Towards natural interaction in immersive reality with a cyber-glove *

L. Almeida[1,2], E. Lopes[1], B. Yalçinkaya[1], R. Martins[1], A. Lopes[1], P. Menezes[2], and G. Pires[1]

***Abstract*— Over the past few years, virtual and mixed reality systems have evolved significantly yielding high immersive experiences. Most of the metaphors used for interaction with the virtual environment do not provide the same meaningful feedback, to which the users are used to in the real world. This paper proposes a cyber-glove to improve the immersive sensation and the degree of embodiment in virtual and mixed reality interaction tasks. In particular, we are proposing a cyber-glove system that tracks wrist movements, hand orientation and finger movements. It provides a decoupled position of the wrist and hand, which can contribute to a better embodiment in interaction and manipulation tasks. Additionally, the detection of the curvature of the fingers aims to improve the proprioceptive perception of the grasping/releasing gestures more consistent to visual feedback. The cyber-glove system is being developed for VR applications related to real estate promotion, where users have to go through divisions of the house and interact with objects and furniture. This work aims to assess if glove-based systems can contribute to a higher sense of immersion, embodiment and usability when compared to standard VR hand controller devices (typically button-based). Twenty-two participants tested the cyber-glove system against the HTC Vive controller in a 3D manipulation task, specifically the opening of a virtual door. Metric results showed that 83% of the users performed faster door pushes, and described shorter paths with their hands wearing the cyber-glove. Subjective results showed that all participants rated the cyber-glove based interactions as equally or more natural, and 90% of users experienced an equal or a significant increase in the sense of embodiment.**

I. INTRODUCTION

Virtual and immersive reality (VR) are technologies that can find many applications that go far beyond gaming, in areas such as rehabilitation, real estate promotion, education and medical training, museum exhibitions, showrooms, simulation of accident scenarios, police training, social training, etc. The potential of adapting any space to a dynamic new virtual world in which the user can move in, opens a whole of new challenges related to immersion. The effectiveness of VR environments strongly depends on providing the same stimuli as those experienced in the real world. In order to enhance user's immersion, embodiment and presence [1][2][3], we need to support a natural consistency between the vestibular and proprioceptive feedback in addition to the visual feedback, while enabling a precise tracking of body parts [4]. Interaction based on active movements contributes for the "sense of agency", that is, the sense of having "*global motor control, including the subjective experience of action, intention, control, motor selection and the conscious experience of will*" [5].

There are several low-cost commercial VR systems available that provide an effective user experience in large spaces (e.g., HTC Vive, Oculus Rift S), with a very reliable body tracking. For user interaction with VR, most systems use hand-based controllers with click buttons and inertial sensors. However, the interaction is not always perceived as natural, because while users hold these controllers they cannot grab or touch real objects in a mixed reality interaction, or it compromises the embodiment in virtual reality interaction. In a previous paper [6] we explored the notion of telepresence and physical embodiment. The aim was to virtually transfer the operator to the remote robot to improve teleoperation, maximizing task performance and minimizing the operator's physical and cognitive workload. One of the system's limitation was the lack of hand interaction with objects. Although human body parts were mapped through a skeleton representation, the hands and fingers were not tracked, compromising the manipulation tasks. Recent approaches based on glove systems can help achieve a more natural user interaction, freeing user's hands, allowing the detection of finger movements, haptic feedback and gesture recognition [7][8][9][10]. Cyber-gloves open a new range of applications in gaming, industry, surgery training, rehabilitation and education. Gloves with haptic feedback are being proposed for hand and finger rehabilitation [11][8], or surgery training [12]. These glove–based systems aim to provide feedback to the users to enable the perception of virtual objects. Several technological approaches to this problem have been proposed in literature, which include: the use of force sensitive resistors combined with vibro-tactile actuators to provide force feedback to the user [8]; fingertip contact pressure sensors, capable of providing vibratory and visual stimulation [11]; or twisted string actuation integrating force sensors and small-size DC motors [13]. The use of bend sensors and IMU (inertial measuring unit) is also commonly used to track, respectively, fingers and hand position and orientation [11]. The use of cyber-gloves for gaming is proposed in [14] and [15]. The work in [15] describes an exoskeletal VR glove that tracks the user's physical finger movement, and is capable of translating the movement to virtual fingers in a game environment. Haptic feedback is provided by attaching motors to each finger joint. A VR glove for falconry is proposed in [14], which is intended to give the player the illusory sensation of a falcon standing

*This work was supported by the project HTPDIR - Human Tracking and Perception in Dynamic Immersive Rooms, POCI-01-0247-FEDER-017644, {SketchPixel, IPT, UC} and developed at Lab. VITA.IPT - Life Assisted by Intelligent Environments, Tomar, Portugal

[1]Polytechnic Institute of Tomar, 2300 Tomar, Portugal. {laa, anacris, gppires}@ipt.pt, {elioclopes, berilyalcinkayaa, vanheelsing.martins}@gmail.com

[2]Institute of Systems and Robotics, University of Coimbra, 3000 Coimbra, Portugal. paulo@isr.uc.pt

Original paper published in:
Luis Almeida, Elio Lopes, Beril Yalçinkaya, Rodolfo Martins, Ana Lopes, Paulo Menezes, and Gabriel Pires,
"Towards natural interaction in immersive reality with a cyber-glove",
2019 IEEE International Conference on Systems, Man, and Cybernetics (IEEE SMC 2019), 06-09 October Bari, Italy.

in their hand. All of these approaches are prototypes and yet lack the desired usability and wearability combined with reliable exteroceptive perception, which makes user interaction still not very natural.

In this paper we propose a cyber-glove to improve the immersive sensation and the degree of embodiment in virtual and mixed reality interaction tasks. In particular, we are proposing a glove system that can track wrist movements, hand orientation and finger movements. Most VR systems do not provide a decoupled position of the wrist and hand, although actual hand manipulation tasks require that these two movements are independent. Thus, the perception of these two different degrees of freedom significantly increases the embodiment perception in all kind of hand interaction tasks, for which the joint between the hand and the wrist is not rigid. Furthermore, the curvature angle of the fingers is detected, supporting an effective perception of finger movements. Cyber-glove has features comparable to other commercial products such as CyberGlove III [16]. However, the cost of the cyber-glove prototype is significantly lower (a few hundred of US dollar versus more than $10K). Additionally, our device has longer autonomy and enables a direct contact of the palm of the hand with objects. It has also a heart rate sensor and a range sensor on the back of the hand that detects nearby obstacles, alerting the user with a vibro-tactile stimulation. The system is being tested in a virtual environment where users have to perform interaction tasks such as grab and rotate door handles, push or pull drawers. We compare the naturalness, usability, immersion and embodiment perception using the developed cyber-glove and the HTC hand trackers. These interaction tasks are part of a global set commonly used by a person when exploring a real house. This work is being developed in the scope of a major project (called HTPDIR) in partnership with a company that aims to do real estate promotion. The tests aim to understand how gloves can improve user interaction with the house being visited.

II. The System – Immersive room testbed

The present application builds a VR immersive scenario based on Unity 3D providing egocentric visualization and interaction. It is being developed targeting mixed reality applications where real objects are dynamically mapped in the VR scenario through several Kinect RGB-D sensors [17]. This paper is only focused on the design and development of an immersive cyber-glove and its use in VR environments that include manipulation tasks.

A. Immersive cyber-glove – hardware architecture

The immersive glove detects wrist, hand and finger movements with the purpose of complementing the immersive tracking system. The absolute position of the wrist is tracked with HTC Vive trackers, while the hand and finger movements are tracked with our own customized glove (see Fig. 1). The hardware architecture is shown in Fig. 2. The glove prototype is composed of the following modules: an IMU Sensor (BNO055) with ARM Cortex M0 incorporated,

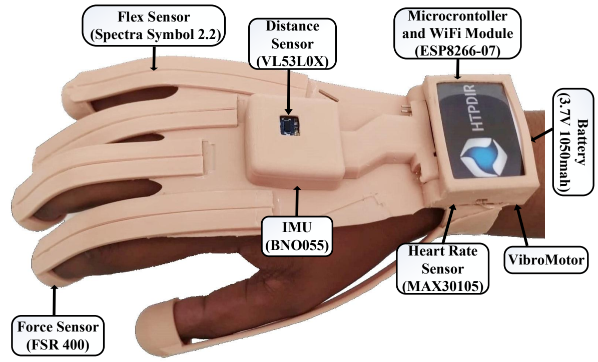

Fig. 1. Photo of the developed cyber-glove prototype (HTPDIR). Description of main hardware components integrating the cyber-glove.

an wi-fi module ESP8266-07 with a Tensilica Cadence L106 embedded microcontroller, a PPG sensor (MAX30105) that is responsible for detecting the heart rate (that can be used to evaluate emotional reactions), a micro-laser range sensor (VL53L0X) responsible for measuring the distance to physical obstacles, 5 Flexible sensors (Spectra Symbol 2.2) that sense the curvature angle of the fingers, 5 force sensors (FSR 400) that provide touch information in mixed reality interaction, a vibro-motor that is actuated when the back of the glove is near a physical obstacle (for safety reasons) and a LiPo battery (BAT525). The BNO055 is a system in a package, that integrates a triaxial accelerometer, a triaxial gyroscope, a triaxial geomagnetic sensor and a 32-bit microcontroller. It merges the accelerometer, gyroscope and the magnetometer within 9 degrees of freedom, returning an absolute orientation with a high throughput without distortion of the magnetic field. The microcontroller of the ESP8266-07 module receives via I2C the data from BNO055, namely the rotation in quaternions and the acceleration data in x, y, z coordinates. The ESP8266-07 also interfaces all the remaining analog, digital and I2C sensors, computes the heart rate, and sends to BNO055 its initial configuration settings. The wi-fi module of the ESP8266 sends all glove's data in UDP/IP packets to the Unity application running on the host PC that does the data processing and visual rendering. To prolong the battery autonomy of the cyber-glove, several sensors were programmed to be in "sleep mode" whenever they are not being used. In normal operating mode the cyber-glove power consumption is about 95 mA, while in "sleep mode" it is about 30 mA. The minimum duration of the battery in the normal operating mode is approximately 8 hours. The glove was designed in SolidWorks and printed in a 3D printer Sigma using FilaFlex material, a very resistant and flexible material (elongation at break – 665%) that provided a good hand fit sensation. The palm of the hand is free which is quite important for the mixed reality experiments.

B. Immersive environment - Unity 3D

Each task and effect created in the virtual environments is based on various Unity scripts and GameObjects. The script that interacts with the glove receives all the data via

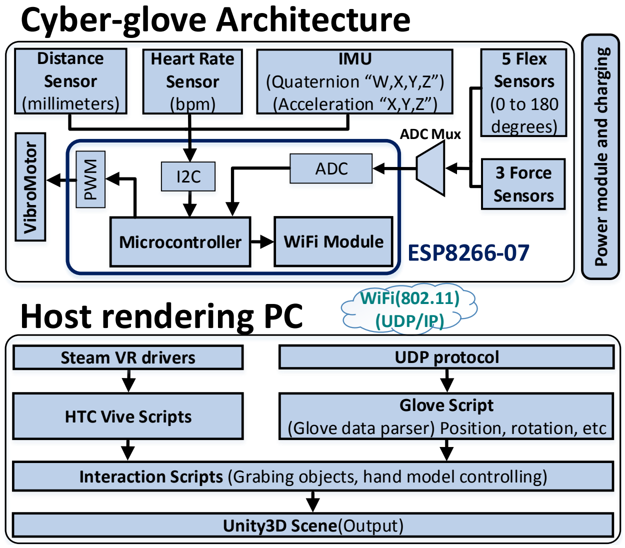

Fig. 2. Cyber-glove and 3D Unity framework architecture.

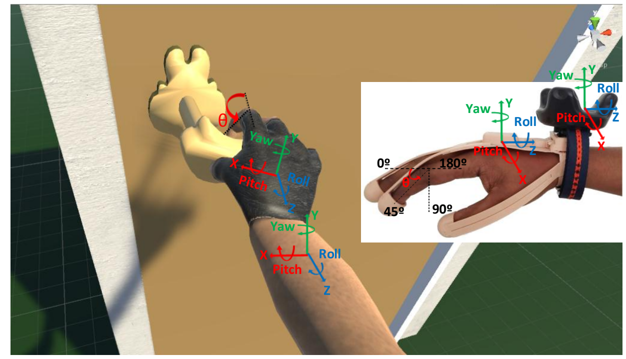

Fig. 3. Picture of the immersive scenario during a hand manipulation task: door handle rotation. Reference systems of hand and wrist in the immersive environment from an egocentric view, and respective reference systems of the cyber-glove and wrist tracker in real world.

UDP packets every 20 ms, namely, angular position of the hand, acceleration, range sensor distance, heart rate, fingers curvature, pressure feedback, and sends commands to actuate the vibro-tactile motors that provide haptic feedback to the user. These data are forwarded to specific scripts attached to each object to be manipulated. The hand's script receives the quaternions to animate the hand model (see Fig. 3). This hand model is attached to the wrist position detected by the HTC Vive Tracker. The wrist reference system $\{x,y,z\}_{wrist}$ has 6-DoF to which the hand reference system $\{x,y,z\}_{hand}$ is attached, having 3-DoF (roll, pitch, yaw). The reference system $\{x,y,z\}_{hand}$ is a translation of $\{x,y,z\}_{wrist}$ along the z-axis. Additionally to 3D position, we get linear acceleration values for each coordinate. Fingers curvature values are obtained from flexible sensors that return a bending angle in a range of 0^{o} to 180^{o} and feed a Unity's Hinge Joint component that couples two rigid GameObjects. This enables a rotation along one of the common axis, reproducing prehensile gestures. In the extremity of each finger there is a force feedback sensor to inform the VR application that thumb and index finger are touching each other (i.e. a gesture event) or that the fingers are in contact with a real object. Interaction with objects is managed through scripts that parents the object to the hand on pickup. The attachments between objects can be rigid or use a Joint to integrate force feedback for the physics engine. These scripts also define the pick-up and release methods. When a hand and finger models are in contact with virtual objects, the respective Collider triggers the vibrotactile motors to simulate the real touch feedback. The heart rate sensor provides information that can be used to assess the user's engagement and for example change the application dynamics.

For this experiment, a virtual door scenario was created to compare the performance of the cyber-glove and the HTC Vive Controller. Two input methods were implemented to open the door: the "DoorViveController" method that enables door opening using the HTC Vive Controller and the "DoorGlove" that refers to the door being opened by the cyber-glove. In "DoorViveController" the user presses a controller's button to grab the door's handle while in "DoorGlove" the user closes/opens his/her hand (fingers) to grab or release the door's handler. Both door-opening methods use the parenting concept to rotate the door's handle and relies on a Hinge Joint. A "Quaternion.LookRotation" method enables the rotation of the door's handle regarding to the hand position. For the "DoorGlove", hand's position results from a translation of the wrist position, provided by Vive Tracker, however their orientations can be independent (see Fig. 3). For the "DoorViveController", the hand and wrist are a rigid body with position and orientation provided by the HTC Vive controller.

The door's handle rotation is computed using the EulerAngles method and it is limited to predefined angles. Consequently, the script that rotates the door is enabled only if the door's handle rotation reaches a predefined angle. After the rotation of the door handle, the position of the hand is used to compute the door's rotation angle. This component is attached to the door frame through a Hinge Joint, which enables a rotation along a vertical axis.

To create a fully VR environment that integrates real objects of the room, we also developed a support framework that relies on HTC Vive controllers to pinpoint the object's corner coordinates.

III. Method

The evaluation of virtual or mixed reality applications requires an analysis of factors like naturalness, usability, immersion, embodiment and task performance, which can be assessed through user's actions such as VR 3D navigation and manipulation. This section describes the proposed evaluation methodology for this VR application and devices.

A. Participants

Twenty-two participants (7 women and 15 men) from the Polytechnic Institute of Tomar were invited to test the system. Participants were mainly students and researchers from engineering courses. Participants were aged between 20 to 46 years old (μ=26.56 , σ=6.66). Participation in the experiment was voluntary. Four of the 22 participants never had contact with video games technology and only 3 subjects had previous experience with interaction devices like the proposed cyber-glove.

B. Materials

Users viewed the virtual and the mixed reality environment through a head mount display (HMD), which is a fully immersive reality helmet that presents three-dimensional stereoscopic views. The HMD is part of the Vive VR System having two AMOLED screens, a resolution of 1080 x 1200 pixels per eye (2160 x 1200 pixels combined), a refresh rate of 90 Hz and a field of view of 110 degrees. Internal inertial sensors (accelerometers and gyroscope) and an outside-in laser tracking system provided user's head position and orientation to render the virtual world accordingly. User's hand movements and gestures were tracked either through HTC Vive controllers, or through a wrist-tracker strapped around the wrist. These trackers, when attached to a real object provided also its position. Additionally, the cyber-glove enabled the mapping of the movements of the wrist, hand and fingers in the immersive environment.

C. Experience design

One of the applications of this work is real estate promotion with virtual enviroments. A typical task commonly performed at home has been designed, *a person crosses the several divisions of a house and for this he/she has to open a door and pass through it*. One of the focus was on the embodiment and realism of the movement of the hand during the handle rotation, for which the detection of movement of the wrist and hand are essential. This simple task comprises a series of small steps that people are used to do in the real world. However, the recreation in the virtual environment presents some technological challenges. Thus we have designed a virtual door and a metaphor to transpose it. Each person, wearing a VR HMD system that provides an egocentric view, was invited to perform the following door opening based sub-tasks (see Fig. 4):

- A - Walk to the door
- B - Rotation of the door handle
- C - Push the door
- D - Pass through the door

These tasks were repeated by each subject 2 times:
1) holding the standard HTC Vive hand controller that has a click button interaction, and provides position and orientation. To grab the door's handle, the user had to press a button; and
2) wearing the developed cyber-glove, that frees the hand and enables grab functionalities. To grab/release the door's handle, the user had to close/open the hand (fingers).

Furthermore, qualitative and quantitative evaluations were performed, using the two hand-based input devices. Figure 5 shows a photo of a subject using the the cyber-glove while performing the immersive interaction task.

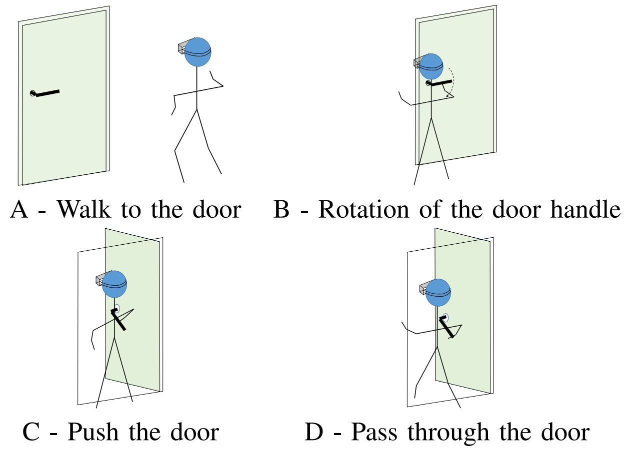

Fig. 4. Steps to open the door in the immersive environment.

D. Experiment procedure

Subjects were invited individually to the lab and informed about the procedure to open the virtual door. One of the project's researcher was in charge of helping the subjects to wear the equipment, and a software application recorded the performance measures during task execution. Each participant performed the task only once in each condition. No training was provided to better assess the intuitiveness of the solution. The experiments involving the HTC Vive controller and the cyber-glove were performed randomly and at the end, users filled subjective questionnaires.

E. Evaluation metrics

Qualitative and quantitative measures were accessed for the two different hand-based input devices:

1) Efficiency measures:

- Time - measures the time taken by a person to open a door and pass through it:
  - Total time: overall time to accomplish the task;
  - Sub-task time: measure the time taken by a person in each door opening tasks (A, B, C and D);
- Length - length of the path described by the hand in each sub-tasks (a shorter paths means less effort and better naturalness);

2) Immersion and presence: In order to evaluate the experience qualitatively, the subjects were invited to fill

Fig. 5. Photo taken at a national exhibition of a subject using the cyber-glove while performing the immersive interaction task.

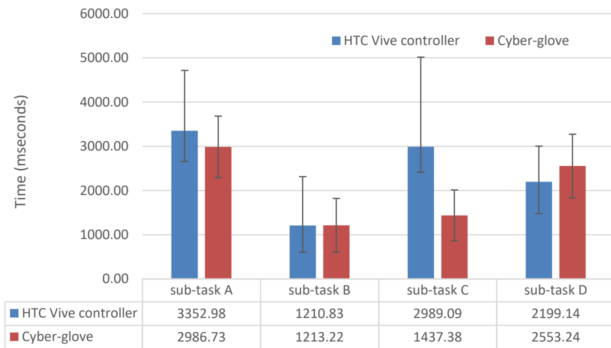

Fig. 6. Mean task-time performance of participants for each sub-task of the virtual door opening global task (HTC Vive controller vs cyber-glove).

a questionnaire on a scale from 1 to 7, where 1 meant *very weakly* and 7 *very strongly*, enabling to determine issues like naturalness (question Q1), usability (question Q2), immersion feeling (question Q3) and sense of embodiment (question Q4). These questions were adapted from IBM Computer Usability Satisfaction Questionnaire [18] and from Usoh and Slater Presence Questionnaire [19].

- Q1 - How natural was the interaction with the VR environment?
- Q2 - How easy was manipulating and moving objects in the VR environment?
- Q3 - How strongly was the immersion feeling in the VR environment?
- Q4 - Did I feel that my own hand was manipulating and moving objects in the VR environment?

IV. Results

A. Task Performance

1) Objective Results: Figure 6 shows the mean of task-time performances in each sub-tasks of the virtual door opening task, using the HTC Vive controller or the cyber-glove. Statistical significance was assessed using repeated measures (within subjects) ANOVA (analysis of variance) test (asterisk mark indicates statistically significant). Results show that in sub-task C users pushed the door faster wearing the cyber-glove ($p < 0.05$):

- sub-task A: F(1,22)=0.69, p=0.4156
- sub-task B: F(1,22)=4.34E-05 , p=0.9948
- sub-task C: F(1,22)=6.51, p=0.0181*
- sub-task D: F(1,22)=1.29, p=0.2680
- Total task-time : F(1,22)=1.59, p=0.2204

Figure 7 shows the mean length of the path described by the hand in each sub-tasks of the virtual door opening task, using the HTC Vive controller or the cyber-glove. Statistical significance was assessed using repeated measures ANOVA test:

- sub-task A: F(1,22)=0.014, p=0.9054
- sub-task B: F(1,22)=0.751, p=0.3952
- sub-task C: F(1,22)=9.012, p=0.0065*
- sub-task D: F(1,22)=1.781, p=0.1956
- Total task-length: F(1,22)=3.575, p=0.0718

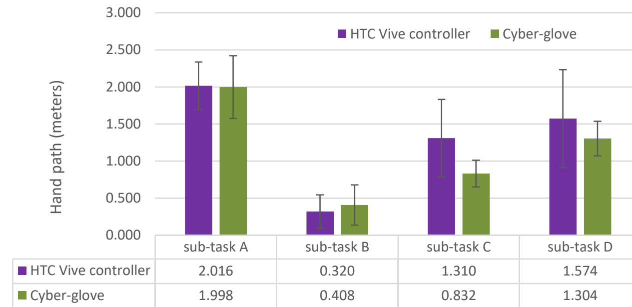

Fig. 7. Mean length of the path described by the hand of participants, for each sub-task of the virtual door opening global task (HTC Vive controller vs cyber-glove).

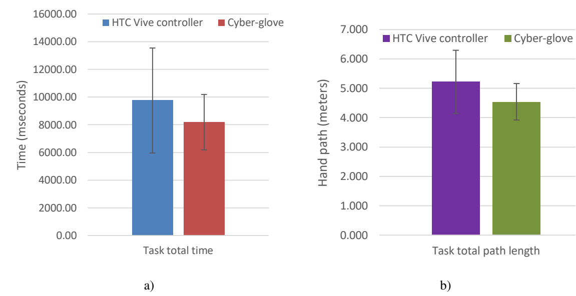

Fig. 8. a) Total mean task-time, and b) total mean length of the path described by the hand of participants while performing the virtual door opening global task, HTC Vive controller vs cyber-glove.

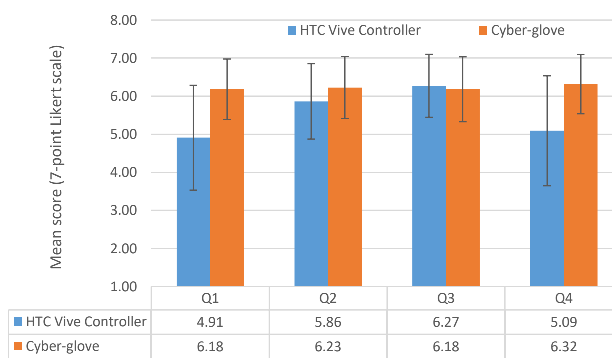

Fig. 9. Results of subjective questionnaires to participants to evaluate the virtual door opening task.

Metric results revealed that 83% of the users performed faster door pushes, and described shorter paths with their hands wearing the cyber-glove ($p < 0.05$).

In Fig. 8 we present the total mean task-time results, and the total mean length of the path described by the hand of participants. The time and length of the global task are smaller for the cyber-glove. The statistical significance test for the total path length presents a p=0.0718.

2) Subjective Results: Figure 9 illustrates the results of the questionnaire.

The within subjects ANOVA one-way test for each question shows its statistic significance (asterisk marks):

- Q1: F(1,42)=14.10, p=0.00052*
- Q2: F(1,42)=1.77, p= 0.19018
- Q3: F(1,42)=0.13, p=0.72144

- Q4: F(1,42)=12.29, p=0.00109*

100% of the participants rated the cyber-glove based interactions as equally or more natural, and 90% of users experienced an equal or a significant increase in the sense of embodiment.

B. Discussion

Objective results related with task-time performance in sub-task A ("Walk to the door") shows that there is not a significant time difference at reaching the door, neither there is any differences in the length of path described by the user's hand, i.e. the hand device does not influence this sub-task. Concerning the time performance in sub-task B ("Rotation of the door handle") the participants took the same time to perform this sub-task with both devices. Users with the HTC controller described a path slightly shorter than with cyber-glove while rotating the door's handle. According to our expectations and in relation to sub-task C ("Push the door"), users pushed the door to an angle of 60^{o} faster with the cyber-glove than with the HTC controller. The length of the trajectory described by the hand while wearing the cyber-glove was also shorter. Users reported that releasing the door's handler was easier with the cyber-glove because they just had to open the hand/fingers, and they were not concerned about the instant to release the HTC controller button. Thus, users performed sub-task C better with the cyber-glove, being both task-time and hand's length path statistically significant. Concerning sub-task D ("Pass through the door"), users were faster transposing the door's frame holding the HTC Vive controller than when they were using the cyber-glove, however they described a longer path holding the HTC Vive controller. For this sub-task, the start matches the moment when the user removes their hand from the door handler and moves himself to a certain distance from the door.

Qualitative evaluation based on questionnaires to the users shows that the cyber-glove contributes for a greater naturalness. Factors like usability and immersion feeling seem similar for both devices, and the sense of embodiment is significantly improved with the cyber-glove. Several participants reported orally that with the cyber-glove they had more freedom of movement, while with the HTC Vive controller they felt hand movement constraints, and were afraid of dropping the controller during the release of the door handle. Overall, the results of the ongoing cyber-glove prototype are very promising. Yet, some limitations were identified during the experiments, namely, the size of the glove is not suitable for every users due to different hand sizes, and the movement of the virtual fingers exhibits a small latency in relation to the real fingers movement, due the animation model.

V. CONCLUSIONS AND FUTURE WORK

This paper describes a cyber-glove system that tracks wrist movements, hand orientation and finger movements, aiming to improve the immersive sensation and embodiment in virtual and mixed reality environments. The proposed system is capable of decoupling the position of the wrist and hand, contributing for the sense of embodiment in 3D VR manipulation. The comparative study between the cyber-glove and the HTC Vive controller showed that the task-time performance of pushing a virtual door's, is faster when wearing the cyber-glove, and additionally the hand of the users describes shorter paths. The subjective questionnaires show that the cyber-glove contributes for a greater naturalness, present similar degrees of usability and immersion feeling, but improves significantly the sense of embodiment. Future work includes glove refining to better adapt to the different hand sizes, and improve VR models of the fingers. More complex tasks in virtual and mixed reality will be carried out to validate the overall system.

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