Embodiment of a humanoid robot is preserved during partial and delayed control

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***Abstract*— Humanoid robot surrogates promise a plethora of new applications in the field of disaster management and human robot interactions. However, whole body embodiment for teleoperation or telepresence with mobile robot avatars is yet to be fully explored and understood. In this study we investigated whether partial and delayed control, necessitated by the large degree of freedom of a humanoid system, affects embodiment of a walking humanoid robot surrogate. For this, we asked participants 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 utilized an embodiment questionnaire to evaluate the embodiment of the humanoid in each condition. Our results show first person visual feedback and congruent visuo-audio feedback to be sufficient for embodiment of the moving robot. Interestingly, participants 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 partial and delayed control typical of humanoid robots.**

I. Introduction

Recent humanoid robots are increasingly required to function as human surrogates in real life environments like after a disaster as in the Darpa Robotics Challenge [1], social interactions [2] [3], or for the assistance of the elderly [4]. Embodiment of the robot by the human driver in such teleoperation scenarios is crucial for the quality of their social and physical interaction with their environment [5] [6]. We define embodiment or, more specifically, mediated embodiment, as the technologically induced illusion of adopting an artificial body in which one perceives to be located [7]. Due to the large degrees of freedom of a humanoid system and the complexity of the environments, most of the scenarios require hybrid control where the robots are partially controlled by human drivers, who either control particular levels of the control, for example task choice decisions [8], or particular degrees of freedom of the robot [9]. Furthermore, the control can include latencies or delays such that there is a time lag between a driver command and the robot action. It is however unclear whether partial controllability and delays affect the sense of embodiment of the humanoid robot avatars. We examined this issue in this article.

The sense of embodiment is believed to be composed of the sense of self-location, sense of body ownership and sense of agency [10]. 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 embodiment began with the rubber hand illusion experiment [11] in which the authors showed that participants develop ownership of a fake rubber arm when provided with synchronous visuo-tactile stimulations. Since then, several studies have examined embodiment of not just individual artificial limbs [12] but also the entire body [13], [14]. Other studies have assessed the influences of the body ownership and self-location on the sense of embodiment. For example in [15], participants were observed to disown their body after experiencing an illusory displacement of their sense of self-location.

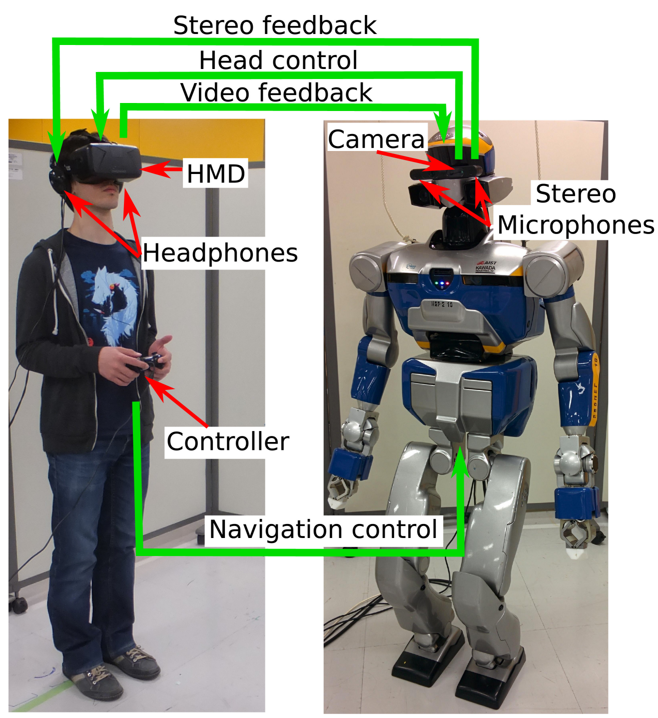

Fig. 1: Description of equipment used in the experiment.

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 embodiment. On the other hand, they have shown that first person vision in the presence of multisensory congruencies are enough to induce embodiment. Agency is known to increase embodiment when the control is precise [16] but

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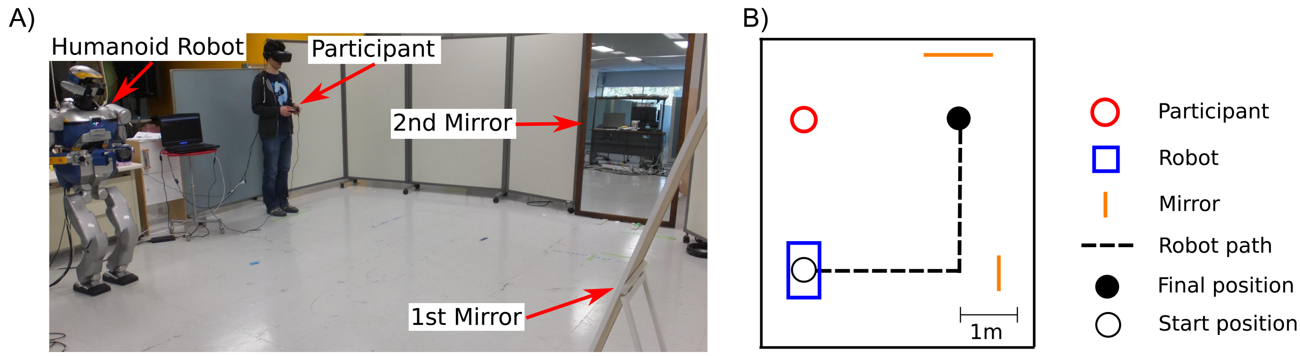

Fig. 2: View of the experiment set-up.

it is not clear how partial control and reaction delays affect embodiment. Delays in sensory stimulation have been previously shown to be disruptive for the sense of ownership [17], 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 [18]. However, as far as the authors know, 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 investigated how partial and delayed control of a humanoid surrogate during whole body motions (specifically bipedal locomotion) influences the feeling of embodiment. Specifically we asked three questions:

1) *Can first person vision and multi-sensory (visuo-auditory) congruency induce a sense of agency towards a moving humanoid robot surrogate even when the movements are not controlled?*
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 participants embodied a humanoid robot, namely HRP-2, shown in Figure 1, by getting 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 were not able to 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. Furthermore, the joint speed and balance constraints of the whole body robot controller introduced a delay between the commands issued by the participant and the robot response. The delay was observed to be between 0.5 to 2 seconds depending on the phase of the gait cycle a (turn, start or stop) command was issued.

II. Method

A. Participants

Our study included 13 participants (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 participants were naïve to the purpose of the study. Participants read and signed an informed consent form and received 1500JPY to participate. Working in the robotics or neuroscience field was used as exclusion criteria. In addition, the experiment was pretested with 5 volunteers. The study was conducted with ethical approval of the *National Institute of Advanced Industrial Science and Technology (AIST) in Tsukuba, Japan*.

B. Procedure

After signing the consent form, participants completed a survey containing basic demographic information (age, gender, field of work or study), videogame playing habits, and likeability of and familiarity with humanoid robots. The participants then embodied an HRP-2 unit. For this, they wore a head mounted display (HMD) [19] which gave visual feedback from the robot's eyes (camera mounted on the robot's head). They received audio feedback through a pair of headphones from a stereo microphone placed on the robot's head, like seen in Figure 1.

The participants 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 human participant and facing the same direction as the participant such that the participant was out of its field of view as seen in Figure 2.A.

The participants started the experiment by answering three questions of the *embodiment questionnaire* (see section II-D) 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 walk an L-shaped path twice (shown in Figure 2.B). In the first trial, subjects did not control the robot's walk and only held a fake joystick in their hands. In the second trial, participants controlled the walking direction of the robot using a joystick [20] and were asked to follow the same L path indicated by markings on the floor. Participants used two different buttons on the joystick to control the robot: the guide button was used as an start / stop motion and the directional pad was used to walk straight, turn left, and turn right. Any verbal instructions provided to the participant were provided by talking to the robot, such that the participant 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 through its own camera. The participants then went on to the main experiment which again consisted of a robot control condition and a non-controlled condition. In the experiment conditions the participants thus received a visual feedback of their walk (the sway in the visual feedback due to the walk and their reflection in the mirror) 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, participants 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 participants 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 0.5s and 2s. In the non-control condition, participants again held a joystick but were not able to control the walk or the head movement. Participants 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. The robot again followed the same L-shaped path while the participant saw the robot reflected in the mirrors through its eyes[a].

The robot movement in both conditions started by looking left and right (In the controlled conditions, the participants were instructed to perform these head movements). Followed by which, the robot walked straight towards the first mirror. After spending few seconds there, the robot turned left and walked towards the second mirror. When the robot arrived at the second mirror, it stopped completely and the participants were shown and 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. Participants 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, after which 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 participants.

C. Robot framework

The Robot Operating System (ROS) [21] was used to integrate the HMD, joystick controller and robot's camera. To make the humanoid walk, we used the walking pattern generator from [22], which receives the desired speed and computes the corresponding desired foot positions utilizing the stack of tasks controller (SoT) [23]. In the SoT, the 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 as 0.1 m/s throughout our experiment.

D. Measures

A 3-item embodiment questionnaire was designed to measure sense of embodiment in the humanoid body. The questionnaire was designed to be responded *in situ* during the experiment, when participants were seeing their robot's body in front of the mirror through the HMD. It contained three questions, one for each of the sub-dimensions of embodiment: body ownership, self-location, and agency [10]. 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 $= .000$.

III. Results

We calculated Mean and SD for body-ownership, self-location, and agency, as well as for the average of the embodiment scale (See Table I). We ran paired-sample T-tests in which we compared the levels of embodiment before and after the experiment to make sure that the illusion of embodiment was produced. Levels of embodiment were statistically significant both for control ($t(11) = -4.284$, $p = .007$) and non-control conditions ($t(11) = -3.335$, $p. = .001$).

Next paired-samples T-test were conducted to compare embodiment in the (robot) controlled and non-controlled conditions (see Figure 3 and Table I). Results showed that being able to partially control the robot (M $= 4.59$, SD $= 1.37$) did not generate significantly different embodiment than when the robot was not controlled (M $= 4.31$, SD $= 1.75$);

[a]In the main experiment, participants continued further in the task until completing a U path. The last part of the experiment observed a different variable than the one examined on this paper which is not reported here.

n=13	Control M(SD)	No-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 I: Means and SD for global embodiment and its subcomponents for control and non-control conditions.

$t(12) = -.744$, $p = .471$. 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; $t(12) = -1.036$, $p = .321$.

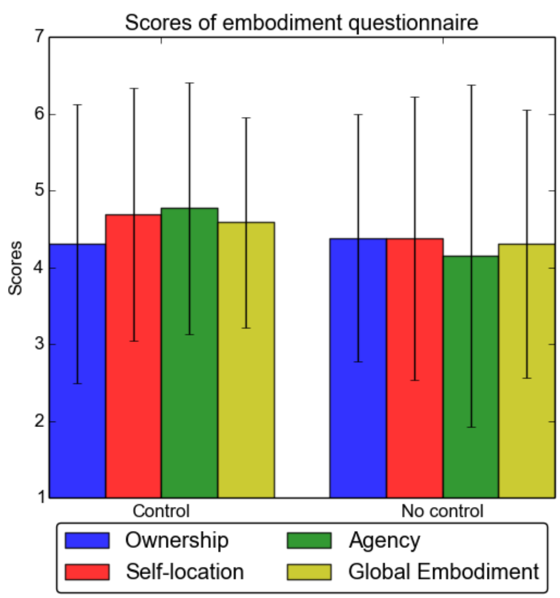

Fig. 3: Graph of the means and SD for global embodiment and its subcomponents for control and non-control conditions.

IV. Conclusion and Discussion

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

In our study, participants used a joystick to control the movement direction of the robot. We define this control as partial because the participants do not control individual robot joints. We chose this scenario of partial control over a scenario where participants 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 in the participants. Interestingly, we observed that the embodiment 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 conditions. This suggests that in our experiment the sense of agency was an illusion caused by the embodiment resulting from the visual and auditory feedback. This result, that partial control is neither better nor worse than no-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.

On the other hand, our results certainly do not imply that control is irrelevant to the feeling of embodiment. As with individual limbs, *good control*, in terms of movement correspondence between the avatar and the driver, would also probably help in the whole embodiment of moving robot avatars. However, our results and others [24] [25] suggest sensory correspondences to be more critical for embodiment. Future studies need to investigate how embodiment to moving robot avatars change with different sensory feedbacks in order to recognize the best sensory modes for optimal embodiment.

Acknowledgment

This work was supported in part by the European Union with the Marie Curie Fellowship HumRobCooperation No PIOF-CT-622764 and the FP7 Integrated Project VERE No. 257695. We also thank Prof. E. Yoshida for his support in the ethical procedures.

References

[1] D. T. T. Office, “DARPA Robotics Challenge,” 2012.
[2] S. Nishio, H. Ishiguro, and N. Hagita, “Geminoid: Teleoperated android of an existing person,” *Humanoid Robots: New Developments*, no. June, pp. 343–352, 2007.
[3] K. Kaneko, F. Kanehiro, M. Morisawa, K. Miura, S. Nakaoka, and S. Kajita, “Cybernetic human HRP-4C,” *2009 9th IEEE-RAS International Conference on Humanoid Robots*, pp. 7–14, Dec. 2009.
[4] W.-Y. G. Louie, D. McColl, and G. Nejat, “Acceptance and Attitudes Toward a Human-like Socially Assistive Robot by Older Adults,” *Assistive Technology*, vol. 26, no. 3, pp. 140–150, 2014.
[5] S. Nishio, K. Taura, H. Sumioka, and H. Ishiguro, “Effect of social interaction on Body Ownership Transfer to teleoperated android,” in *Proceedings - IEEE International Workshop on Robot and Human Interactive Communication*, pp. 565–570, 2013.

[6] H. Kose-Bagci, E. Ferrari, K. Dautenhahn, D. S. Syrdal, and C. L. Nehaniv, “Effects of Embodiment and Gestures on Social Interaction in Drumming Games with a Humanoid Robot,” *Advanced Robotics*, vol. 23, no. 14, pp. 1951–1996, 2009.

[7] L. Aymerich-Franch, “Mediated embodiment in new communication technologies,” *in Khosrow-Pour, M. (Ed), Encyclopedia of Information Science and Technology, 4th Edition, Hershey, PA: IGI Global, in press.*

[8] S. M. Goza, R. O. Ambrose, M. a. Diftler, and I. 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*, vol. 6, no. 1, pp. 623–629, 2004.

[9] K. Ogawa, S. Nishio, K. Koda, K. Taura, T. Minato, C. T. Ishii, and H. Ishiguro, “Telenoid,” in *ACM SIGGRAPH 2011 Emerging Technologies on - SIGGRAPH ’11*, pp. 1–1, 2011.

[10] K. Kilteni, R. Groten, and M. Slater, “The Sense of Embodiment in Virtual Reality,” *Presence: Teleoperators and Virtual Environments*, vol. 21, no. 4, pp. 373–387, 2012.

[11] M. Botvinick and J. Cohen, “Rubber hands ’feel’ touch that eyes see.,” *Nature*, vol. 391, p. 756, Feb. 1998.

[12] W. A. IJsselsteijn, Y. A. de Kort, and A. 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*, vol. 15, no. 4, pp. 455–464, 2006.

[13] V. I. Petkova and H. H. Ehrsson, “If I were you: Perceptual illusion of body swapping,” *PLoS ONE*, vol. 3, p. e3832, Jan. 2008.

[14] S. Nishio, T. Watanabe, K. Ogawa, and H. Ishiguro, “Body ownership transfer to teleoperated android robot,” *Social Robotics*, pp. 398–407, 2012.

[15] A. Guterstam and H. H. Ehrsson, “Disowning one’s seen real body during an out-of-body illusion,” *Consciousness and Cognition*, vol. 21, no. 2, pp. 1037–1042, 2012.

[16] A. Kalckert and H. H. Ehrsson, “Moving a Rubber Hand that Feels Like Your Own: A Dissociation of Ownership and Agency,” *Frontiers in Human Neuroscience*, vol. 6, no. March, pp. 1–14, 2012.

[17] M. R. Longo, F. Schüür, M. P. M. Kammers, M. Tsakiris, and P. Haggard, “What is embodiment? A psychometric approach,” *Cognition*, vol. 107, no. 3, pp. 978–998, 2008.

[18] M. Rohde, M. Scheller, and M. O. Ernst, “Effects can precede their cause in the sense of agency,” *Neuropsychologia*, vol. 65, pp. 191–196, 2014.

[19] V. R. Oculus, “Oculus rift DK2-virtual reality headset for 3d gaming,” *URL: http://www.oculusvr. com*, 2012.

[20] Microsoft, “Microsoft Xbox 360 Wired Controller,” *http://www.xbox.com/en-US/xbox-360/accessories/controllers*, 2010.

[21] M. Quigley, K. Conley, B. Gerkey, J. FAust, T. Foote, J. Leibs, E. Berger, R. Wheeler, and A. Mg, “ROS: an open-source Robot Operating System,” *Icra*, vol. 3, no. Figure 1, p. 5, 2009.

[22] A. Herdt, H. Diedam, P.-B. Wieber, D. Dimitrov, K. Mombaur, and M. Diehl, “Online Walking Motion Generation with Automatic Footstep Placement,” *Advanced Robotics*, vol. 24, no. 5-6, 2010.

[23] N. Mansard, O. Stasse, P. Evrard, and A. Kheddar, “A Versatile Generalized Inverted Kinematics Implementation for Collaborative Humanoid Robots: The Stack of Tasks,” in *Int. Conf. on Advanced Robotics ICAR*, no. 8, 2009.

[24] M. Slater, B. Spanlang, M. V. Sanchez-Vives, and O. Blanke, “First person experience of body transfer in virtual reality.,” *PloS one*, vol. 5, p. e10564, Jan. 2010.

[25] H. H. Ehrsson, N. P. Holmes, and R. 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*, vol. 25, pp. 10564–73, Nov. 2005.