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Design Challenges to achieve the Sense of Embodiment while Developing a Teleoperation System

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Abstract — We present i) the role of the Sense of Embodiment in teleoperation, ii) we describe the issues in designing a teleoperation system, and iii) the lack of a standard framework to test and assess it.

Keywords — sense of embodiment, teleoperation, design, standardization, assessment

1. INTRODUCTION (H1)

The role of the Sense of Embodiment (SoE) in improving teleoperation performances [33] gained attention in the last decade, when studies on the embodiment illusion and experience started to be designed and developed [12], [30], [40]. The Sense of Embodiment (SoE) is the experience that the external body or part of it is perceived as one's own. While operating a machine in remote, if a high level of SoE is achieved, the operator's perception of the remote device as mediator decreases [10], increasing the teleoperation system transparency. Starting from this intuition, it was demonstrated that a high level of SoE can improve teleoperation tasks performance [28], [43], [44]. The real problem is a lack of a standard definition and description of the SoE. Of course, this affects the design of a standard framework to test and assess it. Even because, often, it is neither clear which kind of effects or results are expected from a particular task or measure. The complexity of the SoE concept, is also confirmed by the fact that it involves different scientific fields and disciplines, such as robotics, neuroscience, psychology, artificial intelligence, and others. Finding the common ground which satisfies all those different disciplines is another tough aim. In this work: i) we present the SoE describing its three main components; ii) we report the main application fields of teleoperation, and how and at which level the embodiment is involved; iii) we describe the main kind of controllers to telemanipulate a system and how they affect the embodiment; iv) we report the main assessment measures, and their advantages and limitations; v) finally, there are the conclusions.

2. THE COMPONENTS OF THE SENSE OF EMBODIMENT (H2)

The SoE is described by three components:

- The *sense of ownership*: it is defined as the feeling of self-attribution of an external object or device. For example, if the user is teleoperating a robotic arm, we will talk about sense of ownership if the user will experience to own that robotic arm [22];
- The *sense of agency*: the feeling of being able to interact with the environment through the manipulated device. Therefore, the sense of agency is characterized by the trust that operators put in the fact that their intended actions are mirrored by the controlled device [32];
- The *sense of self-location*: it is defined as the volume of space where one feels located. Therefore, the operators should be aware of the space in which they teleoperate, they should feel confident of the distance, position and stiffness of objects, and, if possible, in moving around in the remote environment [3].

One of the first challenges is to design tasks and assessments which clearly disentangle these components. Usually, either the authors want to measure all the three components together or they claim to measure just one or two of them, without really demonstrating why all the components are involved or the other/s are not involved in that assessment. Another challenge is to base the design of a teleoperation system on the sensory cues involved for each component. The sensory cues define how the signals can be perceived and elaborated by the operator from the remote environment. Specifically, these are the sensory cues involved and the embodiment components which mostly affect: point of view(sense of ownership, sense of self-location), field of view (sense of ownership, sense of self-location), view direction control (sense of ownership, sense of self-location), connectedeness (sense of ownership, sense of agency), visuo-tactile synchronicity (sense of ownership, sense of agency), visual likeness (sense of ownership), visual likeness of the environment (sense of self-location), visuo-proprioceptivesynchrnocity (sense of agency), force feedback (sense of agency), haptic feedback (sense of ownership, sense of agency), skin complexion (sense of ownership), movement imaging (sense of ownership, sense of agency).

3. APPLICATION SCENARIOS (H3)

In this section we define the main teleoperation scenarios and at which level the SoE is involved:

- *Social*: Teleoperation in a social scenario is relatedto situations in which the operator has to interactwith other human beings in a dynamic and, often, unpredictable environment. In this scenario, the operated device must enable tasks such as: shaking hands, giving hugs, making eye contact, touching and manipulating everyday objects, moving around in an apartment, expressing emotions, and displaying other cues relevant in social interaction. Usually, the robotic devices that are used in these conditions are humanoid in shape [6], [11]. The role of the SoE, in this context, is fundamental to achieve high level of interaction and user experience. Of course, since the embodiments are mostly humanoid, the design of the embodiment cockpit become a real challenge. Especially because all the components of the embodiment should be achieved at high level.
- *Industrial*: In industrial scenarios, the environment is usually more static and the actions predictable. Even in this case, the operated device will have to manipulate tools, moving objects and moving around in an environment which is not open air, such as a factory [17], [49], but sometimes the environment is not human friendly, due to its temperature, dimension, or security level. Examples of tasks in this scenario are: tubes manipulation, maintenance using tools or robotic arms, moving heavy masses. In this scenario, the sense of agency is the main, and sometimes the only, aim. This is why also the design of the cockpit becomes easier and more focused.
- *Field*: Field robotics includes scenarios in which tasks like inspection, maintenance, and search&rescue have to be accomplished invunstructured environments. Unstructured environments are more dynamic and unpredictable than closed spaces. This kind of robotics is also called exploratory robotics. The robotic devices for this scenario are not humanoid, but mostly animal shaped [4], [16], [41]. This is probably the most complex scenario, indeed all the embodiment components are involved and it is pretty complex to design a system which can achieve high level of all of them. From a practical point of view, the main focus is on the sense of agency and self-location, but achieving also a high level of sense of ownership would improve the level of the performance and of the cognitive workload of the operator. Obviously, achieving high level of sense of ownership with a not humanoid robot is a real challenge.
- *Surgical*: Robot-assisted surgery was developed to overcome the limitations of pre-existing minimally-invasive surgical procedures and to enhance the capabilities of surgeons. The surgeon uses a direct(tele-)manipulator or a computer control to control the instruments. Another advantage of using robot-assisted surgery is that the surgeon does not have to be present, leading to the possibility for remote surgery. In this scenario, tasks of microassembly and microteleoperation are common. Indeed, usually the challenge is to create a connection between a macro and a nano world (as the inside of the human body can be considered) [15], [27], [36]. As for the industrial scenario, here the main focus is on the sense of agency. In this case, anyway, designing a proper controller w.t.r to the task is crucial to the performance, since the manageability is fundamental.

4. CONTROLLERS (H4)

The design and the choice of the physical controller is strictly related to the teleoperated device and the tasks to accomplish. This is the list of the mainly used controllers in teleoperation:

- *Eye Gaze Tracker*: operators can make use of a eye gaze tracker as a user interface to operate machines or robots through gazing [23]. This choice is appropriate just in cases in which the operator is unable to use the limbs (either for a disability or for the teleoperation context) and it requires a high level of cognitive workload.
- *Virtual Reality Set*: it includes, in its basic form, the headset and the two controllers. Operators can assume control of an embodiment (which could bevirtual or physical, human-like or machine-like), seeing out of the 'eyes' and manipulating the 'limbs' [21], [29], [31]. In simple simulation, this is the most used option. Anyway, there are three main issues in other contexts: i) often the need is to teleoperatein the physical remote environment, therefore designing and developing a VR environment is not an option; ii) to provide consistency to the SoE, it is necessary to design and develop a VR environmnet a) which respects the physics of the environment and the objects in it, b) with high level of appearance, and c) which deals with time delays and the dynamics of unexpected events in it (especially with SLAM); iii) finally, wearing a VR headset while moving and exploring an environment often causes the operator's motion sickness.
- *Sensory Glove*: it can be used for teleoperation of complex robots with five finger hands [14]. This controller is very limited to humanoid hands, but at the same time is the one which achieves the highest level of SoE. Of course, also in this case, issues could be encountered while designing the system control of the device and, in case of big time delays, the SoE could be highly compromised, making tasks achievement really hard.
- *Brain Computer Interfaces (BCIs)*: they are systems that extract information from the user's brain activity and employ it in interactive systems [1], [13]. This would be the ideal way to get the highest SoE. Unfortunately, the actual non-invasive technologies and knowledge to design and develop BCIs do not allow to realize really accurate and easy of use systems. Using BCIs is time consuming, since the operator needs a lot of training, and usually the performance level is low and very limited to certain kind of tasks. Moreover, using BCIs to telemanipulate a device requires a high cognitive workload; this makes complicated also the telemanipulation of singule parts of the external environment, and really hard to telemanipulate an entire embodiment.
- *Joystick, Keyboards, and Mouse*: they are used asanalog controllers to manipulate remote devices, machines or 'limbs' [46], [50]. They are the most used forms of controllers, especially the joystick. This is because they are really intuitive and easy to use. The level of SoE, of course, is affected, but the performance is guaranteed especially in an industrial scenario for tasks which do not require precision.

5. ASSESSMENT MEASURES (H5)

Due to the design issues already presented in the previous sections, a standard framework to assess the SoE or its single components does not exist. In this section, the main assessment measures of the SoE in teleoperation are categorized and reported. Moreover, we also provide some pros and cons for each assessment. The first distinction is between qualitative and quantitative measures, where the first typically deal with textual data or words, while quantitative measures analyze numerical data or statistics. The qualitative measures include subjective reports, such as questionnaires, self-reports, and interviews [2], [5], [18], [25]. The main advantages of this measures are that they are versatile, applicable to every study, and there is a lot of literature to support them. However, the main issues are that they are time consuming for the operator, and that they should be combine with quantitative analysis to make them more consistent. The quantitative measures, instead, include a larger spectrum of assessments, in particular: i) proprioceptive and kinestectics, which measure the operator awareness of the controlled embodiment itself and into the remote environment, some examples are the proprioceptive drift [9], [19], [24], [42], and the reaching distance judgement; their main adavantages are that they can be applied to almost every kind of study, and that they are easy to measure. Anyway, operators' performance could be affected by the experiment design (such as, the local and remote environment, the sensory feed-back, the embodiment itself, and others). ii) Physiological measures provide precise information about an individual's bodily functions, such as heart rate [47], skin conductance response [34], skin temperature [48]; but if on one hand they are the most used quantitative measures in these studies and there is a lot of literature to support them, on the other hand, physiological measures are often not reliable, since they are subject to poor signal to noise ratio, and because sometimes it is not clear if the recorded effects are due to what we wanted to assess. Moreover, sometimes the instruments used to measure them are not suitable for every kind of task and they can affect the operator's movements. iii) Measuring the reflexes is another subcategory of SoE assessments, especially identified with reaction time [38]; apart from being easy to measure, unfortunately it can be applied just to certain kind of studies or tasks (e.g. studies which require a comparison between the accomplishment time of the same task using two different kind of system controllers). iv) Finally, recording and measuring neural activities can provide evidence of the SoE. In a less invasive way, it is possible to record the electrical impulses in the brain using an EEG [39]; but, in a more invasive way, it was also possible to observe that several brain areas are implicated in the SoE, thanks to functional magneticresonance imaging (fMRI), positron emission tomography (PET) and to directly stimulate them through the transcranial magnetic stimulation (TMS) [26], [35], [45]. These are versatile measures, which can be used to assess all the components of the SoE and of the user experience with higher precision w.r.t. the other kind of assessments; moreover, they provide interesting and unique insights of the operator's embodiment experience. However, even if these measures always provide interesting results, their application requires a lot of constraints in designing the user study (e.g., metalobjects cannot be introduced into an fMRI scanner, thereforeall experiments with prosthesis are not allowed). Moreover, sometimes neural activity, regardless the chosen instruments, could be difficult to interpret.

6. DESIGN CHALLENGES AND ROLE (H6)

Design methods could provide an important contribution in order to structure and brings together all the previous defined aspects involved in designing a teleoperation system. One method would not be enough, but a combination would be the key towards a standardization, indeed hybrid models already exist [7]. Not only this would standardize the designing phase of the system but, as consequence, even the assessment phase. Particularly, while the systematic approach from Pahl and Beitz [37] could be a starting point to design and implement the teleoperation system (taking in consideration the application context, scenario, and tasks), the representative model from Brunswik [8] could be a standard to test and assess the system performance and the user experience. Moreover, thanks to astandardization it would be possible to create a predictive model for the SoE. Namely, the aim would be to predict, before the actual implementation, the level of SoE which could be achieve using a particular teleoperation system in a certain scenario [20].

7. CONCLUSIONS (H7)

We presented on overview of the importance of the SoE in teleoperation. Mainly, we reported the issues encountered in designing a teleoperation system, tasks and assessments when a high level of SoE is aimed to be achieved. Furthermore, we also presented in which way design approaches could be a starting point towards the standardization. The information related to the definitions and categorization of the scenarios, assessments tasks and measures are based on a literature review in preparation. To sum up the main points discussed in the paper:

- We miss a standard definition of the SoE and a clear picture of what we would like to assess while testing it;
- With the actual assessments and tasks, it is hard to disentangle the three embodiment components;
- Assessment tasks and measures are designed to be strictly related; this makes it complicated to design a standard framework to assess the SoE in teleoperation;
- The teleoperation scenarios strongly affect the design of the teleoperation system;
- A hybrid design approach is needed to create a standard framework.

To conclude, this work does not provide answers but just highlights the main design issues. A lot of work is still needed from the scientific community to solve them, but interestingly the solutions should come from the cooperation of different scientific fields.

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