126]: subsets of points are randomly selected from the currently seen point cloud and from the pre-recorded template, the closest match between the two point sets is computed via FPFH. The transformation between the two point clouds is iteratively refined until convergence, and then used as an initial guess for an iterative closest point algorithm shown in Algorithm 1, that is more accurate for estimating ${}^C\mathbf{T}_O$, since there is no random selection of points like with the SAC-IA estimation. However, the SAC-IA estimation is useful for the first step, since it is robust to large transformations and does not need an initial guess.

³www.cs.ubc.ca/research/flann/

input : Two point clouds: $F = \{f_i\}, C = \{c_i\}$

An initial transformation: T_0

output: Transformation between F and C

$T \leftarrow T_0$ **while** *Not converged* **do**

for $i \leftarrow 1$ **to** N **do**

 Find closest point;

if $\|m_i - T.f_i\| \leq d_{max}$ **then**

$w_i \leftarrow 1$;

else

$w_i \leftarrow 0$;

end

end

$T \leftarrow \operatorname{argmin}_T \sum_i w_i \cdot \|m_i - T.f_i\|$;

end

Algorithm 1: Iterative Closest Point algorithm used to detect the user's forearm.

2.2.2 Robot Simultaneous Localization and Mapping

To develop a semi-autonomous control strategy that saves the user from fine trajectory control, a precise robot localization is required. Although the navigation scheme we seek is target-oriented, we do not want to force the humanoid robot to observe the target at all times. Removing this constraint will benefit the control, since then the head and/or torso of the humanoid robot will not need to be permanently servoed toward the target.

To this end, we apply the Visual Simultaneous Localization and Mapping algorithm D6DSLAM [87] to the RGB-D images from the on-board camera. This library unifies voxel-based and key-frame representations, to provide real-time mapping of the environment, along with the camera pose in the map. As soon as the target object is recognized and localized with any of the approaches in section 2.2.1, its pose in the D6DSLAM map (shown in Figure 2.7) is memorized and updated in real-time, so that ${}^C\mathbf{T}_O$ can be estimated, via the camera pose, even when the object is not visible. The use of ${}^C\mathbf{T}_O$ for Navigation is explained in section 2.4.

2.3 User Interface

In this section the User Interface used by the user to control the humanoid robot is described.

2.3.1 Brain Computer Interface System

In this section, we present the different key elements of a BCI system. The formalism introduced by BCI architecture frameworks such as OpenViBE [121], BCI2000 [131] or TOBI's hBCI [93] divides the BCI in three key elements as seen in Figure 2.8: signal acquisition, signal processing and user application.

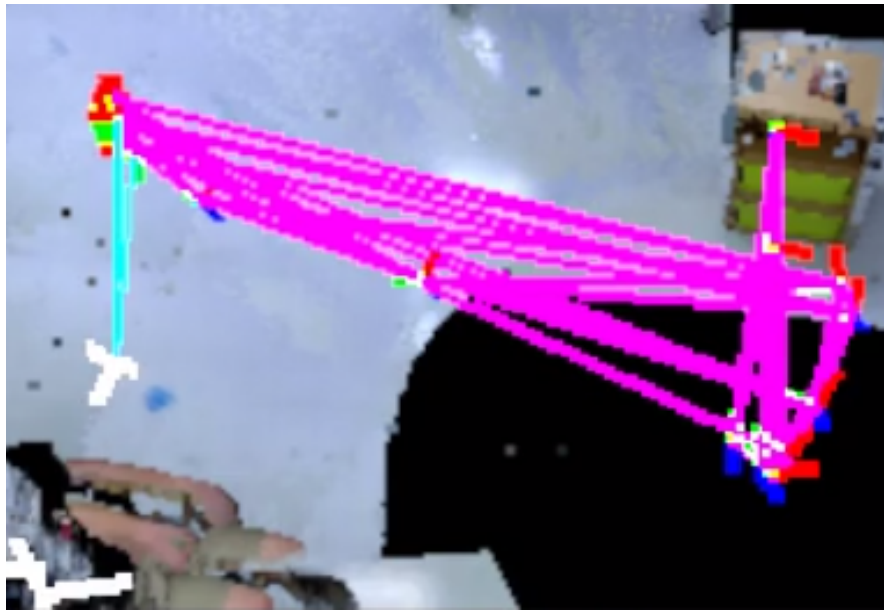


Figure 2.7: Map generated by D6DSLAM with the graph used to determine the localization of the camera mounted on the humanoid robot. The nodes from the purple graph represent the key-frames while the the white nodes represent the current robot position and the target. The blue lines attached to the white node represent the displacement between the current robot position and the nearest key-frame

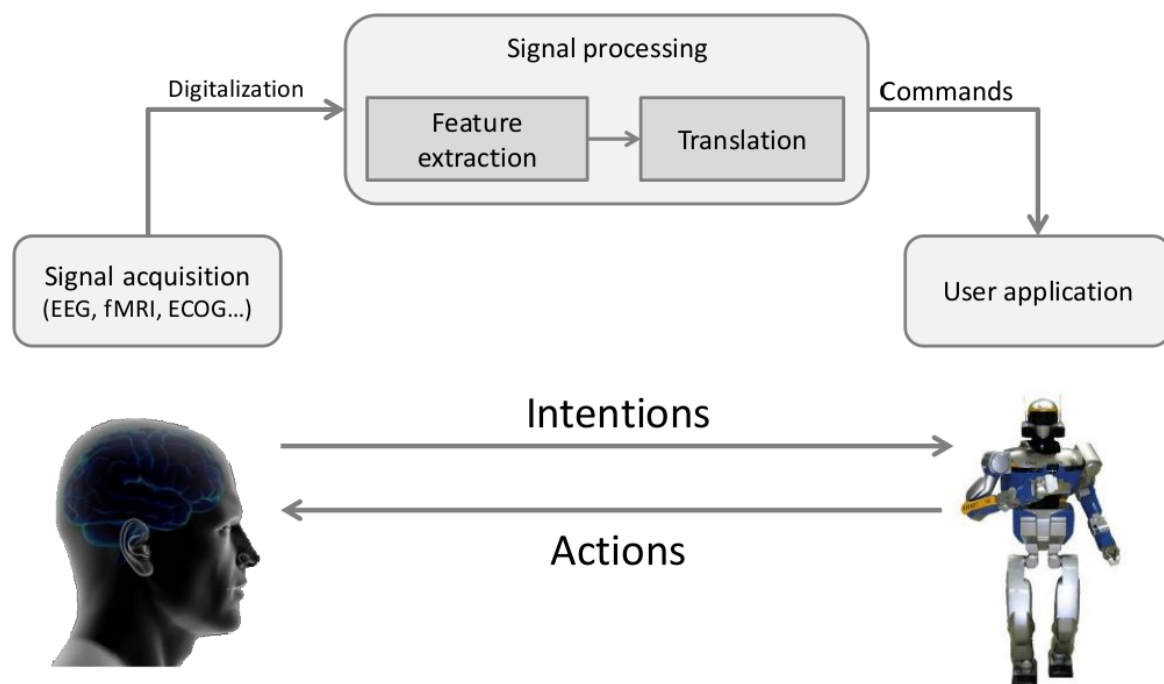


Figure 2.8: General design of a BCI system.

2.3.1.1 Signal acquisition

Signal acquisition designates the technology that is used to acquire the signal from the user's brain activity. In this work we use a non-invasive technology, the well known EEG. Despite poor spatial localization accuracy and low signal to noise ratio, the real-time capacity, cheap cost and non-invasive nature of EEG has made it the most popular technology in BCI.

2.3.1.2 Signal processing

Signal processing describes the method used to extract the user intentions from the signals acquired in the previous step. We chose to rely on the steady-state visually evoked potentials (SSVEPs) presented in section 1.2.1.2.

In our previous work [47], we relied on 4 classes to perform the ensemble of the tasks proposed to the user. However, we trained the classifier to recognize 5 classes in this work to extend the capabilities of the interface. The frequencies of the stimuli were 6, 8, 9, 10 and 14 Hz .

2.3.1.3 User application

User application is the application that is driven by the BCI. Here, we use a humanoid robot. To allow the task selection we use the SSVEP paradigm that we adapted for humanoid control (as shown in section 2.3.2). In Figure 2.9 is shown a screen shot of the interface seen in the HMD by the user while selecting one's own head.

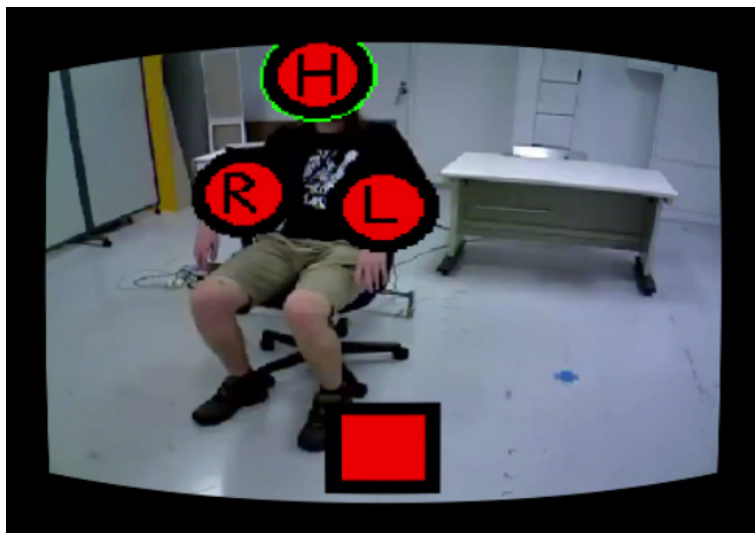


Figure 2.9: User interface with SSVEP stimuli positioned on target, displayed to the user. In this case, the user selected one's own head

2.3.2 Outline of the BCI-controlled self-interaction framework

The experiment is driven by a Finite State Machine (FSM) in order to transit between the different stages of the scenario. Because of the limitations of the BCI, parts of the tasks are executed autonomously by the humanoid robot. For example, in the interaction phase, the only input from the user is the interaction selection; afterwards, the robot autonomously executes the motion. Therefore, the transitions in the FSM are triggered either by the user or by the robot as we can see in Figure 2.10.

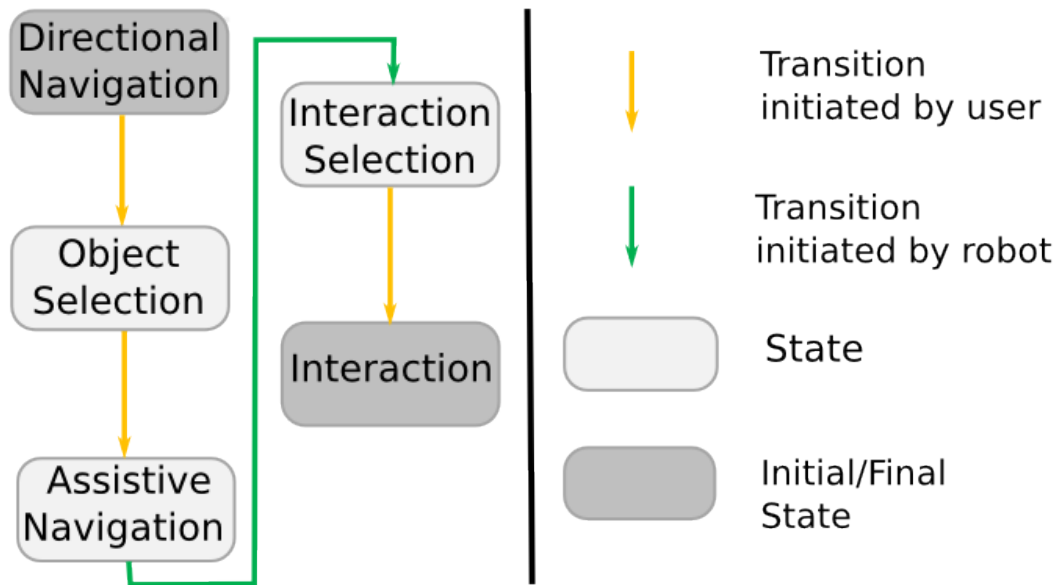


Figure 2.10: Finite State Machine of the framework.

The experiment is divided in five phases that are reflected in the FSM and outlined below.

1. **Directional navigation phase.** In this phase, the user looks for one's self within the world that he sees through the robot's on-board camera. He can trigger the next phase as soon as he sees one's self and he wishes to initiate the interaction.
2. **Body part selection phase.** Once the user appears in the robot field-of-view, s/he interrupts the directional navigation phase to initiate the body part selection phase. The user body parts start to flicker, and the user selects one's part of the body to physically interact with. When the body part is selected, the next phase is initiated. In Figure 2.9, the user chooses to interact with one's own head.
3. **Assistive navigation phase.** The robot navigates semi-autonomously in front of the selected user's body part, in order to interact with it. The next phase is initiated when the robot reaches its destination.
4. **Interaction selection phase.** The user selects the interaction to realize on the selected body part. There are four types of interaction depending on the selected body part. In

our demonstration, the user has the choice to either manipulate one's own arm (three different interactions available) or give one's self a drink.

5. **Interaction phase.** The robot realizes the selected task.

2.4 Control

The `Control` module receives the user intention and the target object pose from the other modules, and generates the motor commands necessary to move the robot in order to realize the desired tasks. The module covers three aspects, `Navigation`, `Interaction` and `Task execution`, that are detailed below.

2.4.1 Navigation

The goal of the `Navigation` module is to pilot the robot in the environment according to the user's intention from the `User Interface`, and to the object pose from `Vision`. The output is the robot Center of Mass (CoM) desired velocity, V_M . As it is commonly done in the literature [37], we consider the humanoid robot as a non-holonomic system, so that only its forward linear velocity along X_M , v , and angular velocity around Z_M , ω , are controlled within known bounds:

$$V_M = [v, \omega]^T \in [0, v_m] \times [-\omega_m, \omega_m] \subset \mathbb{R}^2. \quad (2.2)$$

In our framework, two alternative navigation modes have been devised: a `directional` mode, where the user maintains full control of the robot motion, and a `targeted` mode, where the control is shared with the robot. This second mode is proposed to the user only if a target object has been detected in the scene by `Vision`. To seamlessly switch between the two modes, a new user command is taken into account only when a walking step (of period $dt = 0.7s$) is completed. To ensure the stability of the walk v_m and ω_m are fixed respectively at 0.1 m/s and 0.15 rad/s .

2.4.1.1 Directional Navigation

In this mode, the user can pilot the robot forward, turn left, right or stop, without any assistance. This mode is particularly useful when the user wants to explore her/his surrounding with the robot. Four fixed directional commands can be selected in the `User Interface` shown in Figure 2.11, via the BCI. These are:

$$\left\{ [v^*, 0]^T, [0, \omega^*]^T, [0, -\omega^*]^T, [0, 0]^T \right\}, \quad (2.3)$$

with v^* and ω^* fixed hand-tuned velocities.

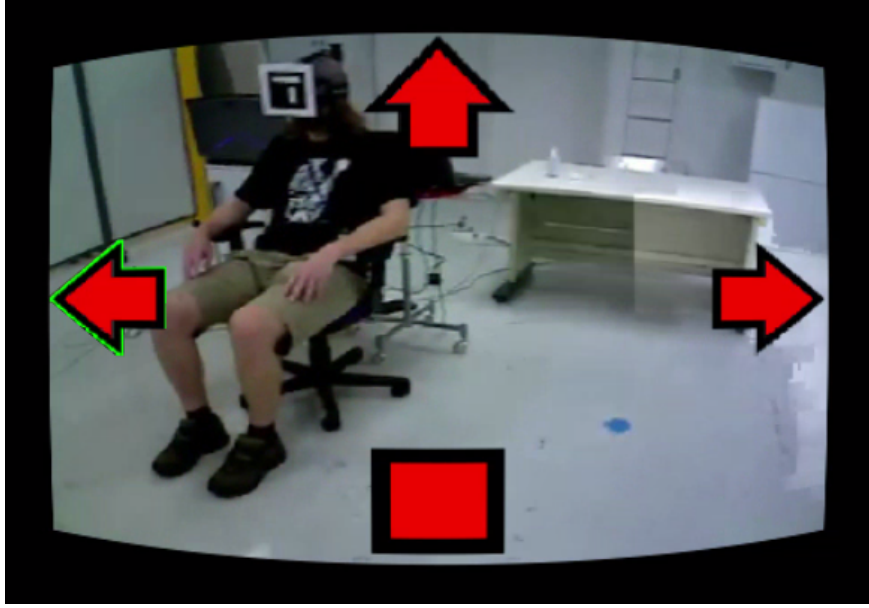


Figure 2.11: User interface seen in the HMD during directional navigation. In this case the user chooses to turn left

2.4.1.2 Targeted navigation

In this mode, the user indicates a target, detected with the vision system, that she/he wants the robot to interact with. The robot then semi-autonomously walks to the target. The input to this mode is the target object, selected by the user with the BCI, and the object pose in the camera frame, ${}^C\mathbf{T}_O$, from any of the `Vision` algorithms. This pose is transformed to the CoM frame, by applying the known transformation ${}^C\mathbf{T}_M$ (via the joint values \mathbf{q} , measured by the robot encoders):

$${}^O\mathbf{T}_M = ({}^C\mathbf{T}_O)^{-1} {}^C\mathbf{T}_M. \quad (2.4)$$

For each object, we define a desired robot pose for interaction, noted M^* , and characterized by ${}^O\mathbf{T}_M^*$. The goal of the `Targeted navigation` is to pilot the robot there: ${}^O\mathbf{T}_M = {}^O\mathbf{T}_M^*$. For instance, to interact with the user's left arm, we choose the pose M^* shown in Figure 2.14, with the robot facing the user on his/her left side, at a distance of 1 m. We also impose the robot to always stay at least 1 m away from the user, i.e., outside a circle Γ of radius $R = 1$ m, to make him/her comfortable. The choice of $R = 1$ m is driven by the human-robot proxemics research in [94].

As a preliminary work [111], this mode relied on several waypoints (namely “waypoint based”), causing a piecewise linear trajectory, uncomfortable for the user. To solve this problem, a new navigation scheme (namely “orbital based”) has been devised, allowing a trajectory closer to the user expectations.

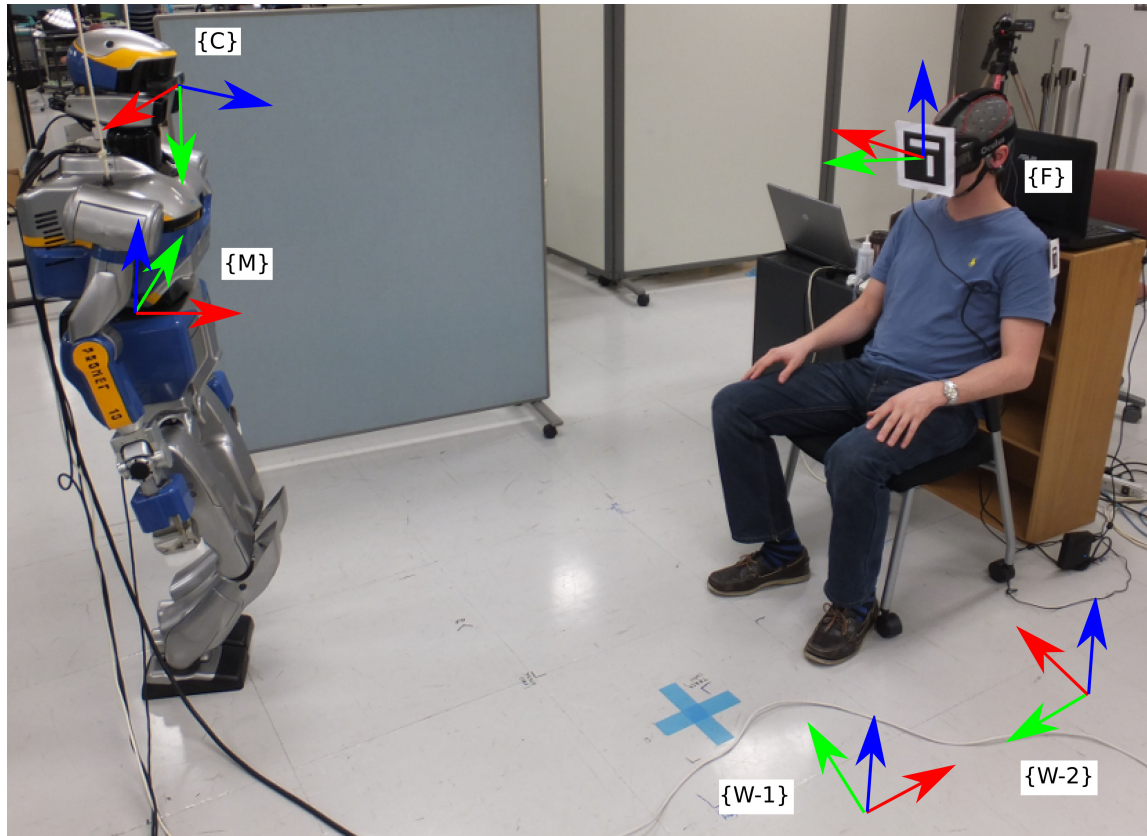


Figure 2.12: Navigation assistance based on waypoint set up and frames.

Waypoint based navigation:

In this scheme, when the navigation assistance is triggered, the control of the robot steering is centered around the target frame $W-i$ with $i \in \{1, 2\}$ in the sequence associated to the selected target: $W-1$ then $W-2$ (as seen in Figure 2.12), hence only two visual stimuli are used in the user interface:

- The “up” arrow is not used to move the robot *forward* but to move the robot *toward* the current frame in the sequence;
- The “stop” button is used to switch back to the global frame (i.e. directional navigation).

The $W-1$ frame is used as a predefined waypoint ensuring that the robot will not enter in collision with the user during the assistive navigation phase. A feedback control scheme described in Equation (2.5) and shown in Figure 2.13 is adopted to control the robot toward the current frame in the sequence. Once the final position is reached, the robot is realigned on $W-i$ before going further in the sequence.

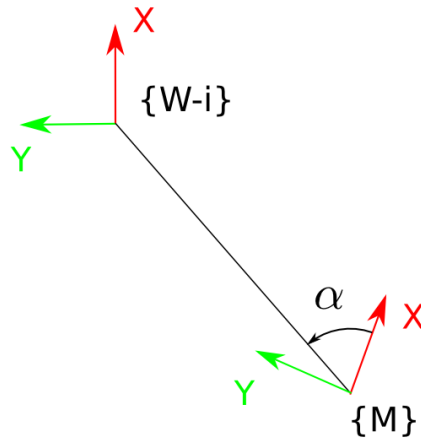


Figure 2.13: Assistive navigation based on waypoint control scheme.

$$\begin{cases} \alpha = \arctan({}^M Y_{W-i}, {}^M X_{W-i}) \\ v_0 = V \\ w_0 = K \times \alpha \end{cases} \quad (2.5)$$

With V and K constants tuned for the robot and v_0, w_0 , the desired speed in M sent to the humanoid robot pattern generator [58].

Orbital based navigation:

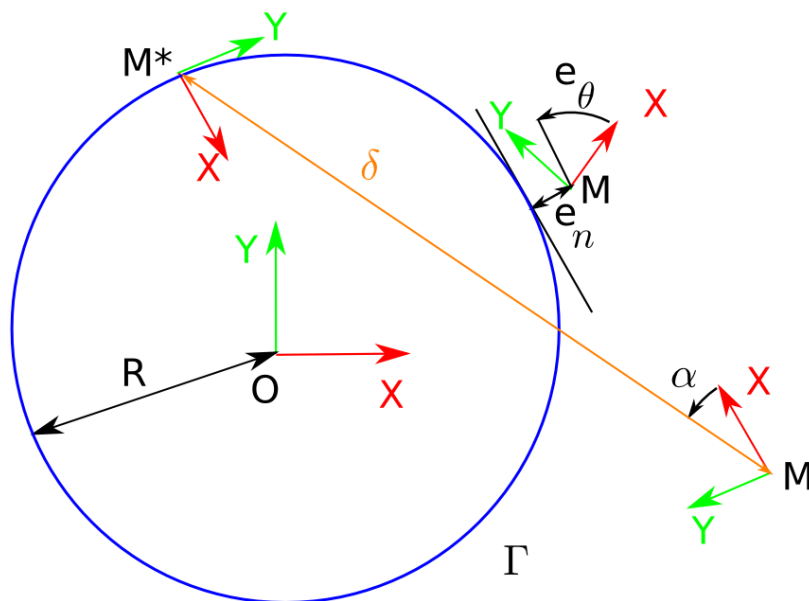


Figure 2.14: Relevant variables used for the orbital based targeted navigation.

With this improved scheme the targeted navigation controller is composed of three phases, listed below (all variables are shown in Figure 2.14).

1. The robot pivots to face the direction toward M^* , i.e.,

to nullify error $\alpha = \text{atan2} \left({}^M Y_{M^*}, {}^M X_{M^*} \right)$.

We apply:

$$v_1 = 0, \quad \omega_1 = \begin{cases} \text{sign}(\alpha)\omega_m & \text{if } |\alpha| > \omega_m dt, \\ \frac{\alpha}{dt} & \text{otherwise.} \end{cases} \quad (2.6)$$

2. The robot walks forward toward M^* , to nullify position error $\delta = \| {}^M \mathbf{P}_{M^*} \|$, while still servoing α :

$$v_2 = \begin{cases} v_m & \text{if } \delta > v_m dt, \\ \frac{\delta}{dt} & \text{otherwise,} \end{cases} \quad \omega_2 = \omega_1. \quad (2.7)$$

If the targeted object is a body part, the trajectory obtained with the controller described in Equation (2.7) must stay outside the circle Γ . If Γ is intersected before reaching M^* , the robot should follow it toward M^* with ω_2 from Equation 2.8, while maintaining the same linear velocity v_2 . Naming e_θ and e_n the signed errors in orientation and normal with respect to Γ (shown in Figure 2.14), and $\kappa = \frac{\text{sign}({}^M Y_M)}{R}$ the signed desired path curvature, we apply the classical non-holonomic circle following controller from [23]:

$$w_2 = \left(\frac{\lambda_1 e_n \sin e_\theta}{e_\theta} - \lambda_2 e_\theta + \frac{\kappa \cos e_\theta}{1 + \kappa e_n} \right) v_2. \quad (2.8)$$

This controller, with properly tuned positive gains $\lambda_{1,2}$, guarantees local stability to the circular path. In all the experiments, we used $\lambda_1 = 10$ and $\lambda_2 = 5$.

3. Once the robot has reached the position M^* , it pivots to align axes X_M and X_M^* , i.e., to nullify their relative angle β . We apply:

$$v_3 = 0, \quad \omega_3 = \begin{cases} \text{sign}(\beta)\omega_m & \text{if } |\beta| > \omega_m dt \\ \frac{\beta}{dt} & \text{otherwise} \end{cases} \quad (2.9)$$

The transition between phases is triggered when the errors norm are below given positive thresholds (e.g., $|\alpha| < \tau_\alpha$ to go from phase 1 to phase 2).

2.4.2 Interaction

Various actions can be realized through the robot for `Interaction` with the environment, and/or with the user. We distinguish between two categories: actions for `touching / grasping objects in the environment` (e.g., touching a body part or grasping a can), and actions for `handing over objects to the user` (e.g., giving a tool or a can). The

chosen action depends on the user intention output from the User Interface. The object pose ${}^C\mathbf{T}_O$, output by `Vision`, is also necessary to provide the feedback to the controller. For `Interaction`, we use the output of `Object Localization`, since it is more accurate than the one from `Robot Localization`. This requires the object to be in the field-of-view of the camera. However, this is not an issue since, when interacting with an object, the robot is close enough to have it in its camera field-of-view. All `Interaction` actions in our framework are realized by setting desired poses of the robot hands in the CoM frame, ${}^M\mathbf{T}_H^*$, and these are realized with the `Inverse kinematic joint controller` explained just below.

The control objective, for both object touching and grasping, consists in regulating the robot hand on the object, so that the two reference frames coincide, i.e., ${}^O\mathbf{T}_H^* = \mathbf{I}$. This is equivalent to servo the hand so that:

$${}^M\mathbf{T}_H^* = {}^M\mathbf{T}_C {}^C\mathbf{T}_O {}^O\mathbf{T}_H^* = {}^M\mathbf{T}_C {}^C\mathbf{T}_O, \quad (2.10)$$

with ${}^M\mathbf{T}_C$ derived from the encoders, as mentioned in section 2.4.1.2. For implementation reasons, in some cases (shown in section 2.5), we use N intermediate waypoints ${}^M\mathbf{T}_{Hi}^*$, $i = 1, \dots, N$, to reach ${}^M\mathbf{T}_H^*$. In the case of grasping, the convergence to ${}^M\mathbf{T}_H^*$ is followed by the hand gripper closure. Also, in some cases, the force/torque sensor data (external wrench on the hand, expressed in H , ${}^H F_H$) is compared to a threshold τ_F to interrupt the grasping/touching motion:

$$\|{}^H F_H\| > \tau_F. \quad (2.11)$$

Typically, this is necessary to realize a pleasant touch [36] when interacting with body parts.

2.4.3 Task execution

A task executor, is used to realize the operations requested by the `Navigation` and `Interaction` modules. This includes both making the robot walk, and controlling the motion of its hands. To make the humanoid walk, we use the walking pattern generator (WPG) from [58], which receives the desired speed V_M , and computes the corresponding desired foot positions. These foot positions, just like the desired hand positions ${}^M\mathbf{T}_H^*$ from Equation (2.10), correspond to tasks to be realized by our inverse kinematic joint controller, the `Stack of Tasks` (SoT, [85]). In the SoT, the tasks are defined as state error vectors in the sensory space, and projected in the robot joint space via the robot kinematic Jacobian. The SoT outputs the desired joint values, \mathbf{q}^* . This tasks function control paradigm is well adapted here, since the explicit trajectories of the interaction motions are unknown beforehand.

2.5 Experiments

In order to assess the different functionalities of the framework, a preliminary experiment is devised to evaluate the assistive navigation and vision loop with a prototype scheme based on SLAM and marked target. The assistive navigation is a key feature of the framework which

allows a safe close interaction between the surrogate humanoid and a human or an object, using a BCI control which is subject to false positive results. This preliminary experiment is realised with a subject which had no prior experience with BCI control in order to verify if the framework is easy to use. The assistive navigation in this preliminary experiment is waypoint based.

After the results of the preliminary experiment, the framework has been updated to improve the assistive navigation to the orbital based scheme presented in section 2.4.1.2. The vision system have been improved as well to allow a smoother trajectory and more complex interactions with the environment and the subject. A main experiment is then presented with a different subject which had prior experience with BCI.

2.5.1 Preliminary experiment

2.5.1.1 Subjects & Material

For this preliminary prototype, only one healthy volunteer participated in the study: a male of age 27. The subject had no prior experience with BCI.

We use a g.USBamp (24 Bit biosignal amplification unit, g.tec Medical Engineering GmbH, Austria) to acquire the EEG data from the user's brain at a sampling frequency of 256 Hz , bandpass filtered between 0.5 and 30 Hz with a notch filter at 50 Hz to get rid of the power line noise. We use 8 Ag/AgCl active electrodes. The electrodes are placed on the POz, PO3, PO4, PO7, PO8, O1, O2 and Oz positions of the international 10-20 system [132], Fpz is used as the ground electrode and the earlobe as a reference.

The frequencies of the stimuli are 6, 8, 9, 10 and 14 Hz . Those are carefully selected to avoid common first or second harmonics, while staying below 20 Hz , to minimize the risk of eliciting an epileptic crisis in healthy subjects as advised in [38].

The experiments are conducted with a HRP-2 humanoid robot. During the experiment, the user is comfortably seated in an armchair, and wears an HMD (Oculus Rift) upon which the user interface is displayed at a refresh rate of 60 Hz .

2.5.1.2 Experiment Protocol

In a first experiment, the user is asked to steer the robot near one of his arms in order to touch it. This task is realized two times, one time using the directional navigation and one time using the preliminary assistive navigation scheme (waypoint based navigation in section 2.4.1.2). Snapshots of the experiment can be seen in Figure 2.15.

In a second experiment, the user is asked to steer the robot near an object placed on a desk in order to grab it. To simplify the set up, we use a controller which mimics the limitations of a BCI. Moreover, in this task, the user is no longer the subject of the interaction which lessens the apprehension of collision with the robot. This task is realized two times, one time using the directional navigation and one time using the preliminary assistive navigation scheme (waypoint based navigation in section 2.4.1.2).

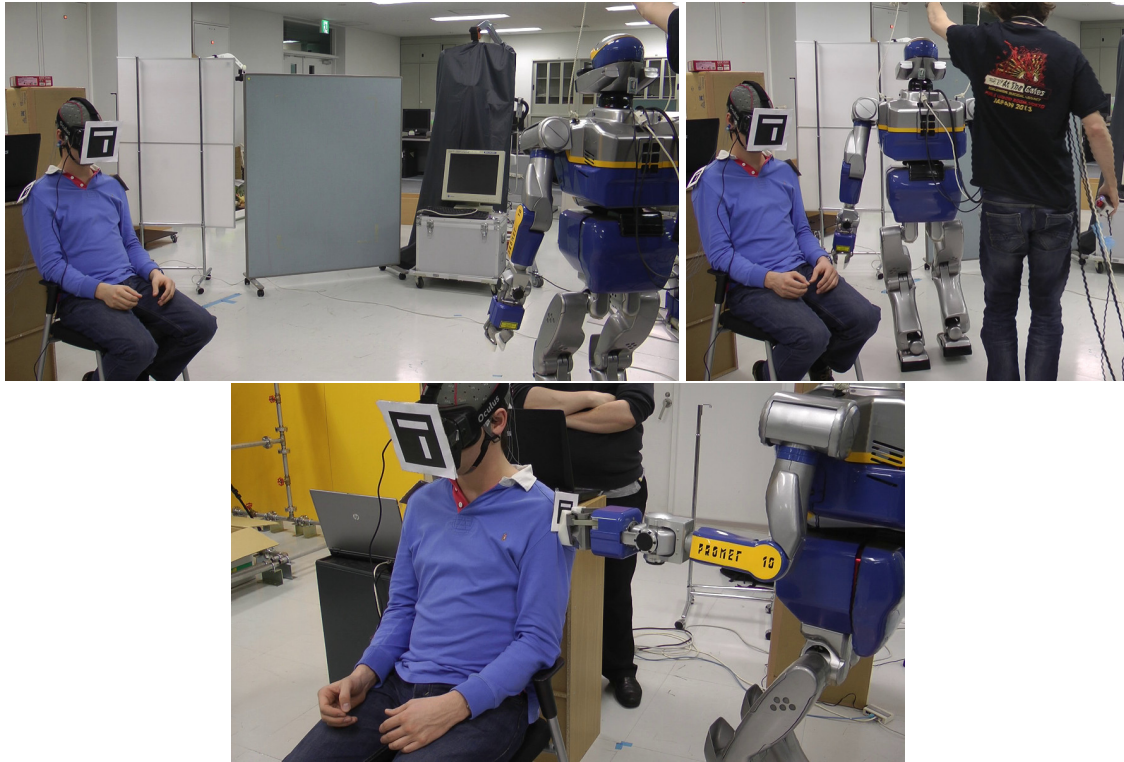


Figure 2.15: From left to right: The user is looking for himself through the feedback from the on-board camera to the HMD by steering the robot in directional navigation ; the user steers the robot to the interaction area using the assistive navigation; the robot detects the marker on the user's arm, adjusts its pose then touches the user's arm.

2.5.1.3 Results

First experiment

Without the assistive navigation, the user steered the robot near his arm with an increasing difficulty when the robot was getting close to him. This can be explained by the distraction caused by the robot going near the user and the apprehension of not being able to stop the robot before collision. Both the distraction and apprehension caused the performance loss of the BCI system which led to a difficulty to steer the robot. The final position of the robot was too close to the user. The marker placed on the user arm could not be detected. So the final pose of the robot did not allow to perform the interaction.

Using the assistive navigation, the user first steered the robot to look for the marker placed on the HMD then stopped the robot in order to initialize the localization. Once the localization was initialized the user only needed to focus on one stimulus to go near his selected arm. The BCI performance was less affected by the fact that the robot went near him knowing that he was free from collision using the assistive navigation. The final pose of the robot in this case was accurate enough to allow the detection of the marker on the user's arm allowing the interaction triggered by the user via BCI.

Second experiment

Without assistive navigation and using a controller, the user collided the humanoid with the desk in an attempt to get closer to the object. In Figure 2.16, we can observe the Center of Mass (COM) of the robot projected on the floor. The user realized the trajectory in 102 s.

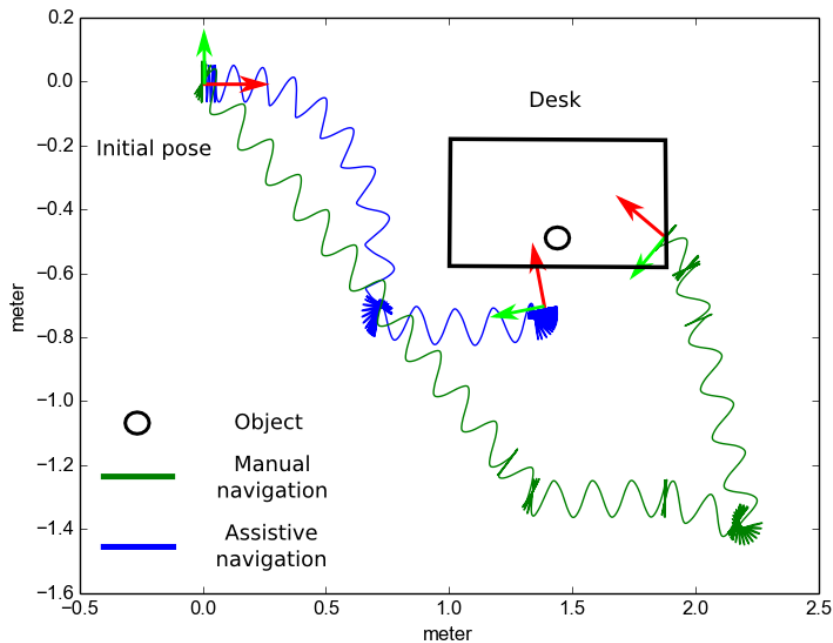


Figure 2.16: Robot CoM trajectories, without assistive navigation (Directional navigation) and with assistive navigation (Assistive navigation).

With the assistive navigation, the humanoid robot arrived correctly in front of the object on the desk to realize the task. In Figure 2.16, we can observe the CoM of the robot projected on the floor. The user realized the task in 65s.

This experiment suggests that the assistive navigation ensures a fast realization of the task.

2.5.1.4 Conclusion

The results of the preliminary experiment suggest that due to the difficulty of an accurate BCI-controlled directional navigation, the assistive navigation is necessary to perform an interaction with the environment.

However, an issue that might come by using an assistive navigation scheme is the decrease of the embodiment feeling caused by constraining the user to take the linear computed trajectory to go to the chosen interaction area. The feeling of embodiment toward the surrogate while walking and the influence of the control are studied extensively in Chapter 3. Nevertheless, the orbital based navigation presented in section 2.4.1.2 is developed in this

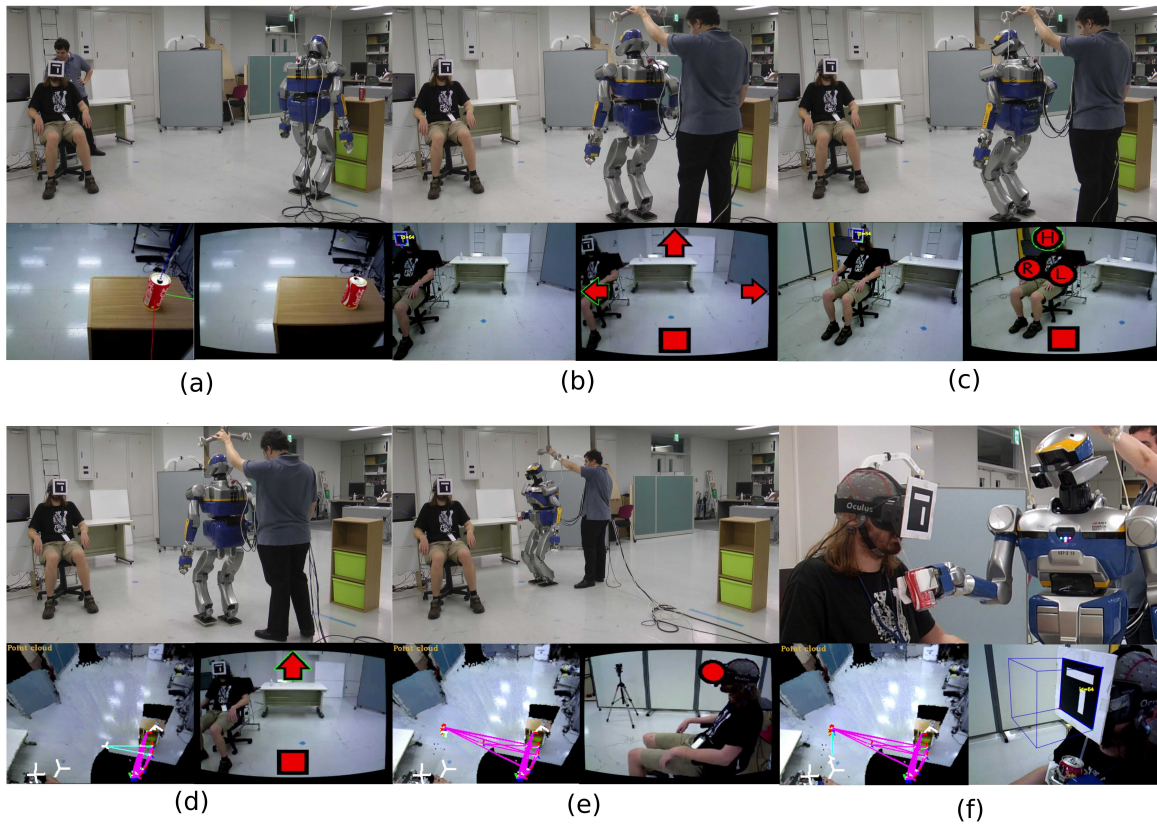


Figure 2.17: Consecutive phases of the first experiment: The user controls the robot to serve himself a drink.

regard in order to generate a trajectory that let the user feel less constrained. Improvements are made in the vision system in order to detect unmarked objects and human body parts. In the following section we present, the experiment with the improved navigation and vision system which allow the realisation of a more complex scenario.

2.5.2 Main experiment

In this section, we present the experiments devised to assess our improved semi-autonomous control framework in two assistive robotics scenarios. One healthy volunteer (a male of age 29) with prior BCI experience participated to test the framework prototype. In both experiments, we rely on SSVEP to extract the user intention from the EEG signal, with up to four stimuli at the frequencies of 6 Hz , 8 Hz , 9 Hz , and 10 Hz . In the first experiment, the user controls the robot to grab a can from a desk, carry it through the room, and hand it to his mouth to take a sip. In the second experiment, the user steers the humanoid near himself, in order to raise his arm.

In the first experiment, shown in Figure 2.17, the user controls the humanoid robot to take a can from a desk, carry it through a room and bring it to his mouth, so that he can take a sip. In this experiment, all the computer vision algorithms are used. First, BLORT is used

to recognize the can B, and estimate its pose ${}^C\mathbf{T}_B$. Once the can is recognized and localized, a stimulus shaped like the can CAD model is projected on the HMD and perceived by the user (see Figure 2.17.a). When the user focuses on this stimulus, and his intention is detected by the BCI, the robot grasps the can. Then, the user controls the robot with the directional navigation mode described in 2.4.1.1, to “look for himself” in the environment, while the Aruco algorithm is running to detect the marker located on the HMD wore by the user (see Figure 2.17.b). In order to keep the walk safe and reactive, the linear and angular velocities are set at $v^* = 0.1 \text{ m/s}$, and $\omega^* = 0.15 \text{ rad/s}$. As soon as the marker is localized (see Figure 2.17.c.left), the user selects his head F, to bring himself the drink through the robot (see Figure 2.17.c.right). Then, targeted navigation is activated, to assist the user in steering the robot near himself. This relies on the pose ${}^F\mathbf{T}_M$, given by D6DSLAM (see Figure 2.17.d). The localization provided by D6DSLAM proved to be accurate and robust enough, in spite of the camera sway during the humanoid robot walk [28]. This is shown by the CoM trajectory, plotted in Figure 2.18, that leads to the desired pose, while avoiding the safety circle Γ shown in Figure 2.14. At the end of this phase, the robot is well placed near the user, and the interaction phase is triggered (see Figure 2.17.e). The Aruco algorithm is then used to determine, the pose of the forehead, ${}^C\mathbf{T}_F$. Then, the humanoid hand control starts, to bring the can close to the user’s chin, while accounting for the mouth and straw length offsets. Finally, the user can drink from the can (see Figure 2.17.f).

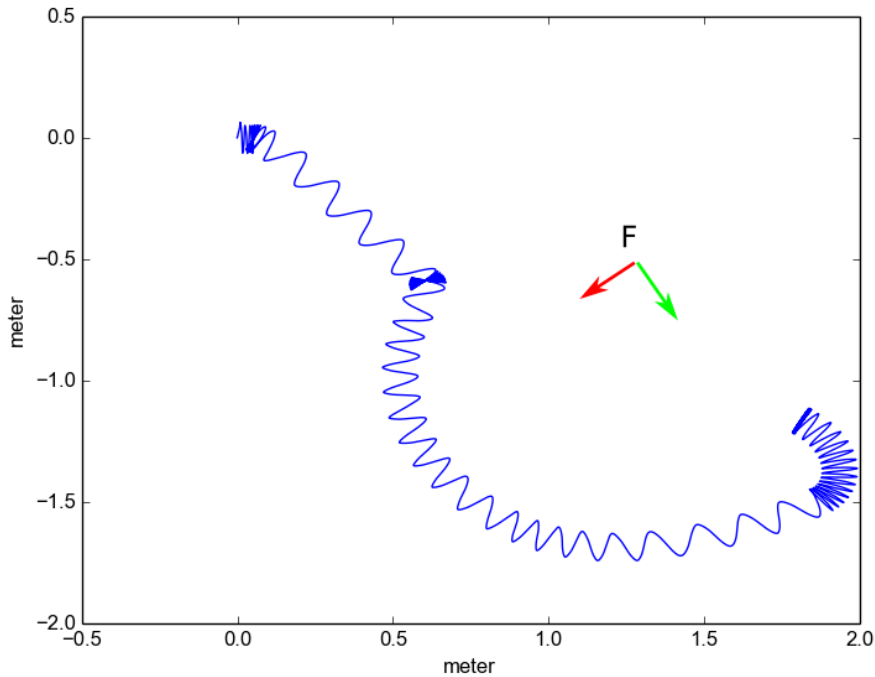


Figure 2.18: Trajectory of the robot CoM in the user forehead frame \mathbb{F} , obtained from the encoder measures.

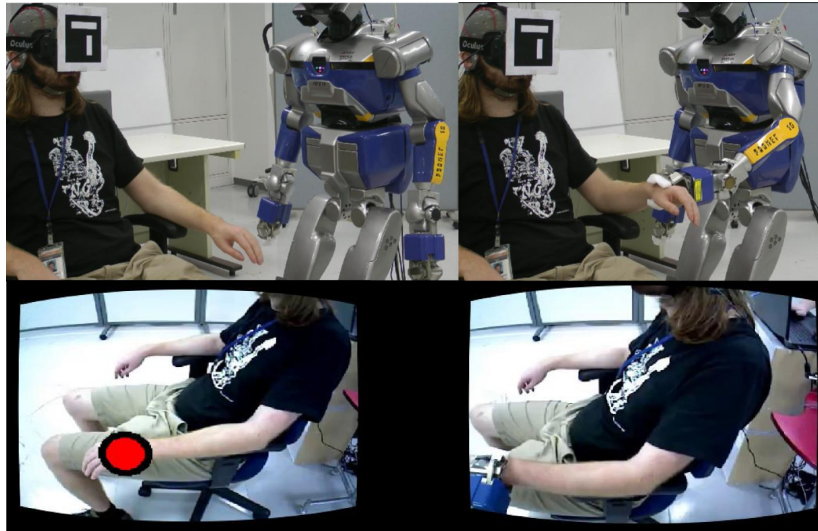


Figure 2.19: The user arm is grabbed and raised by himself using the humanoid robot surrogate.

In the second experiment, shown in Figure 2.19, the user steers the robot toward himself and uses it to raise his forearm. The robot is steered toward the forearm using, again, the targeted navigation. The accurate forearm pose ${}^C\mathbf{T}_A$ is given by the algorithm presented in section 2.2.1.3. In this case, the humanoid hand motion passes through three waypoints. The first waypoint is used to raise and orient the humanoid hand without approaching the forearm. To reach the second waypoint, the humanoid hand translates along the X_M axis and stops when it encounters the user forearm (i.e., when the external wrench is above a threshold, as indicated in (2.11)). Once touched, the hand gripper is closed and the humanoid hand is translated upward along the Z_M axis, toward the third waypoint. After 5 seconds, the humanoid hand goes downward along Z_M to the second waypoint, and the humanoid hand finally returns to the first waypoint.

2.6 Conclusion

In this chapter, we have presented an integrated framework, enabling a user to remotely control a humanoid robot with a BCI, to assist her/him in domestic tasks. The feeling of embodiment is given to the user via a HMD and a BCI control. To bypass the BCI bandwidth limitations, the framework is made semi-autonomous, by integrating various visual object recognition and localization algorithms, a targeted navigation mode and a shared control. To my knowledge, this is the first time that navigation and interaction (both with the environment objects and with the user) have been integrated in the same BCI-based framework. The results and the interviews from the subjects raised interesting issues relative to the embodiment feeling in the critical phases of the scenarios, hence steering the robot and interacting with one's self or the environment.

An important issue, raised by the interaction related experiments is the visual aspect of the humanoid robot arms. Indeed, when the humanoid robot grabs an object or interacts with

the subject, the robot arm is visible to the subject through the HMD in a first person view. As seen in Chapter 1, the visual aspect of the surrogate is most of the time “human-looking” in the embodiment experiments. However, the humanoid robot used in the experiments of this work does not have “human-looking” arms or even anthropomorphic hands. In this regard, an experiment is designed to solely investigate the effect of “robotic-looking” arms over the embodiment toward a humanoid robot in Chapter 4.

The BCI is an appropriate control for self manipulation scenarios. It leaves the subject limbs and legs unconstrained (i.e. free to be manipulated) which is not the case with other controllers used in teleoperation (for example joystick, keyboard or pedal). But the lack of accurate direct control over the robot’s arm motion, during self-touch or self-manipulation, may impair the study of the feeling of the subject during these phases. Therefore, another self-interaction experiment is realised using gesture control and is presented in Chapter 4

Lastly, as seen in the previous experiments, the assistive navigation is necessary to interact with the environment or with one’s self. In section 1.15 the work described from [4] and [5] shows that in a grasp scenario, the embodiment toward a Geminoid is high for the subjects with a high BCI performance, due to the fact that they have experienced few control errors due to the BCI. In this regard, the assistive navigation helps the subjects maintaining a high BCI performance since only one stimulus is required instead of three to navigate the robot toward a target. It is however unclear how the decrease of control and thus agency over the robot affects the embodiment toward the surrogate. For this purpose, the effect of control over the embodiment while steering a humanoid robot is studied in the next chapter.

Whole body embodiment

In the previous chapter, a framework designed to study the feeling of embodiment when one directly interacts with one's self have been presented. The framework features a shared control navigation to assist the subject in steering the humanoid toward a target. In this chapter, we study the effect of reduced control over the embodiment while steering a humanoid robot. The work describes in this chapter resulted from a shared collaboration with Dr Laura Aymerich-Franch (IOF Fellow).

In this chapter, two studies are presented in regard to the whole body embodiment of a humanoid robot, especially during a walking task. In usual teleoperated systems, an inherent delay exists (due to the network and control) and might affect the feeling of embodiment and agency of the subjects. Moreover, the type of control used in teleoperation is often different from the type of motion generated. In the case of walking for example, other controls such as joystick and BCI are often used instead of a bipedal system such as a treadmill. In this regard, a first study evaluates the feeling of embodiment over a humanoid robot with a partial and delayed control. Then, a second study compares different types of control and their influences over the embodiment.

This chapter is organised as follows. In section 3.1 a complete study over the influence of partial and delayed control on the embodiment of a walking humanoid robot is presented. First, the problematics of controlling a walking humanoid robot are introduced in section 3.1.1. Then the procedure and the robot framework used in the experiment are presented respectively in sections 3.1.3 and 3.1.4. The measures and results of the experiment are then presented and discussed respectively in sections 3.1.5, 3.1.6 and 3.1.7. Finally a complementary study about the influence of the type of control on the feeling of embodiment is presented in section 3.2.

3.1 Influence of partial and delayed control

Humanoid robot surrogates promise a plethora of new applications in the field of disaster management, human robot interactions [48] and assistive robotics [79] [108]. However, whole body embodiment for teleoperation or telepresence with mobile robot avatars has not been fully explored and understood. In this study, we investigate whether partial and delayed control, necessitated by the large number of degrees of freedom of a humanoid system, affects the embodiment of a walking humanoid robot surrogate. For this, we asked subjects to embody a walking humanoid robot in two conditions, one in which they had no control of its movement, and another in which they could control its direction of walking, but with delays. We used an embodiment questionnaire to evaluate the embodiment of the humanoid in each condition. Our results show that first person view visual feedback and congruent visuo-audio feedback are sufficient for the embodiment of the moving humanoid robot. Interestingly, subjects reported a sense of agency even when they did not control the robot, and critically the sense of agency and embodiment were not affected by the partial and delayed control typical of humanoid robots.

3.1.1 Walking embodiment

Recent humanoid robots are increasingly required to function as human surrogates in real life environments such as after a disaster as in the Darpa Robotics Challenge [103], social interactions [9] [98] [70], or for the assistance of the elderly [83]. Embodiment of the robot by the human pilots in such teleoperation scenarios is crucial for the quality of their social and physical interactions with their environments [99] [72]. Due to the large degrees of freedom of a humanoid system and the complexity of the environments, most of the scenarios require a hybrid control where the robots are partially controlled by human pilots, who either control particular levels of the control, for example task choice decisions [50], or particular degrees of freedom of the robot [104]. Furthermore, the control can include latencies or delays such that there is a time lag between a user's command and the robot action. It is however unclear whether a partial and delayed control affects the sense of embodiment of the humanoid robot surrogates. We examine this issue in this chapter.

As presented in section 1.1.1, the sense of embodiment is believed to be composed of the sense of self-location, sense of body ownership and sense of agency [71]. The sense of self-location represents the volume of space where one feels located. The sense of body ownership defines the feeling of self-attribution. The sense of agency represents the feeling of being able to interact with the environment with our body. The works on the embodiment began with the rubber hand illusion experiment [20] in which the authors showed that subjects develop ownership of a fake rubber arm when provided with synchronous visuo-tactile stimulations. Since then, several studies have examined the embodiment of not only individual artificial limbs [62] (as seen in section 1.1.3) but also the entire body [112], [100] (as seen in section 1.1.4). Other studies have assessed the influences of the body ownership and self-location on the sense of embodiment. For example in [53], subjects were observed to disown their body after experiencing an illusory displacement of their sense of self-location.

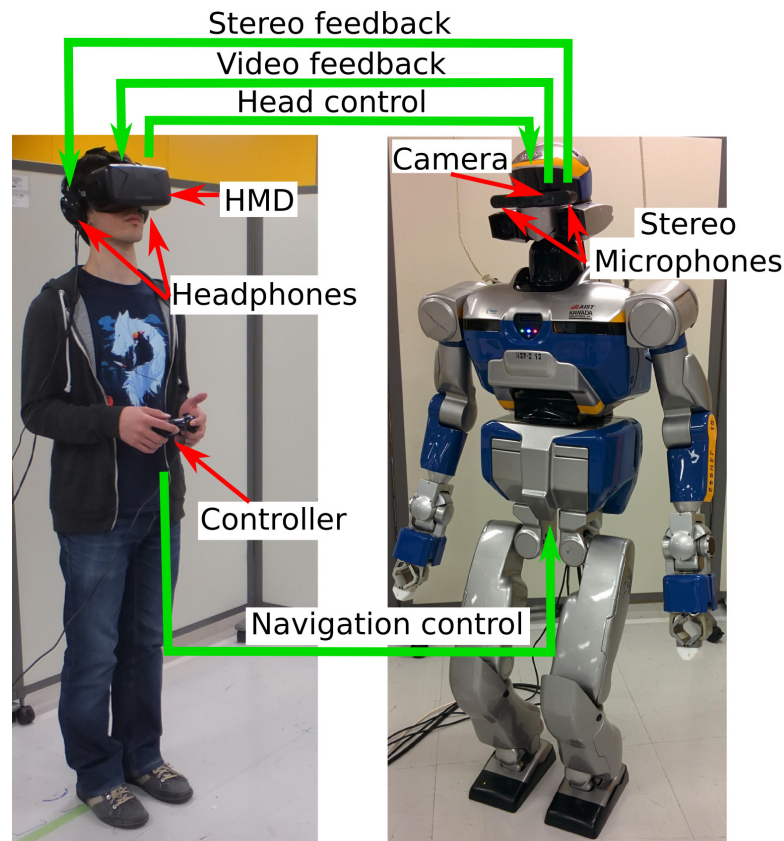


Figure 3.1: Description of the equipment used in the experiment.

Most of the embodiment studies have utilized passive fake limbs, mannequins or video projections which do not provide information about the influence of the sense of agency on the embodiment. On the other hand, these studies have shown that first person vision in the presence of multisensory congruencies is enough to induce embodiment. Agency is known to increase the embodiment when the control is precise [67] but it is not clear how partial control and reaction delays affect the embodiment. Delays in sensory stimulation have been previously shown to be disruptive for the sense of ownership [82], while the sense of agency was observed to be robust to time delays at least in the case of a (low degree of freedom) button press task [122]. However, to the best of our knowledge, no study has looked into the effect of agency on the embodiment of a multi-degree of freedom system like a humanoid robot performing whole body motions.

Here we investigate how partial and delayed control of a humanoid surrogate during whole body motions (specifically bipedal locomotion) influences the feeling of embodiment. Specifically we ask three questions:

1. *Can first person vision and multi-sensory (visuo-auditory) congruency induce a sense of agency toward a moving humanoid robot surrogate even when the movements are not controlled?*

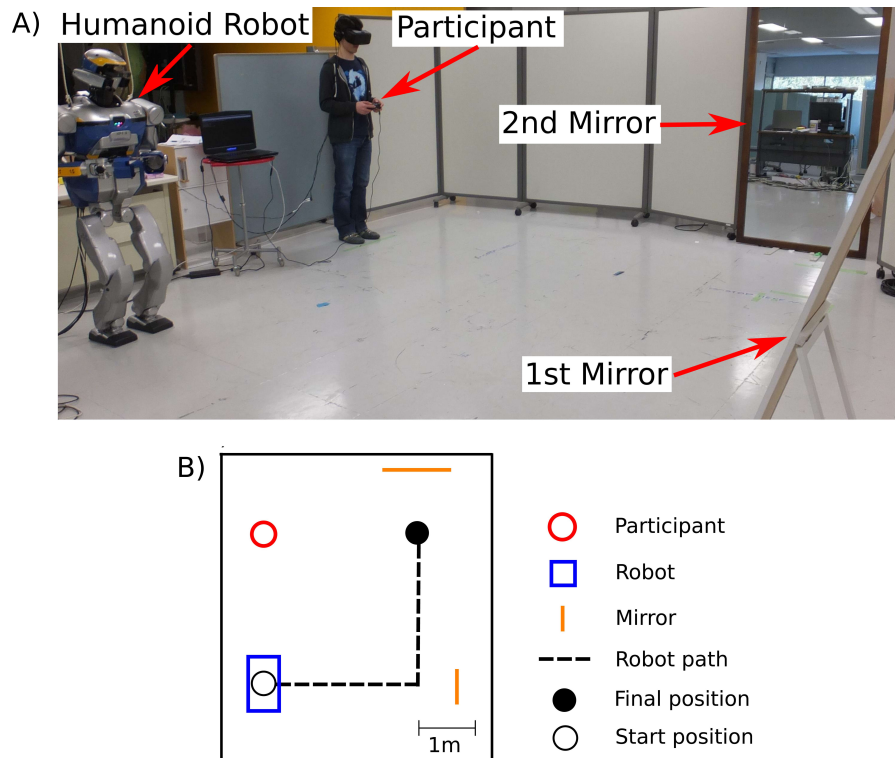


Figure 3.2: View of the experiment set-up.

2. *Is first person vision accompanied by visuo-auditory congruency enough to induce whole body embodiment of the moving humanoid surrogate?*
3. *Does partial and delayed control reduce the sense of agency and/or embodiment of the robot surrogate?*

In order to answer these questions, we conducted an experiment in which subjects embodied a humanoid robot, namely HRP-2, shown in Figure 3.1, by getting an audiovisual feedback from the robot. We compared their perception of agency, ownership and self-location when they experienced the robot walking in two different conditions, one in which they would not control the robot movement, and another in which they partially controlled (only the movement direction and not the individual limbs of) the robot's movement using a joystick. Even in the latter condition, the joints speed and balance constraints of the whole body robot controller introduced a delay between the commands issued by the subject and the robot responses. The delay was observed to be between 0.5 to 2 seconds depending on the phase of the gait cycle (turn, start or stop) a command was issued.

3.1.2 Participants

Our study included 13 subjects (7 females and 6 males), aged 21-43 ($M = 27.38$, $SD = 7.7$) who were either university students or researchers of different nationalities. The subjects were naïve to the purpose of the study. Subjects read and signed an informed consent form and received 1500 Japanese Yens to participate. Working in the robotics or neuroscience field was used as an exclusion criteria. In addition, the experiment was pretested with 5 volunteers. The study was conducted with the ethical approval of the *National Institute of Advanced Industrial Science and Technology (AIST) in Tsukuba, Japan*.

3.1.3 Procedure

After signing the consent form, the subjects completed a survey containing basic demographic informations (age, gender, field of work or study), videogame playing habits, and likeability of and familiarity with humanoid robots. The subjects then embodied an HRP-2 robot. For this, they wore an HMD [102] which gave a 2D visual feedback from the robot's "eyes" (camera mounted on the robot's head). They received the audio feedback through a pair of headphones from a stereo microphone placed on the robot's head, like seen in Figure 3.1.

The subjects stood at one location throughout the experiment, and in the same room as the robot. The robot started the experiment about 2.3 meters away from the subjects and faced the same direction as the subjects such that the subjects were out of its field of view as seen in Figure 3.2.A.

The subjects started the experiment by answering three questions of the *embodiment questionnaire* (see section 3.1.5) displayed one by one in front of the robot's eyes by the experimenter. Next, they performed two initial training trials in which they wore the HMD and headset and experienced the robot walking an L-shaped path twice (shown in Figure 3.2.B). In the first trial, the subjects did not control the robot's walk and only held a fake joystick in their hands. In the second trial, the subjects controlled the walking direction of the robot using a joystick [90] and were asked to follow the same L-shaped path indicated by markings on the floor seen through the HMD. The subjects used two different buttons on the joystick to control the robot: the guide button was used as a start / stop motion and the directional pad was used to walk straight, turn left, and turn right. Any verbal instructions provided to the subjects were provided by talking to the robot, such that the subjects could hear them through the headset.

After the training, one of the researchers uncovered two big mirrors which were placed at strategic locations such that the robot reflection was visible to the subject during the experiment. The subjects then went on to the main experiment which again consisted of a robot controlled condition and a non-controlled condition. In the experiment conditions the subjects thus received a visual feedback of their walk (the sway in the visual feedback due to the walk and their reflection in the mirrors) through the HMD and a corresponding and congruent auditory feedback of the sound of the robot steps through their headset.

In the robot control condition, the subjects were given the joystick to control the robot's

walk along the same L-shaped path that they trained on. Critically, they were also able to control the robot's head movement with their own head movement. If the subjects looked down, they were able to see the robot's hands holding a fake joystick controller. The robot movements in this condition were delayed such that it responded to the direction change command between 0.5 s and 2 s. In the non-control condition, the subjects again held a joystick but were not able to control the walk nor the head movement. The subjects were told that "the robot would control the movement by itself". Instead, one of the researchers controlled the robot's walk as well as the head movement of the robot using another joystick controller. The robot again followed the same L-shaped path while the subjects saw the robot reflected in the mirrors through its eyes.

The robot movement in both conditions started by looking left and right (In the controlled condition, the subjects were instructed to perform these head movements). Followed by which, the robot walked straight toward the first mirror. After spending few seconds there, the robot turned left and walked toward the second mirror. When the robot arrived at the second mirror, it stopped completely and the subjects were again asked to answer the same three embodiment questions that they answered at the start of the experiment. Completing each path condition took about 3 minutes. The subjects were given a short rest for few minutes after each condition, during which the robot was brought back to the start position by an experimenter. Afterwards, they moved on to the next condition. After finishing the two conditions, they were thanked for their participation and paid.

The order of the controlled and non-controlled conditions was counter-balanced across subjects.

3.1.4 Robot framework

The Robot Operating System (ROS) [120] was used to integrate the HMD, joystick controller and robot's camera. To make the humanoid walk, we used the walking pattern generator from [58], which receives the desired walking speed and computes the corresponding desired foot positions utilizing the stack of tasks controller (SoT) [85]. In the SoT, the robot tasks are defined as state error vectors in the sensory space, and projected in the robot joint space with the robot kinematic Jacobian. The robot walking speed was fixed at 0.1 m/s throughout the experiment.

3.1.5 Measures

A 3-item embodiment questionnaire (see section B.1) was designed to measure the sense of embodiment toward the humanoid robot. The questionnaire was designed to be responded *in situ* during the experiment, when the subjects were seeing their robot's body in front of the mirror through the HMD. It contained three questions, one for each of the subcomponents of embodiment: body ownership, self-location, and agency [71]. Each question was rated on a 7-point scale ranging from (1) *Not at all* to (7) *Very Strongly*. The complete questionnaire was the following:

Do you feel as if...

1. The robot's body was your own body

Not at all 1-2-3-4-5-6-7 Very Strongly

2. You were located at the position of the robot

Not at all 1-2-3-4-5-6-7 Very Strongly

3. You could use the robot's body to push objects near him if you wanted

Not at all 1-2-3-4-5-6-7 Very Strongly

The responses were treated as interval data and the means of the three items were averaged to form the embodiment scale. Reliability of the scale was $\alpha = .89$, KMO = .692, and Bartlett's test of Sphericity = .000.

3.1.6 Results

We calculated the Mean and SD for body-ownership, self-location, and agency which are believed to be the three subcomponents of the embodiment feeling [82]. We averaged the results of the three subcomponents to obtain the global embodiment. The Table 3.1 and Figure 3.3 show the Means and SD obtained at the end of the experiment.

In order to determine if the embodiment feeling was created during the experiment, we ran a paired-samples T-test in which we compared the levels of embodiment at the beginning and at the end of the experiment. In the rest of this work t and p correspond respectively to the "t ratio" and "P value" obtained by the paired-samples T-tests. The levels of embodiment for both conditions (control ($t(11) = -4.284$, $p = .007$), non-control ($t(11) = -3.335$, $p = .001$)) were significantly higher at the end of the experiment compared to the beginning of the experiment which show the creation of the embodiment during the experiment.

Paired-samples T-test were conducted to compare the embodiment feeling in the controlled and non-controlled conditions (see Figure 3.3 and Table 3.1). Results showed that being able to partially control the robot ($M = 4.59$, $SD = 1.37$) did not generate a significant different embodiment than when the robot was not controlled ($M = 4.31$, $SD = 1.75$); $t(12) = -.744$, $p = .471$. The dimension of agency alone was also not significantly different between the controlled ($M = 4.77$, $SD = 1.64$) and the non-controlled ($M = 4.15$, $SD = 2.23$) conditions; $t(12) = -1.036$, $p = .321$.

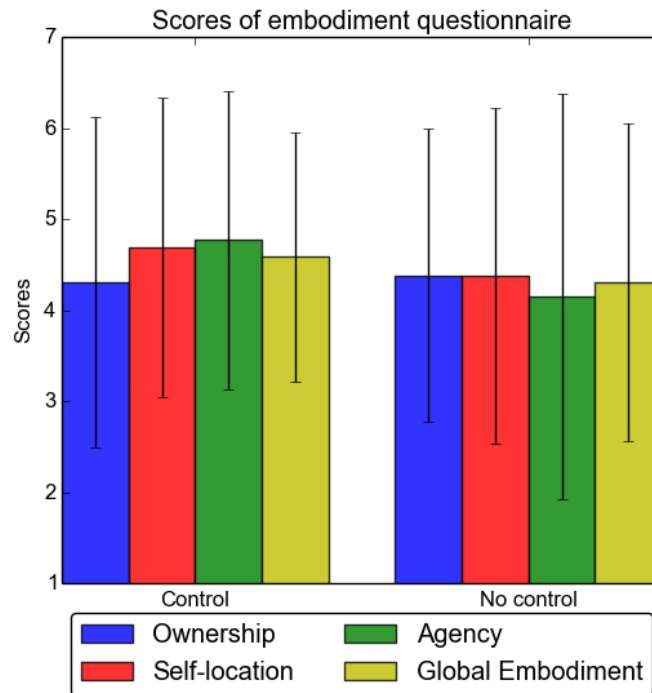


Figure 3.3: Graph of the means and SD for global embodiment and its subcomponents for control and non-control conditions.

3.1.7 Discussion

In this study we investigated the effect of controllability on the embodiment of a humanoid robot avatar performing whole body motions. Specifically we aimed at understanding three issues that were listed in section 3.1.1 to understand whether and how partial and delayed control affects the embodiment of humanoid robots. Our results strongly suggest that a first person view presented in parallel with congruent visuo-auditory feedback is enough for subjects to feel both a sense of agency and embodiment, toward the humanoid robot surrogate. Furthermore, we observed that the agency, the embodiment and the feeling of self-location (at the robot location) were maintained even during partial control, when the subjects controlled only the general direction of walking and while the robot control was affected by variable delays.

In this study, the subjects used a joystick to control the walking direction of the robot. We define this control as “partial” because the subjects did not control individual robot joints. We chose this condition of partial control over a condition where the subjects are able to control certain robot limbs but without delays, due to its increased relevance to walking humanoid avatars and video games. Furthermore, in our scenario, the subject movements (which were mostly finger movements to operate the joystick) were very different from the robot limb movements. We were therefore very interested to see how this limb movement difference affects the sense of agency of the subjects. Interestingly, we observed that the embodiment

n=13	Control M(SD)	Non-Control M(SD)
Ownership	4.31(1.82)	4.38(1.61)
Self-location	4.69(1.65)	4.38(1.85)
Agency	4.77(1.64)	4.15(2.23)
Global Embodiment	4.59(1.37)	4.31(1.75)

Table 3.1: Means and SD for global embodiment and its subcomponents for control and non-control conditions.

results were not different from what has been observed with static robots or mannequins; subjects could embody a moving robot even when they were themselves stationary and not in control of the movement. Furthermore, they perceived agency even in the non-controlled condition. This suggests that in our experiment the sense of agency was induced by the embodiment resulting from the visual and auditory feedback. This result, that partial control is neither better nor worse than non-control, gives interesting insights for the design of future humanoid robot avatar applications and recent human-machine interactions applications like self driving cars. We expect these results to be also helpful in the domain of embodiment in virtual reality.

3.2 Influence of control input in the embodiment of a humanoid robot

In the previous section, we demonstrated that the embodiment toward a humanoid robot is not impaired by partial and delayed control, when the subject steers the robot with a joystick. However in the scenario presented in Chapter 2, the subject controls the robot with a BCI. In this section, we investigate how the results obtained in the previous section (section 3.1) are influenced by the type of control used by the subject. An exploratory experiment was conducted with six internal volunteers from the lab. The subjects experienced three conditions, one in which they controlled the robot using a BCI, one in which they controlled the robot using a joystick, and one in which they did not control the robot.

3.2.1 Participants

Our study included 6 volunteer subjects from the laboratory (2 females and 4 males), aged 21-25 ($M = 23.2$, $SD = 1.78$).

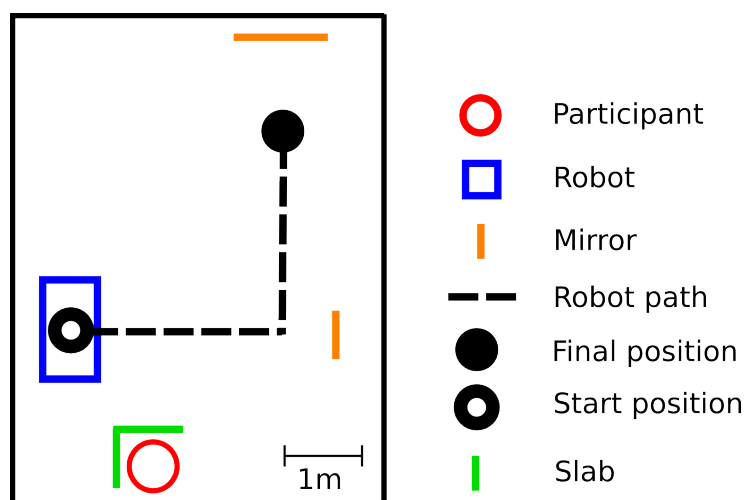


Figure 3.4: View of the robot trajectory and the subject location.

3.2.2 Procedure

Before the experiment, the subjects completed a survey relative to the demographic information. Then the subjects were asked to wear a HMD which displayed the video feedback from the robot's head mounted camera and an EEG cap. The subjects were seated at a location away from the humanoid as well as out of its field of view as seen in Figure 3.4. In this configuration, the subjects and the humanoid were not facing the same direction. Each subject underwent a training to use the BCI system (previously presented in section 2.3.1) which relied on SSVEP.

After the BCI training performed, the subjects were asked the three questions of the embodiment questionnaire as previously described in section 3.1.5. Next, they performed three initial training trials in which they experienced the robot walking an L-shaped path (as seen in Figure 3.4) in each condition. In the first trial, the subjects held a fake joystick and did not control the humanoid, instead an experimenter controlled the humanoid. In the second trial the subjects steered the humanoid with a joystick controller [90] and were asked to follow the L-shaped path previously experienced and indicated by markings on the floor. The "Guide" button of the controller was used to start or stop the robot walking motion. The directional pad of the joystick controller was used to walk front, turn left, and turn right. In the final trial, the subjects controlled the humanoid robot with the BCI using the interface shown in Figure 3.5.A. In the three training trials, the mirrors were covered or turned backwards so that the subjects were unable to see the humanoid robot own reflection as seen in Figure 3.5.A.

Once the three training trials were over, the mirrors were turned correctly and uncovered so that the humanoid reflection could be observed by the subjects through the HMD as seen in Figure 3.5.B. The subjects then performed the main experiment which consisted in realizing the L-shaped path in each condition. In the BCI and joystick conditions, the subjects controlled the robot's head by moving their own head. However, in the non-control condition, the subjects were unable to control the robot's head. In the non-control condition,

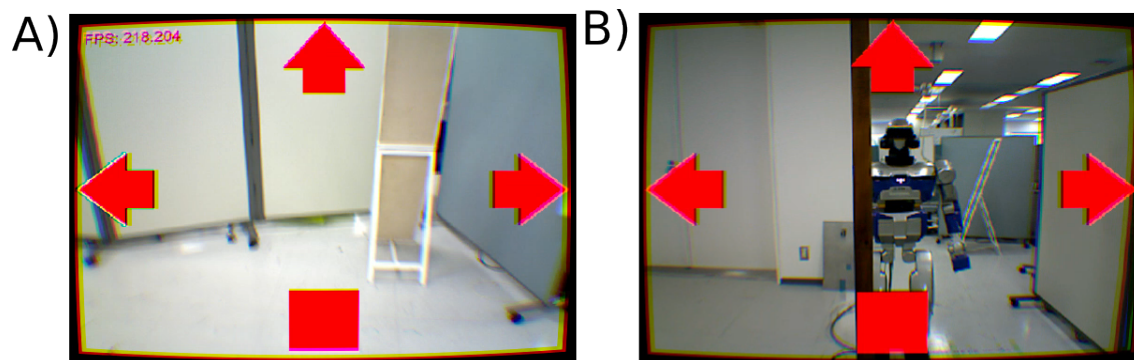


Figure 3.5: BCI interfaces used by the subjects in the training (A) and in the main experiment (B).

n=6	BCI control	Joystick control	No-Control
	M(SD)	M(SD)	M(SD)
Embodiment	4.554(1.06)	3.61(0.77)	2.44(1.42)

Table 3.2: Means and SD of the embodiment for BCI control, joystick control and non-control conditions.

the subjects held a fake joystick and were told that the robot would be controlled by itself, but in reality an experimenter steered the humanoid (and controlled its head) to realize the L-shaped path by using another joystick controller.

In order to realize the L-shaped path the subjects were instructed to start the walking motion of the robot, then to go forward while moving their head left and right to observe the environment. Then the subjects were asked to go in front of the first mirror and observe their own reflection for a few seconds, as seen in Figure 3.5.B. Next, the subjects were instructed to turn left and go straight to the second mirror. There, they were asked to stop the walking motion and observe their own reflection again for a few seconds. After that, they were asked the questions from the embodiment questionnaire (see section B.2) to assess their feeling of embodiment. At the end of one condition, the subjects were asked to take a short rest to be ready for the next condition. The order of the conditions was counter balanced across the subjects. The measure of the level of embodiment was realized through the embodiment questionnaire for each condition (see section B.2).

3.2.3 Results

On a 7-point scale, the overall sense of embodiment obtained an average of ($M = 4.554$, $SD = 1.06$) in the BCI control condition; an average of ($M = 3.61$, $SD = .77$) in the joystick control condition; and an average of ($M = 2.44$, $SD = 1.42$) in the non-control condition as seen in Figure 3.6 and Table 3.2. In particular, paired-samples T-test showed that the subjects experienced significantly more embodiment in the BCI control condition compared to the joystick control condition ($t(5) = 2.795$, $p = .038$). The difference in terms

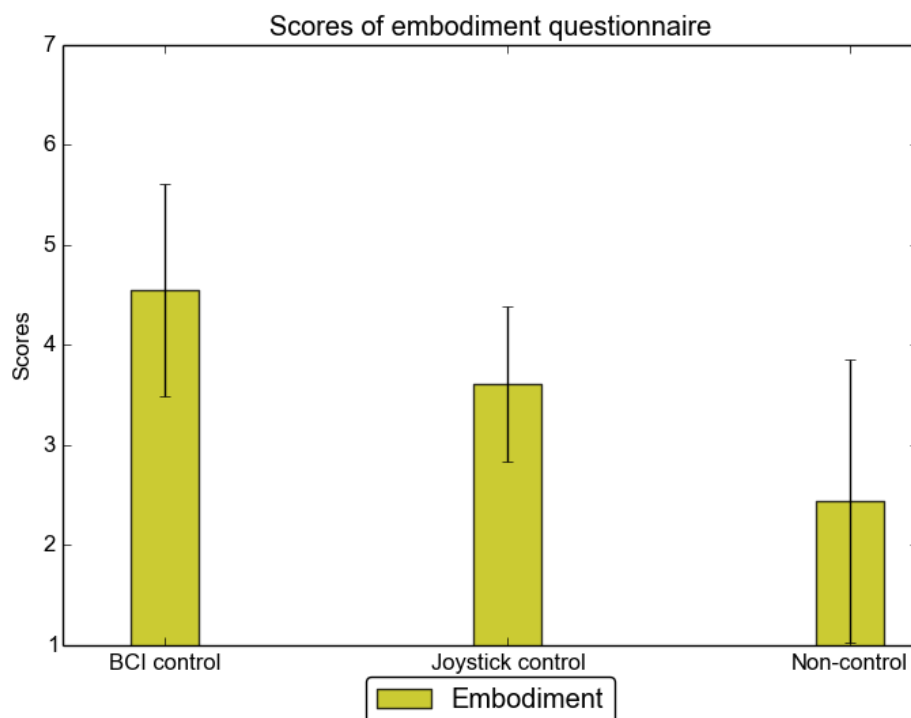


Figure 3.6: Graph of the Means and SD of the embodiment for BCI control, joystick control and non-control conditions.

of embodiment between the BCI control condition and the non-control condition was also significant ($t(5) = 2.281, p = .071$). In contrast, the joystick control condition and the non-control condition showed no significant difference ($t(5) = 1.849, p = .124$), which supports the findings described in the previous section (section 3.1.6).

3.2.4 Discussion

In this experiment, the embodiment scores for the joystick condition and the non-control condition were lower than in the previous experiment described in section 3.1.6. The scores for the feeling of embodiment obtained in the joystick and non-control conditions in the previous experiment were closer to the one obtained for the BCI condition in this study. Further experiments are needed to clarify how individual differences such as the experience of interacting with robots, the demographic and personality traits influence the experience of embodiment when different types of control are provided to the user.

In regard to the scenario presented in Chapter 2, the fact that the subjects obtained a higher feeling of embodiment with the BCI control over the joystick control is promising. Indeed, with the BCI control, the subjects arms are free to be interacted with, like seen in the experiment presented in Chapter 2 where a subject manipulates one's own arm. The

results of this study, added to the results presented in section 3.1, regarding the feeling of embodiment being maintained during partial and delayed control, validate the use of the assistive navigation presented in Chapter 2, since the assistive navigation can be perceived by the subjects as a type of partial control with BCI. In that case these results suggest that the embodiment is maintained during the assistive navigation control with BCI used in the experiment presented in Chapter 2.

3.3 Conclusion

In this chapter, two studies are presented which relate to the whole body embodiment of a walking humanoid robot. These studies focus on the feeling of embodiment obtained by subjects controlling a humanoid robot to realize a walking task. In these experiments the subjects stayed still without a haptic feedback.

In the first study (section 3.1), the subjects steered a humanoid robot with a joystick to realize an L-shaped path. Mirrors were placed along the path so that the subjects were able to observe the reflection of the humanoid robot. The control of the joystick allowed the subjects to go straight, turn left and turn right, with a delay, which is common in teleoperation. The first result demonstrated that a first person view associated with a visuo-auditory congruency feedback was enough for the subjects to feel both a sense of agency and embodiment. In [54] non-corporeal objects are believed to prevent the feeling of embodiment, interestingly the “robotic aspect” of the surrogate used in the experiment did not prevent the establishment of the feeling of embodiment.

Moreover, the results showed that the feeling of embodiment was preserved even with a partial control affected by a delay. This result obtained with a walking task affected by a delay confirmed the results found with a manipulation task in [100] which were in opposition with the results found with the RHI in [133]. If confirmed by future studies (with a delay explicitly tested and controlled), this tolerance to delay with a “robotic looking” surrogate compared to “human-looking” surrogate promises more interesting findings in the embodiment of humanoid robot. This study also demonstrated that the feeling of embodiment toward a walking humanoid could be felt by staying still and using a type of control different from bipedal motion.

Furthermore, no significant differences were found in terms of embodiment between control and non-control conditions. The subjects even felt a slight feeling of agency during the non-control condition. This result is promising for the design of automatic systems such as self-driving cars or in the case of the experiment presented in Chapter 2 assisted navigation. The result showed that the assistive navigation system, necessary for the safety and efficiency of the navigation task, should not prevent the establishment of the embodiment. However, since in Chapter 2 the navigation was performed with a BCI and not a joystick, a second study was realized to evaluate the embodiment between different types of control.

Indeed, in order to confirm that the results found with the joystick controller were still valid with the BCI, a second study was conducted to compare the influence of different types of control over the embodiment felt during the walking task. The experiment showed that

the BCI control generated a stronger feeling of embodiment compared to the control with joystick. This result is promising, even if this study was made with a few volunteers from the lab instead of numerous naïve subjects.

In regard to the scenario developed in Chapter 2, this chapter brings a positive answer to the issue of the embodiment toward a walking surrogate without haptic feedback and with a limited control. In the following chapter, the feeling of embodiment felt during an interaction with the environment or with one's self is investigated.

Limb embodiment

In the previous chapter, we investigated the feeling of embodiment toward a walking humanoid robot with limited control and without haptic feedback. In this chapter, the feeling of interaction with the environment and with one's self is investigated. The work described in this chapter resulted from a shared collaboration with Dr Laura Aymerich-Franch (IOF Fellow).

In this chapter, we present three studies to investigate the feeling of embodiment toward a humanoid robot arm, gesture controlled by a subject. In the literature, most limbs or bodies used in the study of embodiment have human features. On the contrary, the surrogate used in this study is a humanoid robot with clear robotic features. Therefore, first, we studied the embodiment toward a “robotic-looking” arm induced with visuo-tactile and visuo-motor stimuli. Then, once shown that the embodiment toward a “robotic-looking” arm was possible, we investigated in a second study the embodiment felt during an interaction with the environment. In order to explore this feeling, we designed an experiment, where a subject, provided with the first person perspective from the humanoid robot, controlled the humanoid arm through gesture motion to interact with a curtain placed in front of the robot. The results showed that even without a haptic feedback in the control loop, the subjects experienced a pseudo-haptic feeling and felt a strong embodiment. Lastly, in regard to the results obtained for the interaction with the environment, we modified the experimental set-up to study the feeling of embodiment during an interaction with one's self.

The chapter is organised as follows. In section 4.1, the study of the embodiment toward a “robotic-looking” arm is described. The results are presented and discussed respectively in sections 4.1.6 and 4.1.7. Then, the study related to the interaction with the environment is presented in section 4.2, the results and discussion over this study are shown respectively in sections 4.2.5 and 4.2.6. Finally, the study regarding the self-interaction is described in section 4.3, the results and discussion relative to this study are presented in sections 4.3.3 and 4.3.4.

4.1 Embodiment of a robotic-looking arm through visuo-tactile and visuo-motor stimuli

In the self-interaction experiments presented in Chapter 2, the subject sees, through the robot's eyes, the "robotic-looking" arm of the humanoid while interacting with one's self or the environment. In this section, we investigate how the robotic aspect and the controllability of the humanoid arm affect the feeling of embodiment of the subject compared to the classic RHI. For this purpose, an experiment is conducted in which the feeling of embodiment is induced with a visuo-tactile stimulus toward a humanoid robot arm and a human arm in order to assess the influence of the limb aspect's. In another condition, a visuo-motor stimulus is used to induce the feeling of embodiment in order to explore the effect of controllability on the embodiment.

The results demonstrate that the feeling of embodiment toward the humanoid arm is equivalent to the one felt toward the human arm. This result is important for the study of the embodiment, the design of humanoid and prosthetics in robotics. For example, with the rise of the 3-D printing technology, affordable prosthetics are being developed. However, they lack the human skin feature present in "high-end" prosthetics. Even though this result is found with a surrogate, this suggests that a patient with a "robotic-looking" prosthetic hand might be able to experience a strong feeling of embodiment toward it, comparable to a high-end "human-looking" prosthetic hand.

4.1.1 Limb ownership

As seen in section 1.1.2, the feeling of embodiment toward an artificial limb was demonstrated with the classical RHI [20]. In this experiment the subjects developed a feeling of ownership toward a rubber hand induced by a synchronous visuo-tactile stimulation on the fake and real arm's subjects.

Since the classical RHI [20], the embodiment of foreign limb have been induced with different stimuli (see section 1.1.3.1). In [29] the feeling of embodiment is induced with a visuo-thermal stimulus. While in [67], the feeling of embodiment is induced with a visuo-motor stimulus by being able to move a finger of a rubber hand synchronously with one's own finger. Similar results are also found in [100] [67] [68] [141]. These findings support the idea that the feeling of embodiment is successfully induced when there is a congruency between stimuli (see section 1.1.3.4). This concept is confirmed in [33] and [54] using fMRI on subjects which performed the RHI experiment.

The impact of the visual aspect of the limb over the embodiment is still subjects of ongoing research (see section 1.1.3.2). Specifically, whether the use of "human-looking" limb (or surrogate) is required for the establishment of the embodiment. In [140] a variation of the RHI is realized with a wooden stick instead of a rubber hand to explore the question of the visual aspect requirement to elicit the feeling of embodiment. The study suggests that two of the minimum conditions to elicit the feeling of embodiment toward a foreign limb are its human resemblance and its appropriate orientation (corresponding to the proprioceptive

information of the subject). Similar results are shown in [109].

However, in a recent experiment described in [54] the feeling of ownership is induced successfully on an empty space but failed toward a block of wood, [54] then suggests that the feeling of embodiment would fail on a non-corporeal object (in their experiment the block of wood). This statement is supported by the findings presented in [124] where the embodiment is elicited with an amputee patient toward a “robotic-looking” anthropomorphic prosthetic hand.

Our robotic platform allows to study the feeling of embodiment elicited with a visuo-motor stimulus which is not practical to study with a fake limb or a mannequin like it is done usually in the embodiment studies. In [100] a body ownership transfer toward a teleoperated android is realized with a visuo-motor stimulus. A similar result is obtained using a BCI [4] instead. However, both of these results are realized using a Geminoid which is a duplicate android of real person and thus highly “human-looking”.

Therefore, in order to study the embodiment of a “robotic-looking” humanoid limb, we devised an experiment where the subjects were able to embody a human arm and a humanoid robot arm using a visuo-tactile or a visuo-motor stimulus. With our set-up it is then possible to evaluate the difference in terms of embodiment between a “human-looking” arm and a “robotic-looking” arm. This set-up also allows the use of different stimuli to elicit the feeling of embodiment toward the robotic arm. We are then able to compare the effect of the different stimuli in terms of strength of embodiment. In regard to the mentioned results we explored the following hypothesis:

- H1: Synchronous visuo-tactile stimulation between the subject’s arm and another human arm will produce significantly higher feeling of embodiment than asynchronous visuo-tactile stimulation.
- H2: Synchronous visuo-tactile stimulation between the subject’s arm and the “robotic-looking” humanoid arm will produce significantly higher embodiment than asynchronous visuo-tactile stimulation.
- H3: The feeling of embodiment induced by visuo-tactile synchronization of a “robotic-looking” humanoid arm will be similar to that induced by visuo-tactile synchronization on a human arm.
- H4: The feeling of embodiment induced by visuo-motor synchronization of a “robotic-looking” humanoid arm will be similar to that induced by visuo-tactile synchronization.

4.1.2 Method

4.1.2.1 Participants

Twelve participants of different nationalities (six males and six females), aged 21 to 43 ($M = 26.67$, $SD = 8.04$), participated in the experiment. One of the participants was left-handed

and the rest were right-handed. Participants were naïve to the purpose of the experiment and received 1500 JPY (Japanese yen) to participate.

They were recruited through a call for volunteers in the website of the experiment, which was posted on social networks. Working in the Robotics or Neuroscience fields was used as an exclusion criteria. A pretest was conducted with five intern master students of the *Joint Robotics Laboratory (JRL)* in which the study was carried out. The study was carried out with the ethical approval of the *National Institute of Advanced Industrial Science and Technology (AIST)* in Tsukuba, Japan.

4.1.2.2 Experimental Design

A within-subject experiment was conducted in which participants experienced a human arm illusion elicited through visuo-tactile synchronization (see Figure 4.2.A), a “robotic looking” humanoid arm illusion elicited through visuo-tactile synchronization (Figure 4.2.B), as well as their corresponding asynchronous versions. A “robotic looking” humanoid arm illusion was also elicited through visuo-motor synchronization (Figure 4.2.C). Each experiment was repeated twice: once for the left arm and once for the right arm, making a total of 10 trials per participant. Half of the participants started with the left arm and half of them started with the right arm and went through the five trials before switching to the opposite arm. For each arm, we grouped the human arm conditions and the robot arm conditions and randomized the order among the conditions within each group and between robot and arm groups such that each participant experienced the conditions in a different order but human arm conditions and robot arm conditions were not mixed among them.

4.1.3 Apparatus

The human size humanoid robot HRP-2 [69] was used to create the embodiment in the robot arm conditions. The material of the robot arm is composed of plastic and metal with blue and silver colors. Each arm had seven degrees of freedom and a square ending at the place of the hand like seen in Figure 4.1. A RGB-D camera (Asus XtionPRO live [8]) mounted on the robot’s head sent visual feedback to an Oculus Rift [102] Head Mounted Display (HMD) worn by the user like seen in Figure 4.2. Sensors integrated in the HMD allowed the tracking of the user’s head motion in order to control the robot’s head. A second RGB-D camera (similar to the previous one) was used externally to track the hand motion of the user in the robotic arm control condition as seen in Figure 4.2.C. OpenNI [137], a framework to track body and hand motion, was used to track the user’s hand position. In our experiment, only the user’s hand position was tracked. The hand tracker was initialized after detecting a waving motion of the user’s hand. Once the hand was tracked, the participant was asked to place her/his hand in a position corresponding to the robot’s hand position (see section 4.1.4). Following that, the user hand motion was mapped on the robot hand (teleoperation mode). In order to control the robot arm and head, the Stack-of-Task (SoT) controller was used [85], which took as input the hand position provided by OpenNI as well as the user’s head orientation provided by the HMD. In the SoT, the robot tasks are defined

as state error vectors in the sensory space, and projected in the robot joint space with the robot (pseudo-) inverse kinematic Jacobian. The Robot Operating System (ROS) was used to integrate the HMD, the robot's camera, the SoT and the OpenNI human hand tracker.

For the human arm, we used the bare medium-sized arm of a female researcher. The same set-up of the humanoid was used for the human arm (see Figure 4.2.A). During this condition, the humanoid arm was lowered and left aligned to its body. Instead, the researcher placed her arm on a 90° position (like a handshake position) from behind the robot, so that the participant was able to see a human arm when s/he looked down through the HMD as seen in Figure 4.2.A. In order to keep the arm neutral, the female researcher arm and hand did not have any visible clothes or jewelry. The nails were cut short and did not have any nail polish.

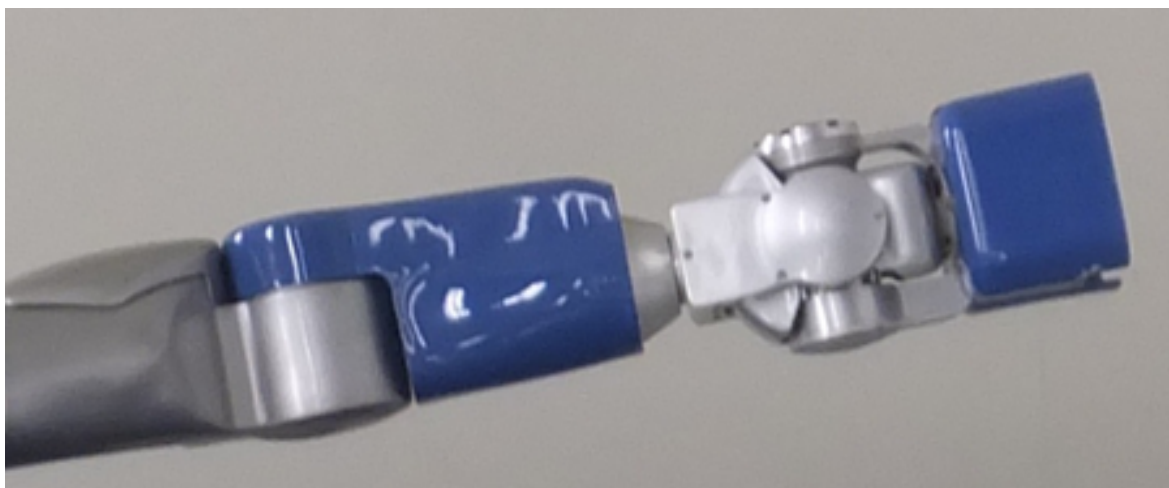


Figure 4.1: Humanoid arm used to induce the embodiment in the robot arm conditions.

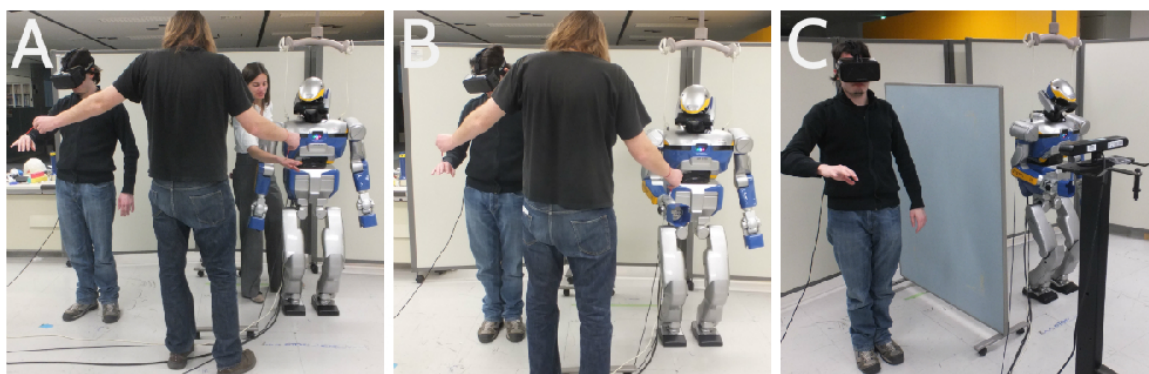


Figure 4.2: Experimental set-up for human arm visuo-tactile (A), robot visuo-tactile (B), and robot visuo-motor (C) conditions.

4.1.4 Procedure

After reading and signing the consent form, participants were placed next to a panel. The humanoid robot (HRP-2) was at the other side of the panel and was not visible to them. Participants then wore an Oculus Rift HMD which was used to display real-time video feedback from the camera located at the forefront of the robot's head, emulating the robot sight. Once the participants wore the HMD, they were able to control the robot's head movement and visualize what the robot was seeing in real-time. The participants were then told to place their arm (left, or right arm, depending on the condition) creating a 90° angle between the arm and the forearm, with the elbow next to the hip, and to leave their hand opened. This specific arm position was similar to the robot's arm posture so that users observed the robot arm coinciding with their own arm position. Also, they were told to look at the fake arm through the HMD. This position was valid for all experimental conditions. After this, the first trial started. For the robot visuo-tactile synchronous and asynchronous conditions, a researcher stroked the robot's arm either synchronously or asynchronously and the participant's arm with two small paintbrushes (see Figure 4.2.B). Pilot experiments showed that 90 seconds of brushing were enough to elicit a sense of embodiment of the fake limb in the participants. Thus, after 90 seconds of stroking, and without stopping the strokes, participants were verbally asked the three questions corresponding to the embodiment questionnaire (see section 4.1.5) by another researcher and responded the answers out loud.

For the robot visuo-motor synchronization condition, participants were told to look front and wave. A camera with tracking capability was placed in front of the participants to track their arm movement. Participants could not see the camera because they wore the HMD. Then, they were asked to place their real arm creating a 90° angle and looking at the robotic arm through the HMD. After that, participants were able to move their arm and the robot's arm responded with the same movement (see Figure 4.2.C). As in the previous conditions, after 90 seconds, participants answered the same questions verbally, while they were still moving the arm. For the human arm synchronous and asynchronous conditions, the robot's arm was removed from the vision of the participant and, instead, one of the researchers put her real arm on the place of the robot's arm while the other researcher stroked the researcher's arm and the participant's arm either synchronously or asynchronously (see Figure 4.2.A). Again, after 90 seconds of stroking, and without stopping the strokes, participants were asked the embodiment questionnaire. Participant's vision was blocked every time the set-up was modified and they only had vision again when the human arm was already in the place where they saw the robot arm before or vice versa. After completing all conditions, they started over with the opposite arm. At the end, participants completed an open-ended question to share their thoughts about the experiment. Finally, they were thanked and paid for their participation.

4.1.5 Measures

Embodiment questionnaire: A 3-item embodiment questionnaire (see section B.3) was designed to measure the embodiment of the robot and the human arm. The questionnaire was

adapted from the full-body embodiment questionnaire used in section 3.1.5 which was designed for verbal response in situ during the experiment. It contained three questions, one for each of the subcomponents of embodiment: body ownership, self-location, and agency [82] as seen in section 1.1.1. The questionnaire was designed so that the same questions were suitable to measure human arm embodiment and robot arm embodiment. Specifically, the questionnaire asked participants to rate on a 7-point scale ranging from (1) *Not at all* to (7) *Very Strongly* how strongly did they feel as if the arm they were seeing was part of their body (body ownership), the arm they were seeing was in the location of their real arm (self-location), and whether they could push an object with the arm they were seeing (agency). The scale obtained an average reliability of $\alpha = .947$, $KMO = .605$, and Bartlett's test of Sphericity = .002.

Demographic measures: At the end of the experiment participants completed their age, gender, and whether they were right or left-handed in a PC-based questionnaire.

Open-ended question: After completing the demographic measures, an open-ended question asked participants to share their thoughts about the experience by explaining in which condition the feeling that the arm was their own arm was stronger.

Manipulation check: At the end of each condition, participants were asked whether the touch and vision were happening at the same time or at different times or whether the robot arm responded to their movements. All participants passed the manipulation check for all conditions. The manipulation check was done after the embodiment questionnaire was answered by the participants.

4.1.6 Results

Descriptive statistics for overall embodiment as well as for each subcomponent are reported by experimental condition in the table shown in Figure 4.3. For each condition, we averaged the results of the left and the right arm, which were not significantly different (Since p value was $p > .05$ in all group comparisons). Paired-samples T-tests were conducted to test the hypotheses.

- H1: The feeling of embodiment of a human arm induced by visuo-tactile synchronization was significantly higher in the synchronous condition, compared to the asynchronous condition ($t(11) = 4.796$, $p = .001$).
- H2: The feeling of embodiment of a robot arm induced by visuo-tactile synchronization was significantly higher in the synchronous condition, compared to the asynchronous condition ($t(11) = 4.939$, $p < .001$).
- H3: The feeling of embodiment of a robot arm induced by visuo-tactile synchronization and feeling of embodiment of a human arm induced by visuo-tactile synchronization were not significantly different ($t(11) = -1.013$, $p = .333$). Levels of embodiment were equally high both for the human and for the robot arm as shown in the Figure 4.4.

- H4: The feeling of embodiment of a robot arm induced by visuo-motor synchronization was not significantly different to the feeling of embodiment of a robot arm induced by visuo-tactile synchronization ($t(11) = .157, p = .878$) or to the sense of embodiment obtained in the human arm synchronous visuo-tactile condition ($t(11) = .737, p = .476$). Levels of embodiment obtained in the visuo-motor synchronization condition were very similar to those obtained in the synchronous visuo-tactile human and robot conditions as shown in the Figure 4.4.

	Human Arm (visuo-tactile)		Robot Arm (visuo-tactile)		Robot Arm (visuo- movement)
	Sync.	Async.	Sync.	Async.	
Embodiment	5.11(1.06)	3.76(1.37)	5.33(1.04)	3.87(1.44)	5.29(1.02)
Ownership	5.5(.96)	3.78(1.38)	5.78(.91)	4.14(2.25)	5.36(1.18)
Self-location	5.75(.69)	4(1.15)	5.64(1.11)	4.5(1.44)	5.07(1.36)
Agency	5.43(1.13)	3.57(1.61)	6.14(.89)	4.5(1.25)	6.14(.94)

Figure 4.3: Mean (SD) for overall embodiment and its subcomponents

4.1.7 Discussion

In this study we showed that people can experience a “robotic-looking” humanoid arm as their own. Moreover, this illusion can be elicited either by visuo-tactile or by visuo-motor stimulation. Both types of stimulation elicited a similar level of embodiment which confirms the finding from [68] using a moving rubber hand or in [100] using a Geminoid arm.

Interestingly the results also show that the feelings of embodiment experienced toward the human arm and the humanoid arm are strong and similar in terms of strength. These results are also confirmed by the open-ended question filled by the subjects after the experiment: “the feeling when I saw the real arm and the feeling when I saw the robot’s arm was pretty the same because I felt of robot’s arm as of my own” or “the robot arm was very similar to my arm...the feeling was very much the same feeling than when I saw the real arm”. These results confirm the findings presented in [54] which suggest that the “human-like” aspect of the limb is not necessary to elicit a feeling of embodiment toward an artificial limb.

Compared to the studies where only a limb is involved, it is worth noting that in our case, we study the embodiment of the limb of a humanoid surrogate where the subject experience its first person view and is able to control the humanoid head with one’s own head. Being able to control the humanoid’s head, certainly put the subject in a favorable state to accept the humanoid arm as it’s own. In this regard, the design of the humanoid in terms of its anthropomorphism is crucial. Indeed as seen in [140] the matching in the proprioceptive

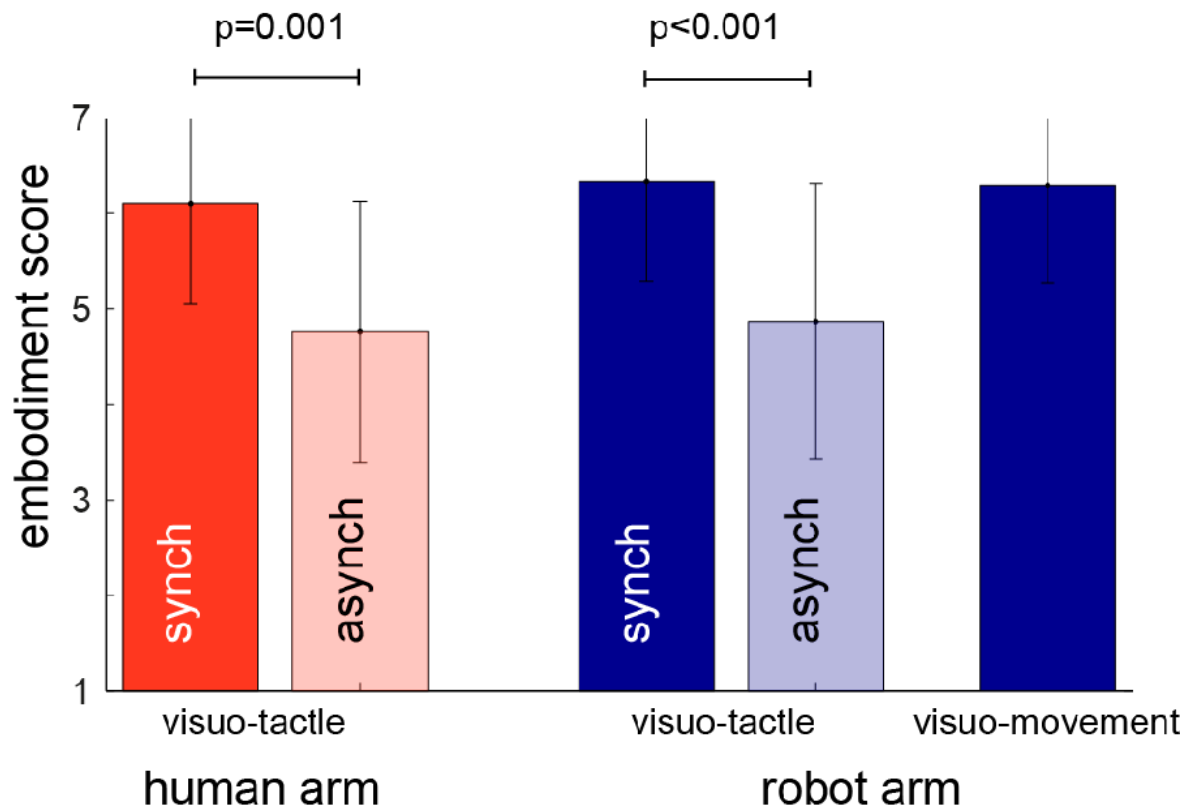


Figure 4.4: Embodiment score by condition

information of the subject's arm and the artificial arm is crucial. Therefore in the case of humanoid robot arm, a coherent visual proprioceptive information is necessary. Interestingly, the embodiment is strong despite the fact that the image displayed in the HMD is only a 2-D image, therefore preventing the subject to experience the visual depth of the scene while seeing the humanoid arm.

Finally our results confirm the findings from [12] [57] in the domain of prosthesis . Indeed, in [57] an effort is made on the functionality and control instead of the visual aspect in the design of the prosthesis in order to improve the feeling of embodiment.

In the experiments presented in Chapter 2 the subject is able to, grab a can from the table, and touch one's own shoulder via BCI control. In order to explore the sensations experienced by the subject toward the embodied robotic arm while interacting with the environment, another experimental set-up was devised.

4.2 Touch illusion with an embodied robotic arm

In the previous section we demonstrated that the subjects were able to experience the “robotic-looking” humanoid arm as their own with a visuo-motor stimulus. In the experiment de-

scribed in chapter 2, interactions with the environment and one's self are realized while the subjects are remotely seated on a chair. During the realization of the interactions, the subjects are able to see the humanoid hand grabbing a can or one's own arm through the robot's eyes. However, in our set-up no haptic interface is used to render the feeling of touch to the subjects. Which raises the question of how the feeling of embodiment is affected by the lack of physical haptic stimulation. This question is important since as we described in section 1.1.3.4, the feeling of embodiment is believed to be induced by multisensory integration [33] [35]. Therefore, the lack of tactile feedback could induce a visuo-tactile discrepancy which could disturb the multisensory integration and therefore could break the embodiment. However findings in the domain of haptic and tactile illusion [75], show that subjects are able to experience a haptic feedback without physical haptic stimulation [73] [15] [74].

In this section, we present an experiment devised to explore the feeling experienced by the subject while its surrogate interacts with the environment. In this experiment the subject controls the humanoid robot arm with one's hand motion. The subject is also provided with the first person perspective of the humanoid robot through a HMD. In addition, the subject's head motion is mapped onto the humanoid's head. In order to study the feeling experienced by the subject during an interaction, the subject is asked to control the humanoid arm to touch a curtain placed in front of the surrogate. The results show that the feeling of embodiment is maintained during the interaction even though no physical haptic stimulation is used on the subject. Interestingly, the subjects with a high response to the illusion reported a tickling feeling in their fingers when they touched the curtain through the surrogate.

4.2.1 Pseudo-haptic feedback

In [75], a review of different tactile and haptic illusions are presented. In this work, we are particularly interested in the illusions elicited without any physical haptic stimulation [15] [74], referred as pseudo-haptic feedback [73]. Pseudo-haptic feedback relies on visual feedback and brain plasticity to display haptic properties. However, most of the pseudo-haptic feedback illusions require a passive device like a computer mouse or a space ball to simulate a force feedback. For example, in [25] a mass is simulated with a spaceball.

Interestingly, some illusions rely only on visual feedback without any passive devices [15] [118] [119]. As an example, in [118], a force field illusion is elicited by using an augmented reality set-up. The illusion is then induced by displaying a modified position of the subject's hand in a HMD. In [15], this kind of illusion is also referred as cross-modal illusion. In [15], it is suggested that the cross-modal illusions are the result of a form of synesthesia [52]. Synesthesia is a neurological phenomenon in which stimulation of one sensory or cognitive pathway leads to an automatic, involuntary experience in a second sensory or cognitive pathway. In the illusion described in [15], the subjects of the experiment manipulated the visual analog of a physical force, a virtual spring, and reported haptic sensations.

In this study, we are interested in pseudo-haptic feedback without device in an embodiment scenario. For this purpose, we devised an experiment where the subjects are provided with the first person perspective of the humanoid robot. They are able to control the humanoid arm through gesture control. In addition their head's motion is mapped onto the robot's

head.

In regard to the experiments presented in Chapter 2, we examine if the embodiment of the subject is maintained while interacting through the surrogate without any feedback devices and despite the visuo-tactile discrepancy. We devised two conditions, one in which the subject controls the humanoid arm, and another one where the subject does not control the humanoid arm. We expected that the robot arm control condition would generate a sense of embodiment significantly higher than the non-control condition (H1).

Regarding the results in pseudo-haptic feedback [73], we were also interested to examine whether the subjects experienced this kind of feedback in an embodiment scenario. In this regard, we expected that the humanoid arm control condition would generate a pseudo-haptic feedback significantly higher than the non-control condition when the subjects touched the curtain through the surrogate (H2).

4.2.2 Participants

Fourteen volunteers of different nationalities (9 females and 5 males), aged 21 to 37 ($M = 28.14$, $SD = 4.99$) took part in the study. All participants were right handed. Participants were recruited through a call for volunteers in the website of the experiment and received 1500 Japanese Yens to participate. Participants were naïve to the purpose of the experiment. Working in the Robotics or Neuroscience fields was used as an exclusion criteria. In addition, the experiment was pretested with five intern master students of the *Joint Robotics Laboratory (JRL)* in which the study was carried out. All participants gave their written informed consent prior to participating. The study was carried out with the ethical approval of the *National Institute of Advanced Industrial Science and Technology (AIST) in Tsukuba, Japan*.

4.2.3 Procedure

We carried out a within-subject experimental design with two different experimental conditions (control and non-control of the robotic arm) which were repeated once for each arm. Thus, in total, the participants experienced four trials (control and non control for left and right arm). Participants carried out the experiment individually. After reading and signing the consent form, they were instructed to stand in front of an Xtion camera mounted on a tripod. They were located at a distance of four meters from an HRP-2 (humanoid robot) (see Figure 4.5). In order to create the feeling of embodiment, participants wore an Oculus Rift HMD which displayed real-time video feedback from the camera located at the forefront of the robot's head. Participants' head movement was also tracked and synchronized to the robot's head movement. In the control condition, in which the participant controlled the humanoid arm movements, the camera was facing the participant so that the participants' arm movement could be tracked and synchronized with the robot's arm movement (Figure 4.5.A). On the contrary, in the non-control condition, the camera facing the participant was flipped and faced one of the researchers, who performed the control instead (Figure 4.5.B). Since participants wore the HMD during the trials, they were unable to see this change or that the

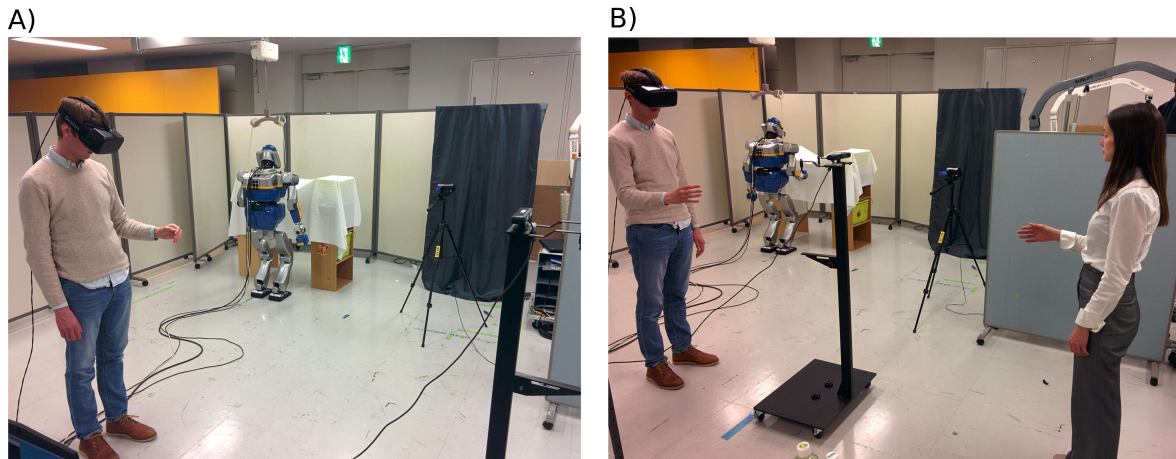


Figure 4.5: A) Set-up for the control condition. In this case the camera tracks the subject's hand motion. B) Set-up for the non-control condition. In this case the camera tracks the experimenter's hand motion.

researcher was performing the control of the arm, as their vision coincided with the robot's vision, and both the participant and the researcher were out of its field of view. In both conditions, participants were instructed to place their arm (either left or right arm, depending on the condition) creating a 90° angle between the arm and the forearm, with the elbow next to the hip, and the hand opened. Then, participants were instructed to look front (Figure 4.6.A) and wave the arm so the Xtion camera could track their movement (they were instructed to do the same in the non-control condition, even if the camera was actually flipped toward one of the researchers). After that, they were asked to look down, to the robot's arm. They were able to see the robot's arm and a big white curtain in front of them (Figure 4.6.B). In the control condition, participants were instructed to move the robot's arm for few seconds and then to touch a white curtain placed in front of the robot performing up and down and left and right movements during 2 minutes (Figure 4.6.C). They were told not to perform sudden movements or drop the real arm during the task. In the non-control condition, participants also placed the arm in the same position and were told that this time they had to look at the arm as well. They were free to move the real arm or keep it still during the 2 minutes and were not specifically instructed on what to do with the arm. After finishing each trial, the HMD was removed. Participants completed a PC-based questionnaire on sense of embodiment and haptic feedback (see section 4.2.4). After that, they carried out the next condition following the same procedure until completing the four conditions. Half of the participants started with the left hand and the other half started with the right hand and experienced both conditions before switching to the other arm. We randomized the order for starting with one or the other arm and for firstly experiencing control or non-control first, for each arm. At the end, they answered demographic questions and were also given the possibility to add any comments they might have and were paid for their participation.

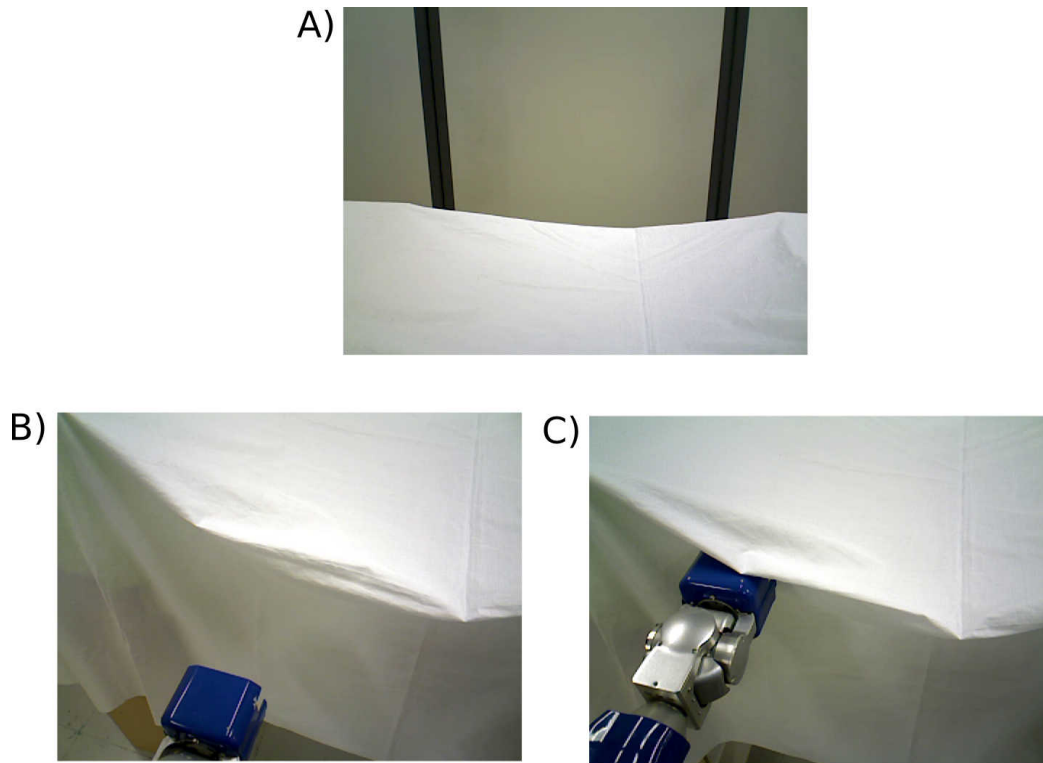


Figure 4.6: Subject's field of view during the experiment. A) Initial view of the subject looking in front of him. B) The subject's view looking down. C) Robot touching the curtain.

4.2.4 Measures

Embodiment questionnaire. We adapted the embodiment questionnaire from [82] to measure the sense of embodiment of the robot's arm. The questionnaire (see section B.4) consisted of twelve items which were rated on a 7-point scale that ranged from (1) *not at all* to (7) *very strongly*. The scale consisted of four sub-dimensions: sense of body ownership (five items), sense of self-location (two items), sense of agency (three items), and sense of touch (two items). Reliability was $\alpha = .83$ for the control condition and $\alpha = .89$ for the non-control condition.

Haptic feedback. Participants rated whether they felt real tickling on the fingers that were virtually touching the curtain on a 7-point scale which ranged from (1) *not at all* to (7) *very strongly*.

Demographic measures. Participants completed information about age, gender, and about being left or right handed.

Manipulation check. Participants were asked in each condition whether they controlled the robot's arm or not. All participants passed the manipulation check question for all conditions.

n=14	Control M(SD)	No-Control M(SD)
Embodiment	5.14(.85)	2.47(1.04)
Ownership	4.81(.99)	2.54(1.37)
Self-location	4.82(1.54)	3.26(1.63)
Agency	6.19(.82)	1.82(.88)
Touch	4.7(1.67)	2.46(1.39)
Haptics	2.82(1.85)	1.68(1.01)

Table 4.1: Mean (SD) for embodiment, its subcomponents, and tickling, for control and non-control conditions.

4.2.5 Results

No significant differences were found for left and right arms in the control ($t(13) = .027$, $p < .979$) or non-control conditions ($t(13) = .653$, $p < .525$). Thus, we were able to average both trials in each experimental condition.

Participants reported significantly higher feeling of embodiment of the robot arm in the control condition than in the non-control condition ($t(13) = 11.277$, $p < .001$), which confirmed H1. Additional analyses with paired-samples T-test were run to study each sub-component independently and all of them were significantly higher in the control condition. Specifically, sense of ownership ($t(13) = 6.783$, $p < .001$), sense of self-location ($t(13) = 5.099$, $p < .001$), sense of agency ($t(13) = 12.775$, $p < .001$), and sense of touch ($t(13) = 6.340$, $p < .001$), were all significantly higher in the control condition than in the non-control condition. Table 4.1 shows mean and SD obtained in each condition for embodiment and for its three subcomponents separately.

To test H2, we again ran a paired-samples T-test. Participants reported significantly higher haptic feedback (expressed as tickling sensation) on their real hand in the control condition than in the non-control condition ($t(13) = 3.200$, $p = .007$). Table 4.1 also shows mean and SD by condition obtained for this variable.

4.2.6 Discussion

In this experiment the subjects experienced a strong feeling of embodiment while controlling the humanoid arm to interact with the environment. Moreover, the feeling of embodiment is strong despite the lack of physical haptic stimulation (visuo-tactile discrepancy). Interestingly, a feeling of tickling is experienced by the subjects when the humanoid hand touches the curtain even though no haptic feedback devices are used. This result confirms previous findings in cross-modal illusion [15] [14], in which a visual stimulus, elicits an illusion of

physical resistance.

From an engineering point of view this result is interesting for the design of prosthesis or teleoperated robots. Indeed, with the high cost and complexity of haptic display, pseudo haptic feedback offers a solution to provide haptic feedback without a dedicated device.

This experiment shows that the level of embodiment of the subject is maintained when the surrogate interacts with the environment despite the lack of real haptic feedback. This could correspond to the grasping of the can described in Chapter 2. The question remains as to how the feeling of embodiment is affected when the subject interacts with one's self via a robotic surrogate. In the next section an experiment is presented to answer this question.

4.3 Self-interaction

In this section, we present an experiment where the subjects are able to interact first with the environment and then with themselves. This set-up takes advantage of the teleoperated surrogate and could not be realized with a mannequin or a fake limb which are usually used in the embodiment experiments. This experiment aims at studying the embodiment feeling of a subject toward the surrogate while interacting with one's self.

In [112], an experimental set-up, previously described in section 1.1.4.2, allowed a subject to embody another person's body. During one experiment, the feeling of embodiment of the subject was studied while shaking/squeezing one's own hand via one's surrogate (In this case the surrogate was another person with a head mounted camera). Despite the fact that the surrogate was not actually controlled by the subject, the experiment gave promising results. The results showed that the subject stayed embodied in the surrogate despite the fact that the subject could see and touch one's self through the surrogate. Interestingly, the haptic sensation felt during the shaking/squeezing seemed to come from the surrogate's hand and not from the subject own visible hand. By using a humanoid robot surrogate in our experimental set-up, the subject is able to control the surrogate movement and so to directly interact with one's self. Therefore, our set-up allows us to further explore the sensations experienced by the subject compared to the set-up presented in [112].

4.3.1 Participants

Our study included 14 volunteer subjects of different nationalities (5 females and 9 males), aged 20 to 45 ($M = 28.71$, $SD = 8.16$) who were either university students or researchers. The subjects were naïve to the purpose of the study. Subjects read and signed an informed consent form and received 1500 Japanese Yens to participate. Working in the Robotics or Neuroscience fields was used as an exclusion criteria. In addition, the experiment was pretested with 5 volunteers of the *Joint Robotics Laboratory (JRL)* in which the study was carried out. The study was conducted with ethical approval of the *National Institute of Advanced Industrial Science and Technology (AIST)* in Tsukuba, Japan.

4.3.2 Procedure

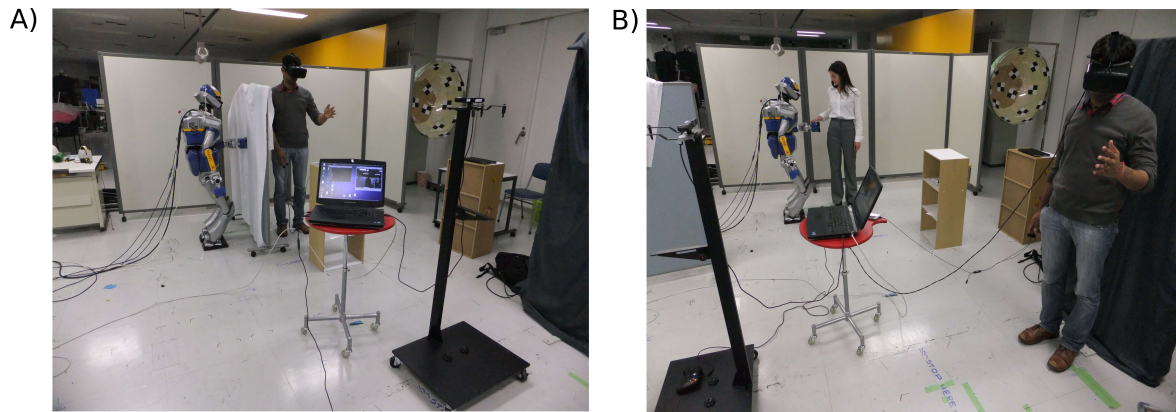


Figure 4.7: A) Set-up of the self condition, B) Set-up of the other condition

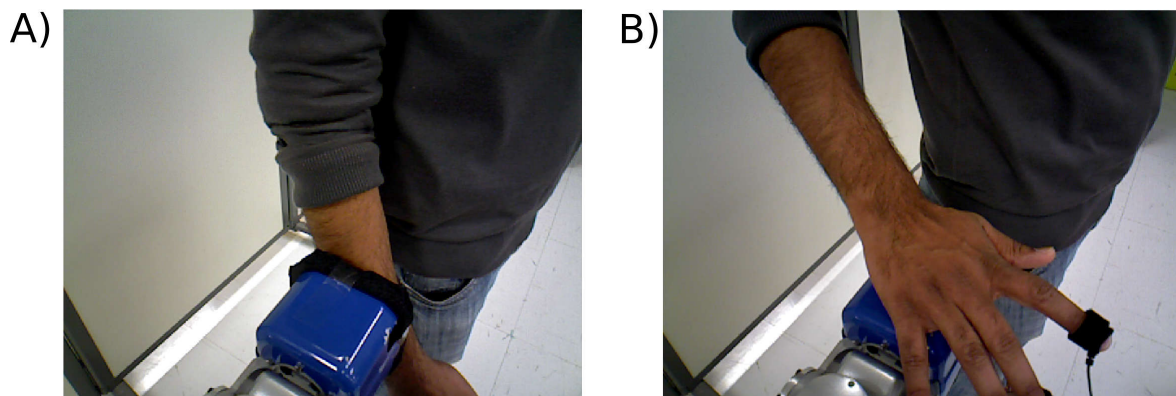


Figure 4.8: A) Robot's view in the touch person task, B) Robot's view in the touch surrogate task

A within-subject experiment is designed with two conditions. In the condition named *self*, the subject controls the surrogate and interacts with one's self. In the condition named *other*, the subject controls the surrogate but interacts with another person. Each condition has 3 main experimental sub-tasks (without considering the training and transitions): (1) A task "touch curtain" where the subject controls the robot arm to touch a curtain placed in front of the robot (Same as section 4.2). (2) A task "touch person" where the surrogate touches the subject (or another person depending on the condition) and (3) a task "touch surrogate" where the subject (or another person depending on the condition) touches the surrogate. Compared to the experiment described in section 4.2.5, the subject controls the robot's arm with her/his left arm only since no significant difference was found in terms of embodiment between the left and right arm in the previous experiment (see section 4.2.5). So in total the subjects experienced a total of 2 trials.

After reading and signing the consent form, the subjects were asked to stand in front of a Xtion camera mounted on a tripod as seen in Figure 4.7 (used to track their hand motion).

A SCR measure device was then placed on the subjects' index as seen in Figure 4.7.B. The first person perspective of the humanoid was provided to the subjects through a HMD which displayed in real-time the video stream from the robot head mounted camera. The subjects' head motion was mapped onto the robot's head so that the subjects could control the robot's head with their own head. In both conditions, the subjects left hand motion was tracked by the Xtion and mapped onto the robot's left hand. In the *self* condition, the subjects were placed behind a panel covered with a curtain with the robot placed in front of it as seen in Figure 4.7.A. In the *other* condition, the subjects were placed away from the robot and another person was placed near the robot instead as seen in Figure 4.7.B.

In the *other* condition, the subjects were out of the robot's field of view. In both conditions, the subjects were asked to place their left arm creating a 90° angle between the arm and the forearm, with the elbow next to the hip and the hand opened as to match the humanoid initial pose. Before starting the experiment, the subjects were asked to relax for 1 *min* in order to establish a baseline for the SCR.

Then, to initialize the hand tracking, the subjects were asked to look front and wave their left arm. Once the tracking initialized, the subjects were asked to place their arm in the 90° position, look down, and to move their arm to touch the curtain. In this "touch curtain" task as in section 4.2, the subjects were asked to move the robot's arm in order to interact with the curtain. The "touch curtain" task lasted 2 *min*.

After that, the panel was removed and the "touch person" task started. The subject could then see one's arm in the *self* condition or the other person's arm in the *other* condition. In both conditions, the subjects were asked to interact with the seen arm. In Figure 4.8.A, the subject is interacting with one's own arm. The "touch person" task lasted 2 *min*.

Finally, in the *self* condition, the subjects were asked to touch the robot arm with their right arm (Since the left arm still controlled the robot's arm) as seen in Figure 4.8.B. Whereas in the *other* condition the other person was asked to touch the robot arm. The "touch surrogate" task lasted 2 *min* as well. After finishing each trial, the HMD was removed. Participants completed a pc-based questionnaire on sense of embodiment and haptic feedback. After that, they carried out the other condition. At the end, they answered demographic questions and were also given the possibility to add any comments they might have and were paid for their participation.

4.3.3 Results

No significant differences were found between "touch curtain" and "touch person" either in the *self* ($t(12) = -1.059$, $p = .310$) or in the *other* ($t(12) = 1.458$, $p = .170$) condition for embodiment. Likewise, no significant differences were found between "touch curtain" and "touch person" either in the *self* ($t(12) = -.693$, $p = .502$) or in the *other* ($t(12) = -.331$, $p = .746$) condition for haptics.

Significant differences were found between active touch (touching a human arm "touch person") and passive touch (being touched by a human hand "touch surrogate") in the *self* as well as in the *other* condition for embodiment. Touching the human arm generated significantly stronger feeling of embodiment than being touched in the robot arm both in the

n=14	Touch curtain	Touch someone	Touch oneself	Being touched by someone	Being touched by oneself
	M(SD)	M(SD)	M(SD)	M(SD)	M(SD)
Embodiment	4.81(1.03)	5.12(1.02)	5.14(1.10)	4.54(1.30)	4.46(1.55)
Haptics	1.73(.94)	2.14(1.79)	2.14(1.61)	2.57(2.06)	2(1.62)

Table 4.2: Mean (SD) for embodiment, and haptic for each task in both conditions

self ($t(13) = 2.981, p = .011$) and in the *other* conditions ($t(13) = 2.276, p = .040$). For haptic feedback, though, no significant differences were found between active and passive touch in the *self* condition ($t(13) = .458, p = .655$) or in the *other* condition ($t(13) = .822, p = .426$).

Embodiment did not significantly decrease when participants touched themselves compared to when they touched someone else ($t(13) = .091, p = .928$). Also, embodiment did not significantly decrease when participants touched the robot arm using their real hand compared to when someone else touched the embodied robot hand ($t(13) = -.163, p = .873$). For haptics feedback, no significant differences were found between the *self* and the *other* conditions during active ($t(13) = .000, p = .1000$) or passive ($t(13) = 1.000, p = .336$) touch. Table 4.2 shows mean and SD obtained in each condition and tasks for embodiment and haptics .

4.3.4 Discussion

With this set-up, subjects were able to interact with the environment, then interact with themselves or another person with an embodied humanoid robot. This experimental set-up allowed to assess the embodiment of the subject toward the humanoid during those different interactions with a questionnaire (see section B.5).

Self-touch experiment have been presented in [19] where blindfolded subjects were able to touch their own back with a robotic system. The results showed that in the case of synchronous stimulation (No delay between the subject's arm motion and the robotic system), the subject's self location was drifted forward the subject's real body. This effect was reported to be higher in the case of synchronous stimulation with haptic feedback. In our experiment, the stimulation is also synchronous but the subject is provided with first person perspective from the robot which differs from the set-up presented in [19]. Interestingly, with the first person perspective, our results show that the subjects stay embodied in the humanoid robot during self interaction and that their self location stays in their body's location, which is different from the results found in [19] with blindfolded subjects.

Our set-up also allowed to compare the level of embodiment in the subjects when they interact with themselves or other. Results in [112] presented in section 1.1.4.2 show that subjects can experience ownership of another person's body while shaking hands with themselves through an uncontrollable human surrogate. Our robotic set-up allowed to go beyond

the set up presented in [112], since in our case, the subjects could control the surrogate (in our case a humanoid robot) arm motion without haptic feedback. Our results showed no significant difference in terms of embodiment between touching the curtain or touching one's own arm which confirmed the finding showed in [112]. Interestingly, the level of embodiment did not significantly decrease when the subjects touched themselves compared to when they touched someone else. The fact that the feeling of embodiment of the subjects toward the humanoid robot stayed strong despite the subjects touching and seeing themselves, showed how resilient the feeling of embodiment is toward the humanoid. Interestingly, haptic feedback was felt by the subjects during "touch person" and "touch surrogate" in both conditions.

4.4 Summary

In this chapter, we have presented three different studies in which we have evaluated the feeling of embodiment of subjects toward a controlled humanoid robotic arm without haptic feedback.

First we demonstrated that people are able to experience a strong feeling of embodiment toward a "robotic-looking" arm with visuo-motor stimuli. Similar results have been found recently in [123] using a myoelectric-controlled robotic hand. In our study, using visuo-tactile stimuli, we also demonstrated that the embodiment felt toward the robotic arm is equally high as the embodiment felt for a "human-looking" arm. In regard to previous studies [140] [54] which strongly suggest that noncorporeal object prevent the embodiment, our finding suggests that the robotic arm is perceived as a corporeal object. The question remains as to what defines a corporeal object for the subject. This result is important in robotics where the majority of humanoid robot's are not highly human-resembling compared to the Geminoid [98]. It is also important in the domain of prosthesis where affordable 3D-printed prosthetic hand are developed and are not as highly human-resembling as other high-end model.

We also demonstrated that, in addition to a strong feeling of ownership toward the robot arm, subjects experienced a pseudo-haptic feedback (without device) while interacting with the environment through the humanoid robot. This result supports findings in virtual reality [15] [14] where subjects experienced physical resistance only with visual cues. In our study, subjects reported a feeling of tickling in their fingertips when the gesture-controlled humanoid robot arm touched a curtain placed in front of it. This result is important and might offer an alternative to teleoperated robots or prosthesis with limited haptic display.

Finally, we showed that the embodiment toward the humanoid robot is resilient enough to allow the subject to interact with one's self or another person. We also demonstrated that the embodiment toward the humanoid robot did not decrease in a successive sequence of interactions corresponding to the same kind of interaction performed in the main experiment presented in Chapter.2.

Conclusion

In this thesis, we have investigated the embodiment toward a humanoid robot using an innovative scenario as a guideline. This work has allowed to solve several issues relative to the context of embodiment in self-interaction tasks, such as:

- We have developed a framework, which allows a user to remotely control a humanoid robot with a BCI, to safely navigate and to interact with the environment, and with one's self.
- We have demonstrated that, the “robotic-looking” aspect of the surrogate, the partial control and delays, do not have negative effects on the feeling of embodiment toward a walking humanoid robot.
- We have shown that, the feeling of embodiment is high and maintained when one interacts with the environment or one's self through a humanoid robot.
- We have exposed that, pseudo-haptic feedback feelings are experienced by users controlling a humanoid robot arm to realize an interaction task with the environment or themselves.

Particularly, in the context of assistive robotics and embodiment, we have developed a prototype which allows a subject to control a humanoid robot with a BCI to realize two innovative scenarios. In the first scenario, the subject controls the humanoid robot to grab a can, bring it to one's self, and take a sip. In a second scenario, the subject steers the humanoid toward one's self, and manipulates one's own arm. The realization of those scenarios brought several important issues that were investigated in this thesis.

In order to give the ability to the subject to interact with the environment and with one's self, with a BCI, several computer vision methods have been implemented and work in association with a control and interaction scheme to assist the subject in the realization of one's task. In the literature, the embodiment toward a surrogate have been extensively studied with corporeal features. Therefore, we first demonstrated that the “robotic-looking” aspect of the surrogate did not prevent the establishment of the embodiment. Thanks to specific scenarios we decomposed the investigation of the embodiment in two parts. In one part, we explored the embodiment of the subject during a walking task. And in another part, we explored the embodiment during the interaction task. Due to the necessity of an assistive navigation

scheme (to control the humanoid safely and accurately) and the delays inherent to teleoperation systems, we investigated their influences over the embodiment. We showed through an experiment where subjects were asked to realize a specific path with the humanoid, that the embodiment was maintained throughout the entire task.

We also explored the feeling of embodiment experienced by the subjects during an interaction task. In this study, the subjects gesture controlled without haptic feedback a humanoid robot arm to touch a curtain placed in front of it. This study showed that the subjects experienced a tickling feeling in their hand when they saw the robot's hand through a first person perspective touched the curtain in synchrony with their own hand motion.

Finally a separate study was conducted to explore the embodiment during self-interaction through a humanoid robot. The results showed that the fact that the subject sees one's self through the humanoid does not destroy the feeling of embodiment, even when one interacts with one's self. In terms of embodiment, no significant difference was found when one interacted with one's self or another person. Interestingly, a haptic feeling is still present when one interacts with one's self through the humanoid robot. However touching one's self with the robot arm generated significantly more embodiment than being touched on the robot arm. The combination of these different results are promising for the realisation of the proposed self-interaction scenarios.

Perspectives

In this work several improvements could be made concerning the following issues.

Technical improvements in the framework

In our experiment, the assistive navigation system circles around the target to place itself in a safe and appropriate location to start an interaction. A better analysis of the scene provided by the SLAM feature could allow a better obstacle avoidance feature. Moreover, the actual control scheme of the assistive navigation proposes to the user only one path. The use of a better shared navigation would offer the subject more freedom while being assisted. Lastly, improvements in the object recognition in the scene would offer the subject more possibilities of interaction.

Measure related to the feeling of embodiment

The different embodiment studies realized in this thesis relied on questionnaires to measure the embodiment feelings of the subjects. Physiological measurements such as SCR, EMG, or fMRI would offer more concrete data about the different findings made in this thesis. For instance, in regard to the findings made about the pseudo-haptic feelings, fMRI measures focused on the somatosensory cortex activity could offer an additional physiological cue of our findings. A more practical way to physically measure the tickling sensation experienced by the subjects could be to use a EMG/NCS measurement on the subjects hand. EMG/NCS (Nerve Conduction Studies) tests are used in the medical field to assess patient experiencing, pain, change of sensation (tickling/numbness), or change in muscle strength.

Embodiment of non-corporeal surrogate

Several studies strongly suggest that non-corporeal surrogate or limb prevent the establishment of the embodiment. However the feeling of embodiment showed by the subject toward the humanoid robot is comparable in terms of strength to the RHI (which was a corporeal object). Which raises the question of what defines a non-corporeal object in terms of embodiment. The result of the embodiment obtained toward the humanoid robot showed that the physical aspect is not the main feature. Would the fact that the humanoid robot is, from the participant view, capable of realizing the same task of a human, be necessary and sufficient for the establishment of the embodiment? Further studies are necessary to explore if the functional capability of the surrogate is the main feature which determines if a surrogate is suitable to be embodied.

Extra capabilities

The embodiment seems resistant to control delays in the case of humanoid surrogate. This differs from a result found with the RHI, which uses a “human-looking” limb. This raises the question of what are the other differences between the embodiment of “robotic-looking” humanoid robot and “human-looking” android/mannequin. For example, are the extra capabilities of the robot such as “insensibility to pain” or “superior strength” affect the subject. A SCR to threat while embodying the humanoid robot arm compared to a SCR to threat while embodying a rubber arm could be a start to investigate this issue.

Embodiment apparatus

The feeling of embodiment toward a surrogate is known to be created with two important factors, the first person perspective [30] and multisensory correlation [20] [81]. In order to obtain these two requirements the subject and surrogate need different features to obtain the necessary perception and control abilities. In the following subsections we will describe the different features and devices used to obtain the first person view and sensory congruency. In the first section we describe the surrogate and its different features, the equipment worn by the subject is described in the second section.

A.1 Humanoid robot surrogate

A.1.1 Robotic platform

The experiments described in this work are conducted on the humanoid robot platform called HRP-2 in the Joint Robotics Laboratory (JRL). HRP-2 is a Japanese humanoid robot shown in Figure A.1. HRP-2 has a height of 154 *cm*, a weight of 58 *kg* and a total of thirty two degrees of freedom. It has two legs of six degrees of freedom, two arms with seven degrees of freedom each, and two hands with one degree of freedom with a gripper located at the end. The torso and the head have each two degrees of freedom. The robot has four 6-axis force sensors located at the wrists and ankles. HRP-2 is also equipped with an inertial measurement unit (IMU) located in the torso, measuring the linear acceleration as well as the angular velocity. As for the vision system, HRP-2 is equipped with two pairs of stereo cameras, one located in the head and another one located on the sides of the head. The stereo cameras are not used in this work. HRP-2 is also equipped with an RGB-D camera Xtion mounted on the head of the robot. In this work we use the Xtion camera. Two computers are located in the robot torso, one is used for the control processing and the other one is used for vision processing. The communication with the computers is done using Ethernet or Wi-Fi.

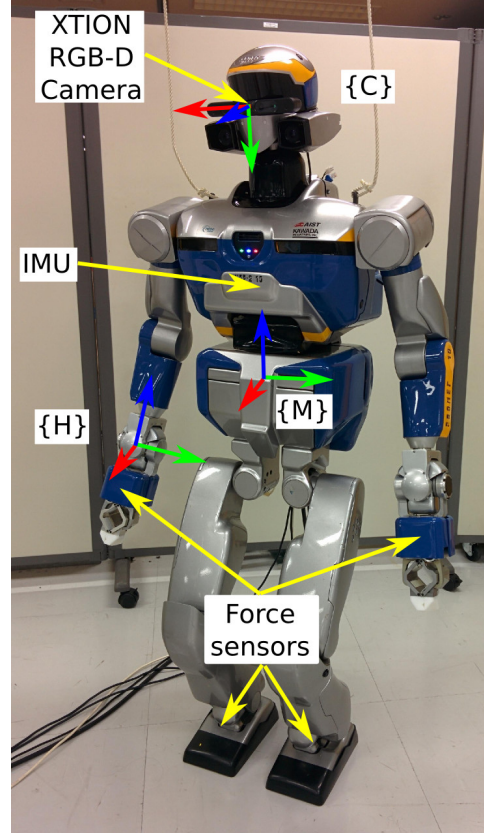


Figure A.1: The humanoid robot surrogate HRP-2 used in this work.

A.1.2 Sensory devices

A.1.2.1 Vision and Audition

The humanoid robot surrogate is equipped with a RGB-D camera Asus Xtion Pro Live [8] shown in Figure A.2. The camera is placed at a specific position on the surrogate's head to emulate the human eyesight. The camera acquires a color image through the RGB sensor at 30 FPS (Frames Per Second) with a resolution of $640 * 480$ (Height * Width). The depth image is obtained through the IR projector and the IR sensor which also acquires at 30 *FPS* with a resolution of $640 * 480$ (Height * Width). The combination of the IR sensor and IR projector is also called the depth sensor. The hardware of the camera is compatible with the tracking framework OpenNI [137] NITE [116] which allows gesture and whole body (or hands) motion tracking without markers. The camera is also equipped with a pair of stereo microphones located at the left and right edges of the camera. The camera is then able to give the sense of sight and hearing to the humanoid surrogate.

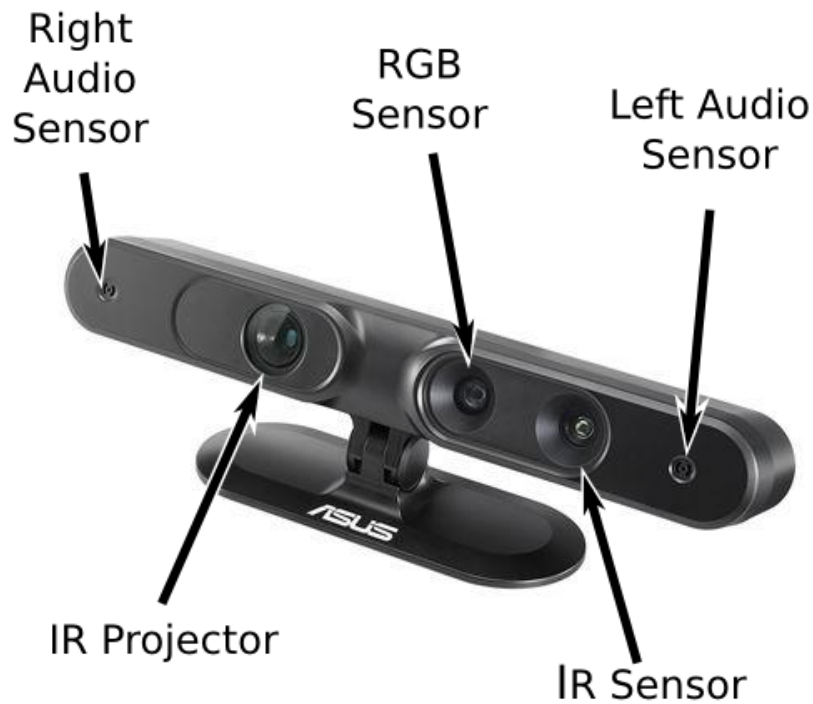


Figure A.2: The RGB-D camera Asus Xtion Pro Live used as 'eyes' of the humanoid surrogate.

A.1.2.2 Position sensor

The position and orientation of the robot's limbs are computed using the forward geometric model and the joint variables. The values of the robot's joints are given by angular sensors.

A.1.3 Control

ROS

In this work, the software development is based on the open source project Robot Operating System (ROS) [120]. ROS promotes the integration of software components into different robotic platforms. Several components such as image acquisition or vision tracking are made available by the community and are ready to be used. ROS facilitates the development and communication of the different software components. Another asset of ROS is the support of different devices such as joystick or camera.

Stack of Tasks

The Stack of Task (SoT) [85] is used in association with ROS to control the humanoid robot. The Stack of Tasks (SoT) uses the generalized inverted kinematics to solve a set

of hierarchical tasks. In the SoT, the robot tasks are defined as state error vectors in the sensory space, and projected in the robot joint space with the robot kinematic Jacobian. After resolution, the SoT gives the desired joint values for the set of the given tasks. The SoT is used with humanoid robots because they are highly redundant. Indeed the SoT is able to take advantage of the redundancy of the robot in order to realize several tasks at the same time. This control architecture allows the realization of a wide range of tasks.

Walking pattern generator

In this work we use the walking pattern generator (WPG) developed in [58] to control the walk of the humanoid robot. In this WPG, the humanoid robot is modeled as a linear inverse pendulum. This model is close to the mass distribution of the humanoid robot. This control uses the Linear Model Predictive Control scheme to calculate the robot footsteps. The footsteps are computed in order to minimize the difference between the previewed robot Center of Mass (CoM) velocity and the desired one. The footsteps are then sent to the Stack of Task controller in order to compute the corresponding joint values, and realize the walking motion. The input of this WPG, is the desired CoM velocity. This only input is useful to control the robot with a joystick or a brain computer-interface (BCI).

A.2 Subject equipment

The perception of the feedback from the different sensors placed on the robot is transferred to the subject through a set of equipment which is described in the following subsections.

A.2.1 Vision and Audition

The subject is able to see what the robot sees by wearing a Head Mounted Display (HMD) Oculus Rift Development Kit 2 [102] seen in Figure A.3. The Oculus Rift is a lightweight (440 g) HMD with a resolution of $1920 * 1080$ split between each eye. The HMD is provided with a magnetometer, a gyroscope and an accelerometer which corrects the gyroscope drift to track the subject's head orientation. The humanoid streams a 2D video to the HMD, therefore the subjects experience the environment in 2D with no depth perception.

In order to hear what the robot hears the subject wears a stereo head set which streams the sound recorded by the robot embedded stereo microphones.

A.2.2 Control

In the different experiments presented in this work the humanoid robot is controlled by three different user inputs which are described in this section.



Figure A.3: The HMD Oculus Rift used to see through the robot's 'eyes'.

A.2.2.1 Joystick

The joystick controller used in this study is the Xbox 360 wired controller which is supported by ROS. The joystick is used by the subject during the different experiments to perform three functionalities related to the robot walk as seen in the Figure A.4. First by pressing the Xbox Guide button the subject can start or stop the robot's walking motion. The directional pad allows the subject to control the directions of the robot walk. The up direction allows the robot to go forward. The left and right directions allow the robot to turn left and right. The down direction is not used during the different experiments. Finally the right stick is used to control the robot's head orientation.

A.2.2.2 Brain Computer-Interface

In this study the BCI is used to control the robot walk and interact with the environment (or one's self) using the robot's hands while the subject stays seated and still.

In this study the BCI relies on the SSVEP EEG signal which is triggered with a visual stimulus. In order to use the BCI the subjects are required to wear an electrode cap as shown in Figure A.5.A. 8 electrodes cover the visual cortex of the subjects. The electrodes are placed on the POz, PO3, PO4, PO7, PO8, O1, O2 and Oz positions of the international 10-20 system [132] as shown in Figure A.5.B, Fpz is used as the ground electrode and the left earlobe as a reference. The 8 Ag/AgCl electrodes placed on the visual cortex are active in order to reduce the noise and improve the signal to noise ratio. The g.USBamp (24 Bit biosignal amplification unit, g.tec Medical Engineering GmbH, Austria) is used to acquire the EEG data from the subject brain. The sampling frequency is 256 Hz, the signal is bandpass filtered between 0.5 Hz and 30 Hz with a notch filter at 50 Hz to remove the power



Figure A.4: The Xbox 360 controller used to control the robot walk.

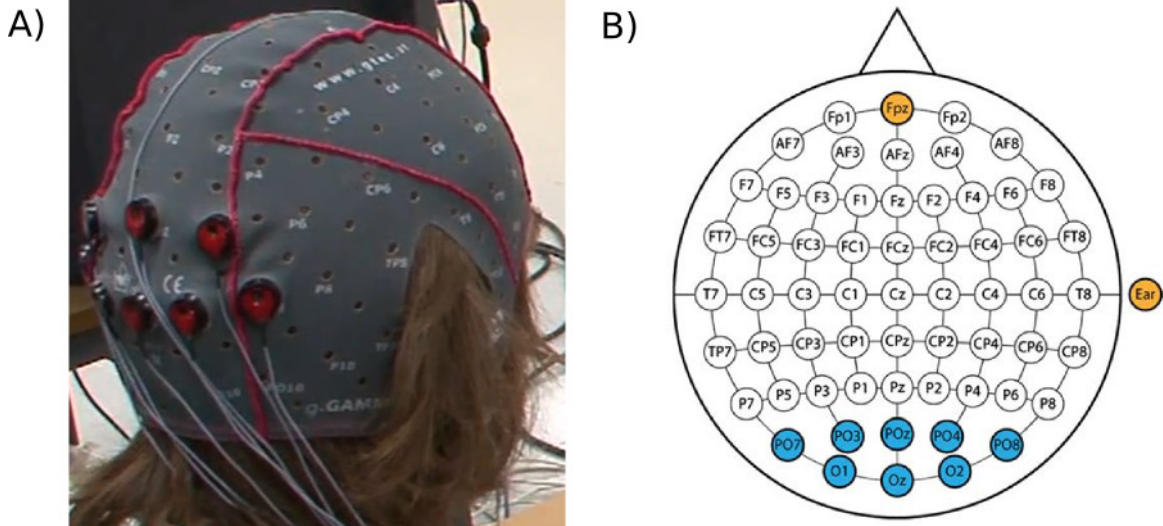


Figure A.5: Electrodes position to record the SSVEP signals.

line noise. The frequencies of the visual stimuli are 6, 8, 9, 10 and 14 Hz . The stimuli are carefully selected to avoid common first or second harmonics, while staying below 20 Hz . This is done to avoid the risk of eliciting an epileptic crisis in healthy subjects as advised in [38]. The visual stimuli are shown to the subject through the HMD.

A.2.2.3 Motion tracker

In this work the subject is able to control the surrogate's hand through gesture control of one's hand. In order to track the subject's hand, we rely on the OpenNI NITE [116] tracking framework. The OpenNI NITE tracking framework is compatible with the Asus Xtion Pro

Live camera. The framework allows either whole body tracking or hand tracking. However the whole body tracking feature does not work with a seated subject, therefore in this study we only use the hand tracking feature. In the experiments where gesture control is required the subject's hand motion is tracked through a Asus Xtion Pro Live camera fixed on a tripod with the subject in front of it. The framework is able to detect hand waving and hand tapping gestures. Those two gestures are used to initialise the hand tracking.

Questionnaires

B.1 Influence of partial and delayed control

Do you feel as if...

The robot's body was your own body
Not at all 1-2-3-4-5-6-7 Very Strongly

You were located at the position of the robot
Not at all 1-2-3-4-5-6-7 Very Strongly

You could use the robot's body to push objects near him if you wanted
Not at all 1-2-3-4-5-6-7 Very Strongly

B.2 Influence of control input in the embodiment of a humanoid robot

Do you feel as if...

The robot's body was your own body
Not at all 1-2-3-4-5-6-7 Very Strongly

You were located at the position of the robot
Not at all 1-2-3-4-5-6-7 Very Strongly

You could use the robot's body to push objects near him if you wanted
Not at all 1-2-3-4-5-6-7 Very Strongly

B.3 Embodiment of a robot-looking arm through visuo-tactile and visuo-motor stimuli

During the experiment, it seemed like...

The arm I was seeing was part of my body
Not at all 1-2-3-4-5-6-7 Very Strongly

The arm I was seeing was in the location of my real arm
Not at all 1-2-3-4-5-6-7 Very Strongly

I could push an object with the arm I was seeing
Not at all 1-2-3-4-5-6-7 Very Strongly

B.4 Touch illusion with an embodied robotic arm

During the experiment, it seemed like...

I was looking directly at my own arm, rather than at a robot's arm
Not at all 1-2-3-4-5-6-7 Very Strongly

The robot's arm began to resemble my real arm
Not at all 1-2-3-4-5-6-7 Very Strongly

The robot's arm belonged to me
Not at all 1-2-3-4-5-6-7 Very Strongly

The robot's arm was my arm
Not at all 1-2-3-4-5-6-7 Very Strongly

The robot's arm was part of my body
Not at all 1-2-3-4-5-6-7 Very Strongly

My arm was in the location where the robot's arm was
Not at all 1-2-3-4-5-6-7 Very Strongly

The robot's arm was in the location where my arm was
Not at all 1-2-3-4-5-6-7 Very Strongly

I moved the robot's arm
Not at all 1-2-3-4-5-6-7 Very Strongly

I was in control of the robot's arm
Not at all 1-2-3-4-5-6-7 Very Strongly

I was responsible for the actions of the robot's arm
Not at all 1-2-3-4-5-6-7 Very Strongly

I could really touch the curtain
Not at all 1-2-3-4-5-6-7 Very Strongly

I could feel the touch of the curtain
Not at all 1-2-3-4-5-6-7 Very Strongly

B.5 Self-interaction

After touching curtain
I feel as if...

The robot arm belonged to me
Not at all 1-2-3-4-5-6-7 Very Strongly

The robot arm was in the location of my real arm
Not at all 1-2-3-4-5-6-7 Very Strongly

I was responsible for the actions of the robot arm
Not at all 1-2-3-4-5-6-7 Very Strongly

I feel as if I could really touch the curtain
Not at all 1-2-3-4-5-6-7 Very Strongly

I feel tickling in my left hand or fingers
Not at all 1-2-3-4-5-6-7 Very Strongly

I feel electricity in my left hand or fingers
Not at all 1-2-3-4-5-6-7 Very Strongly

After touching arm

I feel as if...

The robot arm belonged to me

Not at all 1-2-3-4-5-6-7 Very Strongly

The robot arm was in the location of my real arm

Not at all 1-2-3-4-5-6-7 Very Strongly

I was responsible for the actions of the robot arm

Not at all 1-2-3-4-5-6-7 Very Strongly

I feel as if I could really touch the human arm

Not at all 1-2-3-4-5-6-7 Very Strongly

I feel tickling in my left hand or fingers

Not at all 1-2-3-4-5-6-7 Very Strongly

I feel electricity in my left hand or fingers

Not at all 1-2-3-4-5-6-7 Very Strongly

After hand being touched

I feel as if...

The robot arm belonged to me

Not at all 1-2-3-4-5-6-7 Very Strongly

The robot arm was in the location of my real arm

Not at all 1-2-3-4-5-6-7 Very Strongly

I was responsible for the actions of the robot arm

Not at all 1-2-3-4-5-6-7 Very Strongly

I feel as if I was being touched in my robotic arm

Not at all 1-2-3-4-5-6-7 Very Strongly

I feel tickling in my left hand or fingers

Not at all 1-2-3-4-5-6-7 Very Strongly

I feel electricity in my left hand or fingers

Not at all 1-2-3-4-5-6-7 Very Strongly

Bibliography

- [1] Elahe Abdi, Etienne Burdet, Mohamed Bouri, and Hannes Bleuler. Control of a Supernumerary Robotic Hand by Foot: An Experimental Study in Virtual Reality. *PLOS ONE*, 10(7), jul 2015.
- [2] Tyson Aflalo, Spencer Kellis, Christian Klaes, Brian Lee, Ying Shi, Kelsie Pejsa, Kathleen Shanfield, Stephanie Hayes-Jackson, Mindy Aisen, Christi Heck, Charles Liu, and Richard A. Andersen. Decoding motor imagery from the posterior parietal cortex of a tetraplegic human. *Science*, 348(6237):906–910, may 2015.
- [3] Abdullah Akce, Miles Johnson, Or Dantsker, and Timothy Bretl. A brain-machine interface to navigate a mobile robot in a planar workspace: enabling humans to fly simulated aircraft with EEG. *IEEE transactions on neural systems and rehabilitation engineering*, 21(2):306–318, mar 2013.
- [4] Maryam Alimardani, Shuichi Nishio, and Hiroshi Ishiguro. Body ownership transfer to tele-operated android through mind controlling. In *Proceedings of Human-Agent Interaction Symposium*, pages I–2A–1, 2011.
- [5] Maryam Alimardani, Shuichi Nishio, and Hiroshi Ishiguro. Humanlike robot hands controlled by brain activity arouse illusion of ownership in operators. *Scientific reports*, 3:2396, jan 2013.
- [6] K Carrie Armel and V S Ramachandran. Projecting sensations to external objects: evidence from skin conductance response. *Proceedings. Biological sciences / The Royal Society*, 270(1523):1499–1506, jul 2003.
- [7] Shahar Arzy, Margitta Seeck, Stephanie Ortigue, Laurent Spinelli, and Olaf Blanke. Induction of an illusory shadow person. *Nature*, 443(7109):287, 2006.
- [8] Asus. Asus Xtion PRO Live.
- [9] Gérard Bailly. Beaming the Gaze of a Humanoid Robot. In *Proceedings of the Tenth Annual ACM/IEEE International Conference on Human-Robot Interaction Extended Abstracts*, pages 47–48, 2015.

- [10] Christian J Bell, Pradeep Shenoy, Rawichote Chalodhorn, and Rajesh P.N. Rao. Control of a humanoid robot by a noninvasive brain-computer interface in humans. *Journal of neural engineering*, 5(2), 2008.
- [11] Giovanni Berlucchi and Salvatore Aglioti. The body in the brain: neural bases of corporeal awareness. *Trends in Neurosciences*, 20(12):560–564, dec 1997.
- [12] Elaine A Biddiss and Tom T Chau. Upper limb prosthesis use and abandonment: a survey of the last 25 years. *Prosthetics and orthotics international*, 31(3):236–257, 2007.
- [13] Frank Biocca. The Cyborg’s Dilemma: Progressive Embodiment in Virtual Environments. *Journal of Computer-Mediated Communication*, 3(2):0, jun 1997.
- [14] Frank Biocca, Y. Inoue, A. Lee, H. Polinsky, and A. Tang. Visual cues and virtual touch: Role of visual stimuli and intersensory integration in cross-modal haptic illusions and the sense of presence. *Presence 2002*, pages 376–394, 2002.
- [15] Frank Biocca, Jin Kim, and Yung Choi. Visual Touch in Virtual Environments: An Exploratory Study of Presence, Multimodal Interfaces, and Cross-Modal Sensory Illusions. *Presence: Teleoperators and Virtual Environments*, 10(3):247–265, jun 2001.
- [16] Touch bionics. touch bionics.
- [17] Sarah-Jayne Blakemore, Daniel M. Wolpert, and Christopher D. Frith. Abnormalities in the awareness of action. *Trends in Cognitive Sciences*, 6(6):237–242, jun 2002.
- [18] Olaf Blanke and Thomas Metzinger. Full-body illusions and minimal phenomenal selfhood. *Trends in cognitive sciences*, 13(1):7–13, jan 2009.
- [19] Olaf Blanke, Polona Pozeg, Masayuki Hara, Lukas Heydrich, Andrea Serino, Akio Yamamoto, Toshiro Higuchi, Roy Salomon, Margitta Seeck, Theodor Landis, Shahar Arzy, and Bruno Herbelin. Report Neurological and Robot-Controlled Induction of an Apparition. *Current Biology*, 24(22):2681–2686, 2014.
- [20] Matthew Botvinick and Jonathan Cohen. Rubber hands ‘feel’ touch that eyes see. *Nature*, 391(6669):756, feb 1998.
- [21] Gian Luca Cesa, Gian Mauro Manzoni, Monica Bacchetta, Gianluca Castelnovo, Sara Conti, Andrea Gaggioli, Fabrizia Mantovani, Enrico Molinari, Georgina Cárdenas-López, and Giuseppe Riva. Virtual reality for enhancing the cognitive behavioral treatment of obesity with binge eating disorder: Randomized controlled study with one-year follow-up. *Journal of Medical Internet Research*, 15(6):1–19, 2013.
- [22] Ori Cohen, Sébastien Druon, Sébastien Lengagne, Avi Mendelsohn, Rafael Malach, Abderrahmane Kheddar, and Doron Friedman. fMRI based robotic embodiment: a pilot study. In *IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob)*, pages 314–319, Roma, Italy, 2012.

- [23] Canudas de Wit C., Siciliano B., and Bastin G. Nonlinear feedback control. In *Theory of robot control*, Communications and Control Engineering. Springer, 1996.
- [24] José del R. Millán, Rudieger Rupp, Gernot R. Müller-Putz, Roderick Murray-Smith, Claudio Giugliemma, Michael Tangermann, Carmen Vidaurre, Febo Cincotti, Andrea Kübler, Robert Leeb, Christa Neuper, Klaus-Robert Müller, and Donatella Mattia. Combining Brain-Computer Interfaces and Assistive Technologies: State-of-the-Art and Challenges. *Frontiers in Neuroscience*, 4:161, jan 2010.
- [25] Lionel Dominjon, Anatole Lécuyer, Jean-Marie Burkhardt, Paul Richard, and Simon Richir. Influence of control/display ratio on the perception of mass of manipulated objects in virtual environments. In *IEEE Proceedings. VR 2005. Virtual Reality, 2005.*, volume 2005, pages 19–26, 2005.
- [26] A Doucet, N De Freitas, and N Gordon. Sequential Monte Carlo Methods in Practice. *Springer New York*, pages 178–195, 2001.
- [27] David H Douglas and THOMAS K Peucker. Algorithms for the reduction of the number of points required to represent a digitized line or its caricature. *Cartographica: The International Journal for Geographic Information and Geovisualization*, 10(2):112–122, oct 1973.
- [28] Claire Dune, Andrei Herdt, Olivier Stasse, P-B Wieber, Kazuhito Yokoi, and E Yoshida. Cancelling the sway motion of dynamic walking in visual servoing. In *2010 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 3175–3180. IEEE, oct 2010.
- [29] Frank H Durgin, Laurel Evans, Natalie Dunphy, Susan Klostermann, and Kristina Simmons. Rubber hands feel the touch of light. *Psychological science*, 18(2):152–7, mar 2007.
- [30] H. Henrik Ehrsson. The experimental induction of out-of-body experiences. *Science (New York, N.Y.)*, 317(5841):1048, aug 2007.
- [31] H. Henrik Ehrsson, Nicholas P Holmes, and Richard E Passingham. Touching a rubber hand: feeling of body ownership is associated with activity in multisensory brain areas. *The Journal of neuroscience : the official journal of the Society for Neuroscience*, 25(45):10564–73, nov 2005.
- [32] H. Henrik Ehrsson, B. Rosen, Anita Stockselius, C. Ragno, P. Kohler, and Göran Lundborg. Upper limb amputees can be induced to experience a rubber hand as their own. *Brain*, 131(12):3443–3452, dec 2008.
- [33] H. Henrik Ehrsson, Charles Spence, and Richard E Passingham. That’s my hand! Activity in premotor cortex reflects feeling of ownership of a limb. *Science (New York, N.Y.)*, 305(5685):875–7, aug 2004.

- [34] H. Henrik Ehrsson, Katja Wiech, Nikolaus Weiskopf, Raymond J Dolan, and Richard E Passingham. Threatening a rubber hand that you feel is yours elicits a cortical anxiety response. *Proceedings of the National Academy of Sciences of the United States of America*, 104(23):9828–33, jun 2007.
- [35] Hh Ehrsson. The Concept of Body Ownership and Its Relation to Multisensory Integration. In B. E. Stein, editor, *The New Handbook of Multisensory Processes*, chapter 43, pages 775–792. Cambridge, MA: MIT Press, 2012.
- [36] Greg K Essick, Francis McGlone, Chris Dancer, David Fabricant, Yancy Ragin, Nicola Phillips, Therese Jones, and Steve Guest. Quantitative assessment of pleasant touch. *Neuroscience and biobehavioral reviews*, 34(2):192–203, mar 2010.
- [37] Angela Faragasso, Giuseppe Oriolo, Antonio Paolillo, and Marilena Vendittelli. Vision-Based Corridor Navigation for Humanoid Robots. *IEEE Int. Conf. on Robotics and Automation ICRA*, pages 3190–3195, may 2013.
- [38] Robert S Fisher, Graham Harding, Giuseppe Erba, Gregory L Barkley, and Arnold Wilkins. Photic- and pattern-induced seizures: a Review for the Epilepsy Foundation of America Working Group. *Epilepsia*, 46:1426–1441, 2005.
- [39] N. Franck. Defective Recognition of One’s Own Actions in Patients With Schizophrenia. *American Journal of Psychiatry*, 158(3):454–459, mar 2001.
- [40] Daniel Freeman. Studying and treating schizophrenia using virtual reality: a new paradigm. *Schizophrenia bulletin*, 34(4):605–10, 2008.
- [41] Ola Friman, Ivan Volosyak, and Axel Gräser. Multiple Channel Detection of Steady-State Visual Evoked Potentials for Brain-Computer Interfaces. *IEEE Transactions on Biomedical Engineering*, 54(4):742–750, 2007.
- [42] Ferran Galán, Marnix Nuttin, Eileen Lew, Pierre W Ferrez, Gerolf Vanacker, Johan Philips, and José del R. Millán. A Brain-Actuated Wheelchair: Asynchronous and Non-Invasive Brain-Computer Interfaces for Continuous Control of Robots. *Clinical Neurophysiology*, 119(9):2159–2169, 2008.
- [43] I Gallagher. Philosophical conceptions of the self: implications for cognitive science. *Trends in cognitive sciences*, 4(1):14–21, 2000.
- [44] Shaun Gallagher. *How the Body Shapes the Mind*, volume 20. Cambridge Univ Press, 2005.
- [45] S Garrido-Jurado, R Muñoz-Salinas, F.J. Madrid-Cuevas, and M.J. Marín-Jiménez. Automatic generation and detection of highly reliable fiducial markers under occlusion. *Pattern Recognition*, 47(6):2280–2292, jun 2014.

- [46] Giovanni Gentile, Arvid Guterstam, Claudio Brozzoli, and H. Henrik Ehrsson. Disintegration of multisensory signals from the real hand reduces default limb self-attribution: an fMRI study. *The Journal of neuroscience : the official journal of the Society for Neuroscience*, 33(33):13350–66, 2013.
- [47] Pierre Gergondet, Abderrahmane Kheddar, Christoph Hintermüller, Christoph Guger, and Mel Slater. Multitask Humanoid Control with a Brain-Computer Interface: User Experiment with HRP-2. In *International Symposium on Experimental Robotics ISER*, pages 215–229. Springer International Publishing, 2013.
- [48] Guillaume Gibert, Florian Lance, Maxime Petit, Gregoire Pointeau, and Peter Ford Dominey. Damping robot’s head movements affects human-robot interaction. In *Proceedings of the 2014 ACM/IEEE international conference on Human-robot interaction - HRI '14*, pages 162–163, 2014.
- [49] R. A. R. C. Gopura, D. S. V. Bandara, J. M. P. Gunasekara, and T. S. S. Jayawardane. *Electrodiagnosis in New Frontiers of Clinical Research*. InTech, may 2013.
- [50] S. Michael. Goza, Robert O. Ambrose, Myron A. Diftler, and Ivan M. Spain. Telepresence control of the NASA/DARPA robonaut on a mobility platform. *Proceedings of the 2004 conference on Human factors in computing systems - CHI '04*, 6(1):623–629, 2004.
- [51] Michael S.A. Graziano and Matthew M. Botvinick. How the brain represents the body: insights from neurophysiology and psychology. In W. Prinz and B. Hommel, editors, *Common mechanisms in perception and action: Attention and performance*, chapter XIX, pages 136–157. Oxford University Press, Oxford, 2002.
- [52] Peter G. Grossenbacher and Christopher T. Lovelace. Mechanisms of synesthesia: Cognitive and physiological constraints. *Trends in Cognitive Sciences*, 5(1):36–41, 2001.
- [53] Arvid Guterstam and H. Henrik Ehrsson. Disowning one’s seen real body during an out-of-body illusion. *Consciousness and Cognition*, 21(2):1037–1042, 2012.
- [54] Arvid Guterstam, Giovanni Gentile, and H. Henrik Ehrsson. The invisible hand illusion: multisensory integration leads to the embodiment of a discrete volume of empty space. *Journal of cognitive neuroscience*, 25:1078–99, 2013.
- [55] Arvid Guterstam, Valeria I. Petkova, and H. Henrik Ehrsson. The illusion of owning a third arm. *PLoS ONE*, 6(2), 2011.
- [56] Masayuki Hara, G Rognini, N Evans, Olaf Blanke, A Yamamoto, Hannes Bleuler, and T. Higuchi. A novel approach to the manipulation of body-parts ownership using a bilateral master-slave system. In *2011 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 4664–4669. IEEE, sep 2011.

- [57] Randall B Hellman, Eric Chang, Justin Tanner, Stephen I Helms Tillery, and Veronica J Santos. A Robot Hand Testbed Designed for Enhancing Embodiment and Functional Neurorehabilitation of Body Schema in Subjects with Upper Limb Impairment or Loss. *Frontiers in Human Neuroscience*, 9(February):26, feb 2015.
- [58] Andrei Herdt, Holger Diedam, Pierre-Brice Wieber, Dimitar Dimitrov, Katja Mommaur, and Moritz Diehl. Online Walking Motion Generation with Automatic Footstep Placement. *Advanced Robotics*, 24(5-6), 2010.
- [59] Leigh R Hochberg, Daniel Bacher, Beata Jarosiewicz, Nicolas Y Masse, John D Simeral, Joern Vogel, Sami Haddadin, Jie Liu, Sydney S Cash, Patrick van der Smagt, and John P Donoghue. Reach and grasp by people with tetraplegia using a neurally controlled robotic arm. *Nature*, 485(7398):372–375, may 2012.
- [60] Matej Hoffmann and Rolf Pfeifer. The implications of embodiment for behavior and cognition: animal and robotic case studies. In *The Implications of Embodiment: Cognition and Communication*, pages 31–58. Academic, Exeter: Imprint, 2012.
- [61] Thomas Holz, Mauro Dragone, Gregory M P O’Hare, Alan Martin, and Brian R Duffy. Mixed Reality Agents as Museum Guides. In *Agent-Based Systems for Human Learning (ABSHL) Workshop at the 5th International Joint Conference on Autonomous Agents and Multiagent Systems (AAMAS 2006)*, Future University Hakodate, Japan, 2006.
- [62] Wijnand A. IJsselstein, Yvonne A.W. de Kort, and Antal Haans. Is this my hand I see before me? The rubber hand illusion in reality, virtual reality, and mixed reality. *Presence: Teleoperators and Virtual Environments*, 15(4):455–464, 2006.
- [63] Hiroshi Ishiguro. Hiroshi Ishiguro Laboratory, ATR.
- [64] Hiroshi Ishiguro. Android Science: Toward a New Cross-Disciplinary Framework. In *Proceedings of Toward Social Mechanisms of Android Science: A CogSci 2005 Workshop*,, pages 1–6, 2005.
- [65] Carlos Toshinori Ishii, Chaoran Liu, Hiroshi Ishiguro, and Norihiro Hagita. Speech-driven lip motion generation for tele-operated humanoid robots. In *Auditory-Visual Speech Processing 2011*, 2011.
- [66] K I Kaitin. Deconstructing the Drug Development Process: The New Face of Innovation. *Clinical Pharmacology and Therapeutics*, 87(3):356–361, mar 2010.
- [67] Andreas Kalckert and H. Henrik Ehrsson. Moving a Rubber Hand that Feels Like Your Own: A Dissociation of Ownership and Agency. *Frontiers in Human Neuroscience*, 6(March):1–14, 2012.

- [68] Andreas Kalckert and H. Henrik Ehrsson. The moving rubber hand illusion revisited: Comparing movements and visuotactile stimulation to induce illusory ownership. *Consciousness and Cognition*, 26(1):117–132, 2014.
- [69] Kenji Kaneko, Fumio Kanehiro, Shuuji Kajita, Hirohisa Hirukawa, Toshikazu Kawasaki, Masaru Hirata, Kazuhiko Akachi, and Takakatsu Isozumi. Humanoid robot HRP-2. In *IEEE International Conference on Robotics and Automation, 2004. Proceedings. ICRA '04. 2004*, pages 1083–1090 Vol.2, 2004.
- [70] Kenji Kaneko, Fumio Kanehiro, Mitsuharu Morisawa, Kanako Miura, Shin'ichiro Nakaoka, and Shuuji Kajita. Cybernetic human HRP-4C. *2009 9th IEEE-RAS International Conference on Humanoid Robots*, pages 7–14, dec 2009.
- [71] Konstantina Kilteni, Raphaela Groten, and Mel Slater. The Sense of Embodiment in Virtual Reality. *Presence: Teleoperators and Virtual Environments*, 21(4):373–387, 2012.
- [72] Hatice Kose-Bagci, Ester Ferrari, Kerstin Dautenhahn, Dag Sverre Syrdal, and Chrystopher L. Nehaniv. Effects of Embodiment and Gestures on Social Interaction in Drumming Games with a Humanoid Robot. *Advanced Robotics*, 23(14):1951–1996, 2009.
- [73] Anatole Lécuyer. Simulating Haptic Feedback Using Vision: A Survey of Research and Applications of Pseudo-Haptic Feedback. In *Presence: Teleoperators and Virtual Environments*, volume 18, pages 39–53, feb 2009.
- [74] Anatole Lécuyer, Sabine Coquillart, Abderrahmane Kheddar, Paul Richard, and P. Coiffet. Pseudo-haptic feedback: can isometric input devices simulate force feedback? In *Proceedings IEEE Virtual Reality 2000 (Cat. No.00CB37048)*, pages 83–90, 2000.
- [75] Susan J. Lederman and Lynette a. Jones. Tactile and Haptic Illusions. *IEEE Transactions on Haptics*, 4(4):273–294, 2011.
- [76] Bigna Lenggenhager, Michael Mouthon, and Olaf Blanke. Spatial aspects of bodily self-consciousness. *Consciousness and cognition*, 18(1):110–7, mar 2009.
- [77] Bigna Lenggenhager, S.T. Smith, and Olaf Blanke. Functional and Neural Mechanisms of Embodiment: Importance of the Vestibular System and the Temporal Parietal Junction. *Reviews in the Neurosciences*, 17(6):643–657, jan 2006.
- [78] Bigna Lenggenhager, Tej Tadi, Thomas Metzinger, and Olaf Blanke. Video ergo sum: manipulating bodily self-consciousness. *Science (New York, N.Y.)*, 317(5841):1096–9, aug 2007.

- [79] C. Leroux, O. Lebec, M.W. Ben Ghezala, Y. Mezouar, L. Devillers, C. Chastagnol, J.-C. Martin, V. Leynaert, and C. Fattal. ARMEN: Assistive robotics to maintain elderly people in natural environment. *IRBM*, 34(2):101–107, apr 2013.
- [80] Baldin Llorens Bonilla and H Harry Asada. A robot on the shoulder: Coordinated human-wearable robot control using coloured petri nets and partial least squares predictions. In *Robotics and Automation (ICRA), 2014 IEEE International Conference on*, pages 119–125. IEEE, 2014.
- [81] Donna M Lloyd. Spatial limits on referred touch to an alien limb may reflect boundaries of visuo-tactile peripersonal space surrounding the hand. *Brain and Cognition*, 64(1):104–109, jun 2007.
- [82] Matthew R. Longo, Friederike Schüür, M. P M Kammers, Manos Tsakiris, and Patrick Haggard. What is embodiment? A psychometric approach. *Cognition*, 107(3):978–998, 2008.
- [83] Wing-Yue Geoffrey Louie, Derek McColl, and Goldie Nejat. Acceptance and Attitudes Toward a Human-like Socially Assistive Robot by Older Adults. *Assistive Technology*, 26(3):140–150, 2014.
- [84] David G. Lowe. Object recognition from local scale-invariant features. *Proceedings of the Seventh IEEE International Conference on Computer Vision*, 2([8]):1150–1157, 1999.
- [85] Nicolas Mansard, Olivier Stasse, Paul Evrard, and Abderrahmane Kheddar. A Versatile Generalized Inverted Kinematics Implementation for Collaborative Humanoid Robots: The Stack of Tasks. In *Int. Conf. on Advanced Robotics ICAR*, 2009.
- [86] Donald W Marquardt. An Algorithm for Least-Squares Estimation of Nonlinear Parameters. *Journal of the Society for Industrial and Applied Mathematics*, 11(2):431–441, jun 1963.
- [87] Maxime Meilland and Andrew I Comport. On unifying key-frame and voxel-based dense visual SLAM at large scales. In *2013 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 3677–3683, 2013.
- [88] Thomas Metzinger. Empirical perspectives from the self-model theory of subjectivity: a brief summary with examples. *Progress in brain research*, 168(07):215–45, jan 2008.
- [89] Thomas Metzinger. Why are out-of-body experiences interesting for philosophers? The theoretical relevance of OBE research. *Cortex; a journal devoted to the study of the nervous system and behavior*, 45(2):256–8, feb 2009.
- [90] Microsoft. Microsoft Xbox 360 Wired Controller. <http://www.xbox.com/en-US/xbox-360/accessories/controllers>, 2010.

- [91] MIT. MIT d'Arbeloff Laboratory.
- [92] T Mörwald, J Prankl, A Richtsfeld, M Zillich, and M Vincze. BLORT - The Blocks World Robotic Vision Toolbox. In *Proc. ICRA Workshop Best Practice in 3D Perception and Modeling for Mobile Manipulation*, 2010.
- [93] Gernot R. Müller-Putz, Christian Breitwieser, Febo Cincotti, Robert Leeb, Martijn Schreuder, Francesco Leotta, Michele Tavella, Luigi Bianchi, Alex Kreilinger, Andrew Ramsay, Martin Rohm, Max Sagebaum, Luca Tonin, Christa Neuper, and José del R. Millán. Tools for brain-computer interaction: a general concept for a hybrid BCI. *Frontiers in Neuroinformatics*, 5:30, 2011.
- [94] Jonathan Mumm and B Mutlu. Human-Robot Proxemics: Physical and Psychological Distancing in Human-Robot Interaction. In *IEEE International Conference on Human-Robot Interaction*, pages 331–338, 2011.
- [95] Christa Neuper, Gernot R. Müller-Putz, Reinhold Scherer, and Gert Pfurtscheller. Motor imagery and EEG-based control of spelling devices and neuroprostheses. *Progress in brain research*, 159:393–409, 2006.
- [96] Roger Newport, Rachel Pearce, and Catherine Preston. Fake hands in action: embodiment and control of supernumerary limbs. *Experimental Brain Research*, 204(3):385–395, 2010.
- [97] Ernst Niedermeyer and F H Lopes da Silva. *Electroencephalography: basic principles, clinical applications, and related fields*. Lippincott Williams & Wilkins, 2005.
- [98] Shuichi Nishio, Hiroshi Ishiguro, and Norihiro Hagita. Geminoid: Teleoperated Android of an Existing Person. In *Humanoid Robots: New Developments*, pages 343–352. I-Tech Education and Publishing, jun 2007.
- [99] Shuichi Nishio, Koichi Taura, Hidenobu Sumioka, and Hiroshi Ishiguro. Effect of Social Interaction on Body Ownership Transfer to Teleoperated Android. In *Proceedings - IEEE International Workshop on Robot and Human Interactive Communication*, pages 565–570. IEEE, aug 2013.
- [100] Shuichi Nishio, Tetsuya Watanabe, Kohei Ogawa, and Hiroshi Ishiguro. Body Ownership Transfer to Teleoperated Android Robot. *Social Robotics*, pages 398–407, 2012.
- [101] Nobuyuki Otsu. A Threshold Selection Method from Gray-Level Histograms. *IEEE Transactions on Systems, Man, and Cybernetics*, 9(1):62–66, 1979.
- [102] V R Oculus. Oculus rift DK2-virtual reality headset for 3d gaming. URL: <http://www.oculusvr.com>, 2012.
- [103] Darpa Tactical Technology Office. DARPA Robotics Challenge, 2012.

- [104] Kohei Ogawa, Shuichi Nishio, Kensuke Koda, Koichi Taura, Takashi Minato, Carlos Toshinori Ishii, and Hiroshi Ishiguro. Telenoid: tele-presence android for communication. In *ACM SIGGRAPH 2011 Emerging Technologies on - SIGGRAPH '11*, pages 15:1–15:1, New York, New York, USA, 2011. ACM Press.
- [105] Open Hand Project. Open Hand Project.
- [106] OpenBionics. OpenBionics.
- [107] Max Ortiz-Catalan, Nicholas Sander, Morten B. Kristoffersen, Bo Hakansson, and Rickard Branemark. Treatment of phantom limb pain (PLP) based on augmented reality and gaming controlled by myoelectric pattern recognition: a case study of a chronic PLP patient. *Frontiers in Neuroscience*, 8:24, 2014.
- [108] Amit Kumar Pandey, Rodolphe Gelin, Rachid Alami, Renaud Viry, Roland Meertens, Mohamed Chetouani, Laurence Devillers, David Filliat, Yves Grenier, and Mounira Maazaoui. Romeo2 Project : Humanoid Robot Assistant and Companion for Everyday Life : I . Situation Assessment for Social Intelligence. In *International Workshop on Artificial Intelligence and Cognition, 2nd Edition*, pages 140–147, 2014.
- [109] Francesco Pavani, Charles Spence, and Jon Driver. Research Article VISUAL CAPTURE OF TOUCH : Out-of-the-Body Experiences With Rubber Gloves. *Psychological Science*, 11(5):353–359, 2000.
- [110] Daniel Perez-Marcos, Mel Slater, and Maria V Sanchez-Vives. Inducing a virtual hand ownership illusion through a brain-computer interface. *Neuroreport*, 20(6):589–594, 2009.
- [111] Damien Petit, Pierre Gergondet, Andrea Cherubini, Maxime Meilland, Andrew I Comport, and Abderrahmane Kheddar. Navigation assistance for a BCI-controlled humanoid robot. In *The 4th Annual IEEE International Conference on Cyber Technology in Automation, Control and Intelligent*, pages 246–251. IEEE, jun 2014.
- [112] Valeria I. Petkova and H. Henrik Ehrsson. If I were you: Perceptual illusion of body swapping. *PLoS ONE*, 3(12):e3832, jan 2008.
- [113] Valeria I. Petkova, Hedvig Zetterberg, and H. Henrik Ehrsson. Rubber hands feel touch, but not in blind individuals. *PLoS ONE*, 7(4):1–10, 2012.
- [114] G. Pfurtscheller, C. Brunner, A. Schlogl, and F. H. Lopes da Silva. Mu rhythm (de)synchronization and EEG single-trial classification of different motor imagery tasks. *NeuroImage*, 31(1):153–159, 2006.
- [115] Gregoire Pointeau, Maxime Petit, and Peter Ford Dominey. Embodied Simulation Based on Autobiographical Memory. *Biomimetic and Biohybrid Systems*, 8064:240–250, 2013.

- [116] Primesense. NITE <http://structure.io/openni>.
- [117] Robert Prueckl and Christoph Guger. A Brain-Computer Interface Based on Steady State Visual Evoked Potentials for Controlling a Robot. *Lecture Notes in Computer Science*, 5517:690–697, 2009.
- [118] Andreas Pusch, Olivier Martin, and Sabine Coquillart. HEMP - Hand-displacement-based Pseudo-haptics: A study of a force field application. In *3DUI - IEEE Symposium on 3D User Interfaces 2008*, pages 59–66, 2008.
- [119] Andreas Pusch, Olivier Martin, and Sabine Coquillart. HEMP-hand-displacement-based pseudo-haptics: A study of a force field application and a behavioural analysis. *International Journal of Human Computer Studies*, 67(3):256–268, 2009.
- [120] Morgan Quigley, Ken Conley, Brian Gerkey, Josh Faust, Tully Foote, Jeremy Leibs, Eric Berger, Rob Wheeler, and Andrew Ng. ROS: an open-source Robot Operating System. In *ICRA workshop on open source software*, volume 3, 2009.
- [121] Yann Renard, Fabien Lotte, Guillaum Gibert, Marco Congedo, Emmanuel Maby, Vincent Delannoy, Olivier Bertrand, and Anatole Lécuyer. OpenViBE: An Open-Source Software Platform to Design, Test and Use Brain-Computer Interfaces in Real and Virtual Environments. *Presence Teleoperators & Virtual Environments*, 19(1):35–53, 2010.
- [122] Marieke Rohde, Meike Scheller, and Marc O. Ernst. Effects can precede their cause in the sense of agency. *Neuropsychologia*, 65:191–196, 2014.
- [123] Daniele Romano, Elisa Caffa, Alejandro Hernandez-Arieta, Peter Brugger, and Angelo Maravita. The robot hand illusion: Inducing proprioceptive drift through visuo-motor congruency. *Neuropsychologia*, pages 1–7, 2015.
- [124] Birgitta Rosén, H. Henrik Ehrsson, Christian Antfolk, Christian Cipriani, Fredrik Sebelius, and Göran Lundborg. Referral of sensation to an advanced humanoid robotic hand prosthesis. *Scandinavian Journal of Plastic and Reconstructive Surgery and Hand Surgery*, 43(5):260–266, jan 2009.
- [125] Audrey S Royer and Bin He. Goal selection versus process control in a brain-computer interface based on sensorimotor rhythms. *Journal of neural engineering*, 6(1):016005, mar 2009.
- [126] Radu Bogdan Rusu, Nico Blodow, and Michael Beetz. Fast Point Feature Histograms (FPFH) for 3D Registration. In *IEEE Int. Conf. on Robotics and Automation ICRA*, pages 3212–3217. IEEE, may 2009.
- [127] Radu Bogdan Rusu and Steve Cousins. 3D is here: Point Cloud Library (PCL). In *IEEE Int. Conf. on Robotics and Automation ICRA*, pages 1–4, 2011.

- [128] Maria V Sanchez-vives and Mel Slater. From presence to consciousness through virtual reality. *Nature review neuroscience*, 6(April):332–339, 2005.
- [129] Atsushi Sato and Asako Yasuda. Illusion of sense of self-agency: discrepancy between the predicted and actual sensory consequences of actions modulates the sense of self-agency, but not the sense of self-ownership. *Cognition*, 94(3):241–55, jan 2005.
- [130] Jack W. Scannell, Alex Blanckley, Helen Boldon, and Brian Warrington. Diagnosing the decline in pharmaceutical R&D efficiency. *Nature Reviews Drug Discovery*, 11(3):191–200, mar 2012.
- [131] Gerwin Schalk, Dennis J McFarland, Thilo Hinterberger, Niels Birbaumer, and Jonathan R Wolpaw. BCI2000: A General-Purpose Brain-Computer Interface (BCI) System. *IEEE Transactions on Biomedical Engineering*, 51:1034, 2004.
- [132] F Sharbrough, G.-E. Chatrian, R P Lesser, H Lüders, M Nuwer, and T W Picton. American Electroencephalographic Society guidelines for standard electrode position nomenclature. *Journal of Clinical Neurophysiology*, 8:200–202, 1991.
- [133] Sotaro Shimada, Kensuke Fukuda, and Kazuo Hiraki. Rubber Hand Illusion under Delayed Visual Feedback. *PLoS ONE*, 4(7):e6185, 2009.
- [134] Mel Slater, Daniel Perez-Marcos, H. Henrik Ehrsson, and Maria V Sanchez-Vives. Towards a digital body: the virtual arm illusion. *Frontiers in human neuroscience*, 2(August):6, jan 2008.
- [135] Mel Slater, Daniel Perez-Marcos, H. Henrik Ehrsson, and Maria V Sanchez-Vives. Inducing illusory ownership of a virtual body. *Frontiers in neuroscience*, 3(2):214–20, sep 2009.
- [136] Mel Slater, Bernhard Spanlang, Maria V Sanchez-Vives, and Olaf Blanke. First person experience of body transfer in virtual reality. *PloS one*, 5(5):e10564, jan 2010.
- [137] Structure. OpenNI <http://structure.io/openni>.
- [138] Satoshi Suzuki and Keiichi Abe. Topological structural analysis of digitized binary images by border following. *Computer Vision, Graphics, and Image Processing*, 46:32–46, 1985.
- [139] Manos Tsakiris, Lewis Carpenter, Dafydd James, and Aikaterini Fotopoulou. Hands only illusion: Multisensory integration elicits sense of ownership for body parts but not for non-corporeal objects. *Experimental Brain Research*, 204(3):343–352, 2010.
- [140] Manos Tsakiris and Patrick Haggard. The rubber hand illusion revisited: visuotactile integration and self-attribution. *Journal of experimental psychology. Human perception and performance*, 31(1):80–91, feb 2005.

- [141] Manos Tsakiris, Gita Prabhu, and Patrick Haggard. Having a body versus moving your body: How agency structures body-ownership. *Consciousness and cognition*, 15(2):423–32, jun 2006.
- [142] François-Benoît Vialatte, Monique Maurice, Justin Dauwels, and Andrzej Cichocki. Steady-state visually evoked potentials: Focus on essential paradigms and future perspectives. *Progress in Neurobiology*, 90(4):418–438, apr 2010.
- [143] Jacques Vidal. Toward Direct Brain-Computer Communication. *Annual Review of Biophysics and Bioengineering*, 2:157–180, 1973.
- [144] Daniel Wagner, Gerhard Reitmayr, Alessandro Mulloni, Tom Drummond, and Dieter Schmalstieg. Real-Time Detection and Tracking for Augmented Reality on Mobile Phones. *IEEE transactions on visualization and computer graphics*, 16(3):355–68, 2010.
- [145] Jonathan Weisz, Carmine Elvezio, and Peter K Allen. A User Interface for Assistive Grasping. In *IEEE/RSJ Int. Conf. on Intelligent Robots and Systems IROS*, pages 3216 – 3221, nov 2013.
- [146] Faye Wu and Harry Asada. Supernumerary Robotic Fingers: An Alternative Upper-Limb Prosthesis. In *Volume 2: Dynamic Modeling and Diagnostics in Biomedical Systems; Dynamics and Control of Wind Energy Systems; Vehicle Energy Management Optimization; Energy Storage, Optimization; Transportation and Grid Applications; Estimation and Identification Method*, page V002T16A009. ASME, oct 2014.
- [147] Danhua Zhu, Jordi Bieger, Gary Garcia Molina, and Ronald M Aarts. A Survey of Stimulation Methods Used in SSVEP-Based BCIs. *Computational Intelligence and Neuroscience*, 2010:1–12, 2010.

TITRE : Analyse des exigences sensoriels et système de commande pour l'incarnation de robot humanoïde dans l'interaction avec l'environnement et soi

RÉSUMÉ : Les substituts de robot humanoïde promettent de nouvelles applications dans les domaines des interactions homme-robot et la robotique d'assistance. Cependant, l'incarnation de corps entier pour la téléopération ou téléprésence avec des avatars de robots mobiles est encore loin d'être pleinement explorée et comprise. Dans cette thèse, nous nous concentrons sur l'exploration du sentiment d'incarnation quand on navigue et interagit avec l'environnement ou avec soi-même par l'intermédiaire d'un robot humanoïde. Dans un premier temps, nous montrons une architecture de contrôle conçue pour réaliser des scénarios de navigation et d'interaction avec soi. L'architecture utilise une interface cerveau-ordinateur pour contrôler le robot humanoïde et repose sur plusieurs composants de vision par ordinateur pour aider l'utilisateur à naviguer et interagir avec l'environnement et soi-même. Deux scénarios sont ensuite réalisés avec une partie de cette architecture où les utilisateurs doivent contrôler un robot humanoïde pour réaliser des tâches d'interaction avec soi-même. Tout d'abord, nous examinons comment la rétroaction et la contrôlabilité réduite des utilisateurs affectent leur sentiment d'incarnation vers le robot humanoïde en navigation. Nous présentons ensuite le résultat d'une étude axée sur le sentiment éprouvé par l'utilisateur lorsqu'il commande le bras humanoïde pour "toucher" l'environnement et soi-même. Le résultat montre que, malgré le manque de rétroaction dans le contrôle et le fait de se reconnaître, les utilisateurs restent incarnés dans le robot humanoïde, et ressentent "l'effet tactile du toucher" sur leurs mains à travers le robot humanoïde.

MOTS-CLEFS : Robotique, Humanoïdes, Embodiment, Interface Cerveau-Ordinateur, Contrôle, orienté vision.

TITLE : Analysis of sensory requirement and control framework for whole body embodiment into a humanoid robot for interaction with the environment and self

ABSTRACT : Humanoid robot surrogates promise new applications in the field of human robot interactions and assistive robotics. However, whole body embodiment for teleoperation or telepresence with mobile robot avatars is yet to be fully explored and understood. In this thesis, we focus on exploring the feeling of embodiment when one navigates and interacts with the environment or with one's self through a humanoid robot. First, we show a framework devised to realize scenarios of navigation and self interaction. The framework uses a brain-computer interface to control a humanoid robot and relies on several computer vision components to assist the user navigate and interact with the environment and one's self. Two scenarios are then realized with this framework where the users control a humanoid robot to realize self interaction tasks. We then explore in details key issues encountered during those scenarios. First, we investigate how the reduced controllability and feedback of the users affect their feeling of embodiment toward the walking surrogate. We then present the results of a study focused on the feeling experienced by the user when controlling the humanoid arm to "touch" the environment and then one's self. The results show that despite the lack of feedback in the control, and recognizing themselves, users stay embody in the surrogate, and experience the touch in their hands through it.

KEYWORDS : Robotic, Humanoid, Embodiment, Brain-Computer interface, Vision-based control.

DISCIPLINE : Génie Informatique, Automatique et Traitement du Signal

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