Improving robot teleoperation experience via immersive interfaces

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***Abstract*—This paper investigates approaches capable of inducing sensations of tele-presence in robotic tele-operations. Operator's control actions are simpler, if he feels being in the remote environment. The goal is to replicate some conditions of the remote environment to let operator's perception behaviours approximate to the natural ones. Since immersion aims at providing stimulus to trick the sensory system, we pursue a consistency between outside sensory feedbacks and inside sensory proprioceptive, vestibular information and cognitive models. Seeking operations enhancement, we explore the embodiment concept by virtually place the operator inside the robot. This research develops and evaluates natural-based interfaces for immersive tele-operation. The results indicate a decrease in cognitive workload with gains in task performance.**

***Keywords*—teleoperation; telepresence; embodiment; immersion; human robot interaction; task performance evaluation.**

I. INTRODUCTION

Teleoperation of robots is common in fields such telemedicine, space and sea exploration, war zones, hazards and unstructured environments. Operator's control actions can be simplified, if the operator feels immerse at the remote environment. Traditional interfaces for remote control, based on several displays and manual controls do not provide all types of perceptions, or enable natural actions, as would occur if the operator were really present in the remote environment. Although robot's motion can be commanded, monitored, and the environment observed through remote cameras, the traditional interactions setups require special attention to numerous controls compromising the task performance.

This paper presents solutions to improve robot's teleoperation experience through immersive interfaces. We propose means to induce sensation of being inside the robot at the remote environment, i.e. tele-presence and physical embodiment. By letting the operator perceive the environment, as being there, with his own body, he can act more naturally, maximizing the task performance and minimizing the related physical and cognitive workload. Just like as driving a car where the person has a natural egocentric view, is aware of car's structure and space, and feels his actions on his own body.

One of the relevant elements for telepresence is the natural interaction, the involvement of common sensory and motor organs, enabling an implicit interaction in the remote environment [1]. All the sensory information must be in conforming with our mental models, to enable navigation in the environment and establish the relation between our body and the world.

Researchers found that the perception of motion, the perception of space and its use, shapes the human interaction [2]. Requirements to enhance user's immersion and sense of presence in teleoperation systems, includes motion and whole-body based interactions [3][4][5]. Human's space and motion perception depends not only on visual perception, but also on vestibular system, proprioception and cognitive processes [2][6]. Proprioception system enables humans to sense the relative geometry of body parts, and to sense the muscle's effort used for a movement [7]. Thus, interaction become possible based on the knowledge of body configuration, motion, constraints and spatial structure of the environment. Spatial perception ability (SpA) enables people to move safely and handle objects in a 3D environment [8]. Related research shows improvements in task performances for operators with higher SpA [9][10][11]. Memory psychology points out that spatial awareness states depending only on visual imagery involve higher attentional processing than those supported on familiarity [12]. All sensorimotor information cues, enable humans to mentally register objects around, customize action schemas, manipulate, navigate in the environment and establish the relation between his body and the world [13][14][1]. Literature reviews discuss and classify the factors affecting teleoperation performance on manipulation and remote perception such as camera viewpoint, restricted field of view (FOV), poor video images, depth perception, frame rate, robot attitude, orientation, motion and communications time delay [15]. Proposed solutions to improve performance refer how important are input control and multimodal displays [16][17].

Our approach focus on providing an egocentric controlled point of view, a broaden field of view and a whole-body control interface. This option is consistent with related work on influence of the viewpoint in workload and telepresence [18][19]. This paper is organised as follows: *Section II* describes the proposed method for immersive visual feedback and natural approaches for robot's control. *Section III* presents experiments, to find out the influence of several tele-operation interaction styles. The goal is to evaluate how natural interaction contributes for the user to perceive the remote agent form as his own body. Quantitative analysis of task performance is carried out, followed by a subjective questionnaire, involving

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several participants in a driving task. Finally, *Section IV* presents the results and conclusions.

II. EXPANDING LOCAL OPERATION TO TELEOPERATION

The manipulation of objects, assembling them from parts, folding them, or simply organising them, are operations that humans do with such simplicity, that describing how we do, is not always a trivial task. Gestures learned, during a training process, are automatically performed, requiring little supervision. We often hear people saying that could do it with eyes closed, and that is frequently true as they can prove it. But by not using the eyes, people concentrates on the other senses, and in most situations take longer to do it as the eyes need to be replaced by the sense of touch for instance. In these cases the hands, and even the arms are used to search the workspace for tools, objects, components, and analyse them to see which is the good position and or orientation to use them.

Now, lets consider the situation where a person that is quite skilled to do some operation with their own hands must do the same thing but using some plier or other tools, e.g. eating for the first time with chopsticks. There is no interference with the visual process, but instead it is the touch experience that is constrained, and even if the tool does not present any kind of grip problem it may be hard to use it at first.

Both in direct handling or in the manipulation via some tool, we frequently adjust the viewpoint with respect to the task being execute. Especially when the objects are fixed, we tend to move our head (and eyes) to one side, or to the other side to better perceive the properties or configuration of the objects, or to try to infer about the best way to accomplish the task. As we advance through an environment, we look primarily along the movement direction, but also in other directions, and eventually use the hands to touch the objects or structures that we must go around, or simply to localise ourselves with respect to some characteristic locations, like a particular door, angle on the wall, etc. It helps in the mental processes of following a path while verifying that we are going in the right direction and avoiding the obstacles. This does not imply that we are constantly looking at, or touching these elements, in reality during this process, we mentally predict how their position changed w.r.t. ourselves as we move, we can say that we have a sense (of their) presence. This plays a very important role in our activities as, even if our dead reckoning system and kinesthetic perception are very inaccurate, they are confirmed/corrected by frequent verifications through vision and touch, to enable our predictive execution of these tasks to be performed with minimal effort. When it is not possible to rely on these predictive mechanisms, then a much bigger effort is demanded from our senses as then need to constantly scan for the presence any unpredictable obstacle, feature, or threat.

A. Line of sight remotely controlled devices

This presents new difficulties as the operator needs to learn how to control the device, e.g. a car model, but sees it evolving through some kind of bird eye view. This differs from the above in two aspects: first the operator looses, for instance, the perception of the acceleration that, for a car driver, complements the visual information, to predict the behaviour of the vehicle. But, may still listen to the sounds than may give important information, for example in the teleoperated car the engine noise is related with acceleration and speed.

B. Out of sight remotely controlled devices

These class of devices are the most difficult but very important, given the range of applications that they can be used for. Besides the inherent technical problems, the restrictions in the perception that an operator experiences may compromise the execution of the task, or reduce enormously the scope of applications that may be addressed with such approaches. In many situations a set of sensors are used to capture information, that is somehow represented on a display device available to the operator, and this is the only source of information that he/she may have to accomplishing his mission or task. Good examples are underwater remotely operated vehicles that typically equipped with several sensors, including cameras, barometers, sonars, etc., whose information is displayed across several screens at the teleoperation site. This requires specially trained operators, able to interpret all that information and fuse it into some mental model that possibilitates the necessary reasoning to operate the device. This is an unnatural process that imposes a substantial mental workload, resulting on the fatigue of the operator increasing the possibility of introducing faults that may or may not result in damages.

Aiming at reducing the human errors, and having analysed the main cognitive processes associated with the teleoperation processes, we may now focus on a more egocentric proposal as a solution for this problem.

C. A telepresence-based proposal

The proposed solution virtually incorporates the human operator into a remote agent. This person located in the "operator site" can act in a "remote site", either controlling the motion of this agent or monitoring its position evolution. He is part of the control loop and his perception involves an immersive visualization device to centralize all sources of information while disposing of egocentric view like the real one. The requirements are that control actions and perception information flows must be synchronous and consistent with the real ones. The operator develops an intention to move and the remote agent mediates his orders. Either using a local mechanism with his hand or through gestures or via his body pose. These actions are then translated into agent's position commands and the resulted sensory feedback matched with a desired goal.

First Person View (FPV): The visual input is controlled egocentrically, enabling a view centered on the remote camera, synchronized with operator's head direction. It is a primary approach for inducing the feeling of being embodied into the robot. Basically, the operator sees through the robot disposing of an active first-person view. With this mechanism, whenever the operator looks left-or-right, up-or-down, the remote pan-and-tilt unit (PTU) reproduces these head movements, pointing the remote camera to equivalent directions. Thus, the operator can perform natural visual behaviors through the robot, like ”scan the space”, ”search for an object”, ”track a moving target”, or simply look to his own body parts, now represented by the robot. The operator gets an egocentric perception of the distant environment just as if he was really there, at the position and direction of the robot.

1) Deictic gesture-based control of the robot: Seeking for new natural strategies to tele-control a mobile robot, different to the standard joystick, the present research proposes a gesture-based framework. The operator must perceive that his gestures are a mean to control his own motion, just as if he was moving in the remote environment. The consistency between gestures, proprioception and visual feedback, enables us to explore the physical embodiment sensation. The perception of movement, body actions and robot's space restrictions towards the user to perceive the structure of the robot as his own body. If achieved, the operator will feel inside the robot, as being the robot, and his pointing gestures will command his movements in the foreign environment. The operator expresses his motion's intention through deictic gestures (Fig. 1), i.e. the mechanism involves mapping gestures into robots control commands for angular and linear velocities. This system can identify pointing commands to move back, move forward, turn left, turn right, just like giving position orders to a dog. A 3D skeleton-like model, with 17 joints, based on a Kinect® sensor, enables the mapping of these gestures. The angular velocity Ω, results from the angle's relation between operator's arm and his body sagittal plane. Similarly, linear velocity V (backward and forward velocity) is obtained from operator's arm angle with his coronal plane eq. (1).

$$V = \left(\frac{RS_Z - RH_Z}{\|RS - RH\|}\right) V_{max} \qquad \Omega = \left(\frac{RS_X - RH_X}{\|RS - RH\|}\right) \Omega_{max} \tag{1}$$

where RS_Z means Z coordinates of right shoulder, RH_Z means Z coordinates of right hand, RS the 3D coordinates of right shoulder and RH the 3D coordinates of right hand.

2) Body intention-based control of the robot: We introduce another method of controlling the movements of the robot centered on body expressed intentions, like driving a hoverboard. The user's body posture is used to express motion directions (Fig. 2). For example, placing one foot forward means walking in front while rotating shoulders means turn right or left. A square mark on the floor helps us to relate both feet at a given position. The linear velocity V, derives from the displacement of the advancing foot with relation to the rest position, and the shoulder's rotation determine angular velocity Ω, eq. (2).

$$V = \left(\frac{MF_Z - RF_Z}{\|MF - RF\|}\right) V_{max} \qquad \Omega = \max\left(1, \left(\frac{LS_Z - N_Z}{LS_X - N_X}\right)\right) \Omega_{max} \tag{2}$$

where MF_Z means Z coordinates of moving foot, RF_Z means Z coordinates of the resting foot, MF the 3D coordinates of the moving foot, RF the 3D coordinates of right foot, LS_Z means Z coordinates of left shoulder, N_Z means Z coordinate of neck, LS_X means X coordinate of left shoulder, and N_X means X coordinate of neck.

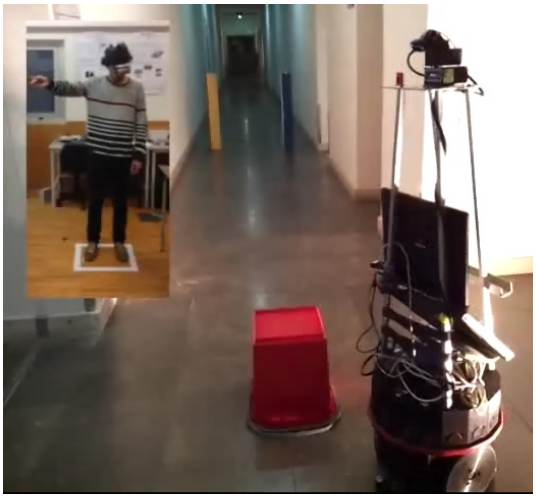

Fig. 1. Motion of the robot controlled using deictic gestures

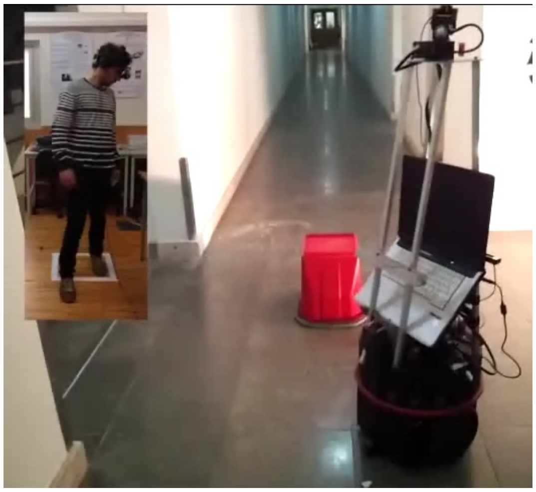

Fig. 2. Motion of the robot controlled using changes in the operator's body posture

III. EXPERIMENTS AND RESULTS

Feeling embodied in a tele-operated agent means acting naturally as no mediation exists. The goal is to evaluate how natural interaction contributes for the user to perceive the remote agent form as his own body. We test, in a real environment, the influence of several tele-operation interaction styles. Quantitative analysis of task performance is carried out, followed by a subjective questionnaire, involving several persons in a driving task. The mediation interfaces sets described as experimental setups 1, 2, 3 and 4, enabled comparison between natural and standard scan view strategies, and natural robot control styles like deictic gestures and body intention. These style interactions defined several combinations of screen monitor, joystick-based controller, RGB-D sensor and head-mounted display (HMD) with inertial measurement unit (IMU).

Architecture: Fig. 3 presents a flexible architecture designed to combine mixes of hardware and software modules involving the control station and the remote mobile agent. All commands and visual feedback streams are based on wireless TCP/IP communications.

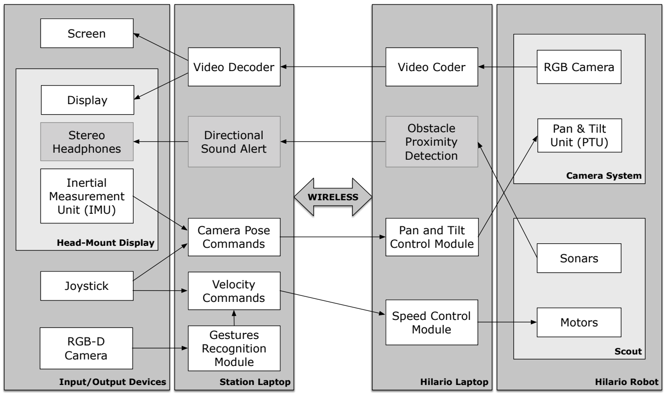

Fig. 3. Architecture of control station and the remote mobile agent

A. Experimental Design

Aiming to assess the influence of natural interaction and the illusory perception of robot as the operator's body, four tele-operation experiments were designed. The effect of *embodiment* and *first person view* on task performance was compared. The tasks consisted on tele-navigate a robot through a remote path (Fig. 4) without colliding with obstacle and as fast as possible. The participants performed the same tasks using the four setups enabling comparisons between natural and standard scan view strategies, natural robot control styles based on deictic gestures and body intention, joystick based.

The developed interaction setups are:

- **"joysticks + monitor":** Setup 1, orientation of the remote camera and motion of the robot controlled through two joysticks
- **"joystick + HMD":** Setup 2, orientation of the remote camera controlled by operator's HMD orientation, and motion of the robot controlled using one joystick
- **"deictic gesture + HMD":** Setup 3, orientation of the remote camera controlled by operator's HMD orientation, and motion of the robot controlled using deictic gestures

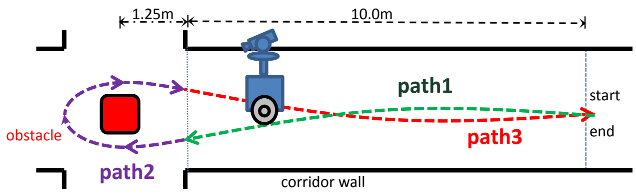

Fig. 4. Task path divided in 3 section (path 1, path 2 and path 3) with one obstacle (red box).

- **"body intention + HMD":** Setup 4, orientation of the remote camera controlled by operator's HMD orientation, and motion of the robot controlled using changes in the operator's body posture

In all instances the operators were standing while driving the robot. In Setup 1, the participants observed the remote video scene stream through a lcd monitor, and in Setups 2, 3 and 4, the video was displayed through the HMD.

Procedure: The experiment involved thirteen participants (11 male, 2 female), mainly graduate and undergraduate students of Coimbra University, with a age mean of 26.46 years and standard deviation of 5.03. The researchers informed the volunteer participants about the involved procedures and the purpose of the experiments. It was explained that the goal of the experiment was tele-operate the mobile robot, circumvent an obstacle without colliding, and finish the task in the shortest time period. While they performed the tasks, using the referred interaction styles, observers counted the obstacle hits and measured the execution times. Finally, they filled a short subjective questionnaire.

IV. RESULTS

As explained above, this research compared the task performance measures and the satisfaction of the participants. We recorded, for each interface, the task's time execution and the number of obstacles collisions. The trajectory of the robot was divided into 3 sections (path 1, path 2, path 3) with different levels of difficulties. This approach enabled us to distinguish variation in performance related to initial adaptation, use of certain devices and interaction mechanism learning.

Fig. 5 presents the performance mean times (seconds) and standard deviation for the 3 trajectory segments while using the 4 setups.

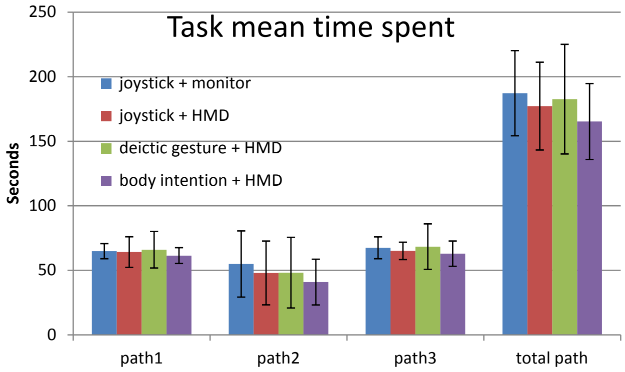

Fig. 5. User's task execution mean time using different teleoperation experimental setups (in seconds).

Fig. 6 depicts for "path2", the performance mean times (sec) to turn around obstacle for the four setups (data outliers removed). The ANOVA (analysis of variance) test was applied and we mark with an asterisk when the results are statistically significant ($F_{3,32} = 0.46$, $p = 0.71$).

Fig. 7 shows for "path2", the performance mean times (seconds) to turn around the obstacle using "joystick + monitor"

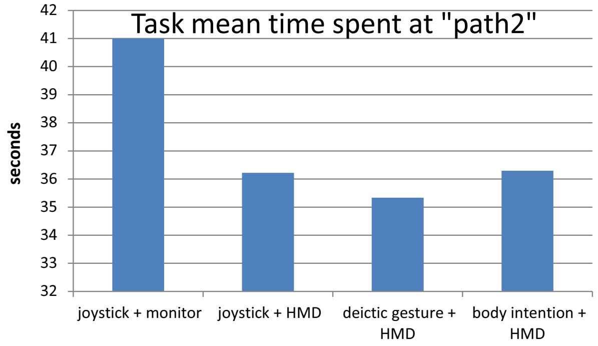

Fig. 6. User's task execution mean time at "path2" (seconds) to turn around obstacle (data outliers removed)

vs "body intention + HMD" ($F_{1,24} = 2.62$, $p = 0.11$), and the mean number of collisions occurred ($F_{1,24} = 5.55$, $p = 0.02^{*}$).

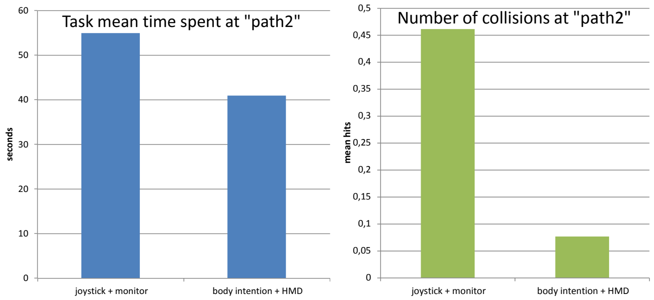

Fig. 7. Users mean time spent to perform the task at "path2" (left) and mean number of collisions (right) while turning around the obstacle, with "joystick + monitor" vs "body intention + HMD".

The feedback questionnaires used a 7 point Likert scale, which contends followed IBM Computer Usability Satisfaction Questionnaire [20]. Users scored their experiences concerning different motion control interfaces and different visual feedback models, and wrote some comments. Subjective issues like usability, easiness, consciousness, embodiment feeling, and time perception. The answered questions were:

- Q1 - It was intuitive to use.
- Q2 - It was easy to learn.
- Q3 - I could get enough visual feedback.
- Q4 - I felt embodied on the robot while performing the task.
- Q5 - I completed the task quickly.

Fig. 8 resumes the obtained scores. Bellow, the ANOVA analysis points out the statistically significance of all questions:

- Q1 - $F_{3,44} = 8.03$, $p = 0.00022^{*}$;
- Q2 - $F_{3,44} = 4.84$, $p = 0.0053^{*}$;
- Q3 - $F_{3,44} = 10.19$, $p < 0.0001^{*}$;
- Q4 - $F_{3,44} = 19.11$, $p < 0.0001^{*}$;
- Q5 - $F_{3,44} = 5.5$, $p = 0.002^{*}$

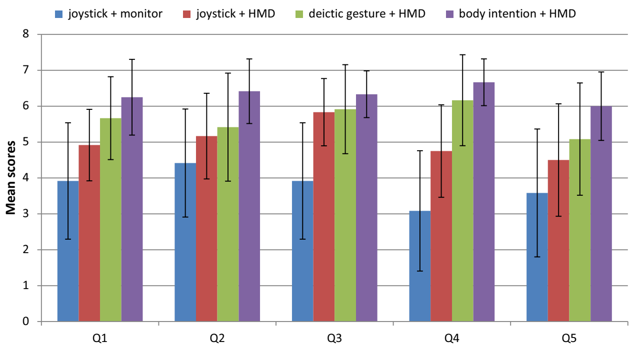

Fig. 8. Mean scores from user questionnaire feedback, scale : 1- Strong Disagree to 7-Strong Agree

1) Discussion: Quantitative results indicate that when users controls the point of view of the remote camera through their head's pose, there is an improvement in task performance. As the visual behavior resembles a natural exploration and the hands are free, the cognitive workload tend to decrease. This new visual strategy is built in setup 2, 3 and 4. When the operator is required to control the orientation of the remote camera and the robot's motion, with their hands on the joysticks (setup 1), he takes more time. Setup 1 mean times for section 1 - 65s (σ=5.9), section 2 - 55s (σ=25.6) and section 3 67s (σ=8.5)

The visual feedback control model, implemented in setup 2, outperforms setup1 in all three sections: μ=64s (σ=11.8), μ=48s (σ=24.7), μ=65s (σ=6.7). The evidence is more significative in path 2 section. There, the operator have to scan the environment, be aware of robot's size and parts, and plan a trajectory to circumvent the obstacle. Due limited field of view and visual feedback delays, the path section 2 trajectory must be anticipated mentally by the operators. The use of HMD cleared improved the time performance. The number of collision with the obstacle registered in setup 2 were less than in setup 1 (4 vs 6). When inquired about gains in visual feedback (question Q3), operators expressed their high scores in setups 2, 3, and 4 (μ=5.83, μ=5.92 μ=6.33), in opposition to traditional setup 1 (μ=3.92).

The natural deictic gestures used to control the robot (setup 3) showed gains in task performance in comparison with setup 1. Once again, in path 2 section, where operator requires higher skills: (setup 1 path 2: μ=55s (σ=25.6) vs setup 3 path 2: μ=48s (σ=27.4)). Operators traversed path 2 faster using setup 4, although setups 2 and 3 had similar times (setup 4 path 2: μ=41s (σ=17.7), setup 2 path 2: μ=48s (σ=24.7) and setup 3 path 2: μ=48s (σ=27.3)).

Body intention-based robot control, that is, setup 4, was the preferred interface in all questions, while quantitive measures confirmed these results (μ=61s (σ=6.1), μ=41s (σ=17.1) and μ=63s (σ=9.7) to accomplish path 1, 2 and 3). Note that σ of setup 4, in path 2 were smaller than in any equivalent section setups, demonstrating operator's performance regularity in this section. All operators felt comfortable and easier operating the mobile robot with their shoulders. In setup 4, *body_intention+HMD*, almost no one collided with the obstacle placed in path 2.

Questionaries showed that natural interaction styles are intuitive (setup 3 μ=5.6 and setup 4 μ=6.2) and setup 4 it is easy to adapt (μ=6.4). Since visual feedback model controller was identical in setups 2, 3, and 4, participants have scored with similar higher values of (μ=5.8, μ=5.9, and μ=6.3). The embodiment feeling appears associated with the implementation of the natural interaction styles (setup 3 and 4). Operators tough they perform faster while using deictic "gesture + HMD" and "body intention + HMD", even when quantitative results might not express that. An explanation for this might arise from the fact that the operator feels immersed in their task.

User's comments expressed their difficulties in looking down due vertical limited field of view. Unseeing the robot body and the ground simultaneously difficult the perception of the robot size. It compromises the task of turning around the obstacles or passing through a door. Blank walls without features diminish the depth perception. Communication delays affecting commands execution was pointed as a negative factor. Issues addressing the field of view (FOV) are presently solved by an enlarged FOV, either with the use of wide angle lens, either with carefully camera positioning (avoiding occlusions with robot parts).

External observers detected operator reactions to a critical event like behaviors as if they were really in the remote environment. In crash situation, the operator's body contracts or tries to step away from the control station. Operators felts the wall proximity. The perspective from a first person view (FPV) might stimuli primary survival mechanisms.

V. CONCLUSIONS

This research suggests that, when an operator has an egocentric perception of the remote environment, and has the ownership illusion toward the remote agent's body, apparently substituting their own, occurs autonomic reactions that corresponds to the real one experienced in the distant place. Natural and immersive teleoperation styles lead to higher embodiment sensations with gains in task performance. Acting as being in remote environment simplifyes the mental transformation processes involved in navigation, such motion and space perception. Operator seems to agree, and experiments confirm, that the active visual feedback based on head's pose control and robot body motion-based decreases their cognitive and physical workload. Future work includes the involvement of new senses exploring auditory and force feedback.

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