Self Representation and Interaction in Immersive Virtual Reality

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Abstract: Inserting a self-representation in Virtual Reality is an open problem with several implications for both the sense of presence and interaction in virtual environments. To cope the problem with low cost devices, we devise a framework to align the measurements of different acquisition devices used while wearing a tracked VR head-mounted display (HMD). Specifically, we use the skeletal tracking features of an RGB-D sensor (Intel Realsense d435) to build the user's avatar, and compare different interaction technologies: a Leap Motion, the Manus Prime haptic gloves, and the Oculus Controllers. The effectiveness of the proposed systems is assessed through an experimental session, where an assembly task is proposed with the three different interaction mediums, with and without the self-representation. Users reported their feeling by answering the User Experience and Igroup Presence Questionnaires, and we analyze the total time to completion and the error rate.

1 INTRODUCTION

In current Virtual Reality (VR) applications, the visual feedback of the user's body is often missing, despite the abundance of enabling technologies, which could be used for its implementation. The drawback of these technologies is mainly the high cost, in fact they are not so used in practice except by big companies.

This paper considers the problem of constructing a self-representation in VR and finding a stable, reliable and affordable solution that can improve the sense of presence of the users in the virtual environment. The aim of our work is to devise a general framework that sets up different VR systems, which combine the most commonly used VR headsets (e.g. the Oculus Rift and the HTC Vive), devices to capture the full body (e.g. off-the-shelf RGB-D devices, like the Intel Realsense d435), and technologies to represent the hands and the fine movement of the fingers, such as the Oculus controllers, the Leap Motion and the Manus Prime haptic gloves.

The importance of the user's avatar is studied comparing the proposed systems with and without the self-representation of the user (i.e., the avatar). The focus is to develop a framework that is compatible with the most common head-mounted displays (HMDs), and that can also be extended to other tracking devices, both for the body tracking and for the hands and fingers tracking.

This would be extremely helpful in many applications, such as training of people or simulation of specific situations (e.g. medical, first-aid, rescue), where the use of avatars of the users would result in a much more immersive scenario, thus increasing the quality of the realism of the application.

To address the self-representation in VR, we propose to fuse the data acquired by an RGB-D camera and an HMD with a hand-tracking device, to reconstruct an accurate avatar of the users. Such an avatar not only moves in a coherent way with the user, but also has a good representation of the hands and the fine movement of the fingers to allow interaction inside the virtual environment. Some authors have already addressed the problem of fusing information acquired by an RGB-D camera and the Leap Motion: e.g. in (Chessa et al., 2016) the authors set up an affordable virtual reality system, which combines the Oculus Rift HMD, a Microsoft Kinect v1, and a Leap motion, to recreate inside the virtual environment a first-person avatar, who replicates the movement of the user's full-body and the fine movements of his/her fingers and hands. Here, we generalize

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that idea by developing a framework that allows us to combine different off-the-shelf devices to obtain immersive VR systems with a self-representation of the user, who is experiencing the VR environment.

2 RELATED WORKS

In the current market, there are several solutions that allow us to build an avatar of the user. The first one uses the Inverse Kinematics (IK) to dynamically reproduce natural body movements via six data points acquired by the headset, which represent the position of the head, the controllers that represent the position of the hands and some trackers, two positioned on the feet and one on the pelvis (Roth et al., 2016; Caserman et al., 2019). IK generates an accurately proportioned virtual human skeleton, and seamlessly re-targets and synchronizes the users' motion to the bones of the chosen avatar. Other approaches use motion capture suits and systems (Rahul, 2018; Takayasu et al., 2019), such as those used for animation in films and games (Bao et al., 2019). Both of these solutions are not easily accessible for everyone, thus we would like to build a cheaper systems.

In the literature, people extensively investigate the role and the impact of a self-representation in VR. There are studies that focus on the process of embodiment of a self-avatar. When embodied within a self-avatar, in some ways the user treats it as own actual body, resulting in the so-called "body-ownership illusion". This shows that the virtual body has an impact on how the person reacts to virtual stimuli (Yuan and Steed, 2010). As an example, there are studies investigating how people judge distances (Ries et al., 2008), thus walking (Canessa et al., 2019; Reinhard et al., 2020), or how embodiment affects presence (Steed et al., 2016). Another important aspect is that the use of self-avatars can invoke psychological effects on user arousal, attitudes, and behaviours in virtual environments. Some of these behaviours and attitudes may extend beyond the interaction in the virtual environment influencing judgments or behaviours in the real world (Biocca, 2014). Also, the presence of a self-avatar improves the interaction with the surrounding virtual environment and simplifies motor-related tasks (Slater et al., 1995). Furthermore, in a shared virtual environment (SVE), the use of a self-representation would allow the users to communicate through their own body, as in reality, with other users (Pan and Steed, 2017). In that case, the use of a personalized avatar (i.e. a mesh that better represent the human figure) significantly increases the body ownership, agency, as well as the feeling of presence as explained in (Waltemate et al., 2018). Consequence of all these effects is the increase of the sense of presence inside the virtual environment.

3 MATERIALS AND METHODS

3.1 Sensor Fusion and Reference Frame Alignments

In this paper, to align the reference frames of the used devices for building the self-representation of the user we follow the method proposed by (Chessa et al., 2016). Before the alignment phase, the data acquired by the different sensors are referred to the sensors' reference frame, thus the resulting components of avatar are not perceived by the user in a first-person perspective as in Figure 1(a). It is worth to note that we use a simple avatar, i.e. a skeleton, since we are mainly interested to the alignment of the reference frames and thus to the related effectiveness of the interaction in VR, than the graphical representation of the body.

To align the data of all sensors, the alignment phase is divided into two steps:

- Rigid transformation, computed just once, among common points from the sensors.
- Live correction to overcome the residual offset present between the avatar body and the hands module.

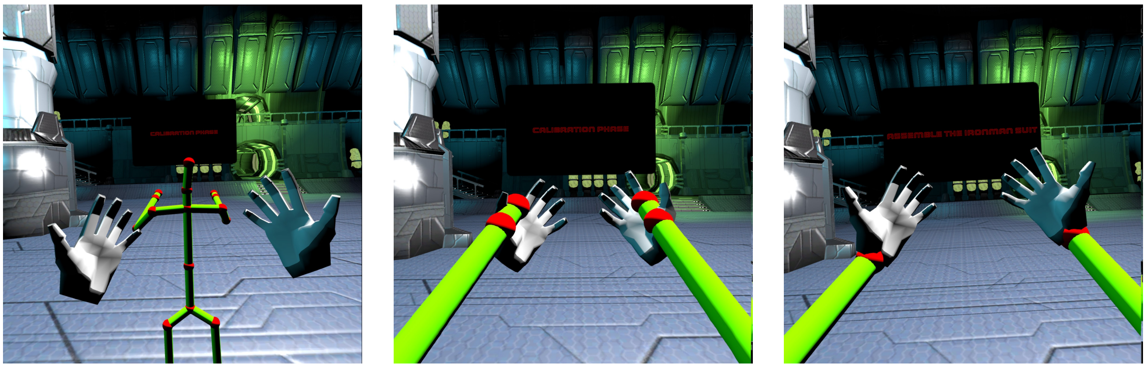
3.1.1 Rigid Transformation

This first step allows us to align the data coming from the different sensors. We use the least-square rigid motion using the Singular Values Decomposition (SVD) technique (Sorkine, 2009) to compute the rigid transformation between two sets of points (Eq. 1).

$$(\overline{R},\bar{t}) = \underset{R,t}{\operatorname{argmin}} \sum_{i=1}^{n} |(Rp_i + t) - q_i|^2 \qquad (1)$$

where:

- R is the rotation matrix between the two sets of points, called P and Q, and $\overline{R}$ the computed estimate.
- t is the translation vector between the centers of mass of the two sets of points, called P and Q, and $\bar{t}$ the computed estimate.
- $P = \{p_1, p_2, \ldots, p_n\}$ are the VR system samples, acquired by the HMD and the hand detection device.



(a) (b) (c)

Figure 1: Reference frame alignment. (a) The body and the hands representations are in their own reference frames (different also with respect the first person view). (b) The head, body and hand reference frames are aligned. (c) The head, body and hand reference frames are aligned and residual errors corrected.

- $Q = \{q_1, q_2, \dots, q_n\}$ are the RGB-D camera samples.
- n is the number of samples.

To properly align the different reference frames of the sensors (i.e. “to move” P towards Q), several correspondences between them are required. In our case, we have some common joints tracked by both the RGB-D camera and the HMD with one of the technologies for the hands and fingers detection: i.e. the head, the palms and the wrists. Nevertheless, the result of the rigid transformation, carried out for a single set of common points (i.e. one sample), often leads to have a visually incorrect alignment. This means that the user does not perceive the avatar as superimpose to his/her body. This can be due to multiple factors, in particular to:

- co-planar points among the common joints selected,
- noise on the points detected by the sensors.

To overcome this problem, we decided to take more samples in time as explained in (Chessa et al., 2016): we take in consideration 5 common points each frame and 500 samples over time. Furthermore, during this step, the user have to move his/her arms up and down, keeping attention that both are tracked by the sensors, to increase the robustness of the tracking. After this step, the result is a partial alignment of the reference frames (i.e. the avatar with the real body of the user), as shown in Figure 1(b).

3.1.2 Live Correction

The second step to obtain a fine alignment between the user and the avatar is to perform a run-time correction. To have a unique body structure (i.e. natural body structure), which shows a continuity between the hands tracked by the Controllers or the Leap Motion and the rest of the body tracked by the RGB-D camera, we have to better fuse the data coming from the different sensors. In particular, we decided to use the position of the wrists acquired by the two technologies used for hand detection, since they are much more precise with respect to the RGB-D camera detection of the wrists. This allows a better alignment of the forearm with the hand. The result of this step is shown in Figure 1(c).

3.2 Hardware Components

The device used for Virtual Reality is the Oculus Rift CV1 [1]: it has an estimated field of view of 110 degrees, a resolution of 2160 × 1200 pixels, and a frame rate of about 90Hz. It contains several sensors, such as the accelerometer, the gyroscope and magnetometer, which are used, together with the infrared constellation, to track the user position and movements.

To manage the data flow from the different sensors simultaneously, we used a machine with the following specifications: a PC equipped with graphics card NVIDIA GeForce GTX 1080, processor Intel(R) Core(TM) i9-8950 @ 2.90 GHz, 32 GB of RAM and as operating system Windows 10 Home 64 bit.

The user body is detected and tracked by an RGB-D camera, specifically developed for tracking, the Intel Realsense d435 [2]. As skeletal tracking SDK, we used Nuitrack [3], a 3D tracking middleware developed by 3DiVi Inc. This software gives information about 19 joints of the user body. Even if this SDK is paid for, we decide to use it due to the wide range of RGB-D camera supported such as Kinect v1, Asus Xtion,

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[1] https://www.oculus.com/rift/

[2] https://www.intelrealsense.com/

[3] https://www.nuitrack.com/

Intel RealSense, and all the other devices on the market.

For the detection and tracking of the hands and the fine movements of the fingers, we used three devices:

- The standard controllers that come along with the HMD we have chosen. The tracking technology is the same of the considered system, i.e. the infrared constellation of the Oculus Rift controllers.
- The Leap Motion [4] device that captures each hand with two 640 × 240-pixel near-infrared cameras and fits the data with a model of the hand. Thus, based on image stereo pairs, it can compute the 3D position of each finger and of the center of the hand. It has a good accuracy and a field of view of $140^\circ \times 120^\circ$, but since it is based on image processing, the measurements are affected by occlusions and noise due to illumination, thus it cannot be used in any environmental condition. In our setup, we attached the Leap Motion device to the headset.
- The Manus Prime haptic gloves [5] that have 3 main components. One is the haptic feedback that is transmitted by linear resonance actuators on the fingertips, whose signals can be adjusted to different strengths for specific application scenarios. Then, mostly important for the system here presented, the hand tracking that is achieve by a HTC Vive tracker through the base station of the Vive system, and fingers tracking that is obtained by bending sensors fused with high-performance inertial measurement units. This, in principle, would ensure a permanently high quality of movement measurement, with a latency of 10ms. However, we will discuss in this paper some compatibility problems which emerged in our sensor fusion approach.

3.3 Software Components

The platform used to develop our solutions was Unity 2019.3.0f6 and Visual Studio 2019 as our IDE to code in C#. The main plugins used are: the SteamVR tool, so that our software is compatible with all the supported HMDs; Math.NET Numerics, to compute the SVD in the Alignment phase; and VRTK, the Leap Motion Unity module or the Manus plugins for Unity, to implement the interaction with the virtual objects based on the chosen technology.

To use the Oculus Rift HMD together with the Manus Prime haptic gloves, a further calibration is needed to align the Vive trakers reference frame, which is used by the Manus Prime haptic gloves, with the Oculus reference frame. To this aim we use OpenVR Space Calibrator [6], a software available on GitHub, which allows us to obtain the correct calibration.

4 EXPERIMENT

Participants. To validate the proposed method and the three developed systems, we performed an experimental session and collected data from 6 subjects (4 males, 2 females). The participants were aged from 20 to 55 (38.5 ± 16.7), and with normal or corrected-to-normal vision. All the subjects were novel to VR. Each subject performed all the experimental conditions in a randomize order to avoid learning or habituation effects.

Procedure. The experiment is performed as follows. Before starting, the experimenter shows how to properly wear the HMD, how to wear/use the given hand tracking device, and starts the simulation. The user's body inside the virtual scene is represented by small cubes for the joints, parallepipeds for the bones, and a 3D hand model for the hands.

The user has to perform the alignment phase, as explained in the previous sections, and then to complete the assembly task that consists of interacting and grabbing pieces of the Iron man suit to assemble it.

As the assembly task starts, several pieces of the superhero suit are on a table in scattered order. The user should grasp the pieces, and put them in a highlighted area, by following an arbitrary order. The pieces should be correctly oriented before attaching them to the suit. The task ends when all the pieces are correctly positioned.

At the end of the assembly task, the user removes the HMD and he/she is asked to fill the questionnaires.

Measurements. During the task, the total time to completion (TTC) and the number of time a piece of the suit falls from his/her hands, as error rate, are recorded. When the user finishes, he/she compiles the User Experience Questionnaire (UEQ) (Schrepp et al., 2014) and the Igroup Presence Questionnaire (IPQ) (Regenbrecht and Schubert, 2002). UEQ is a recent, fast and reliable questionnaire, which covers a comprehensive impression of the user experience, by considering both classical usability aspects (efficiency, perspicuity, dependability) and user experi-

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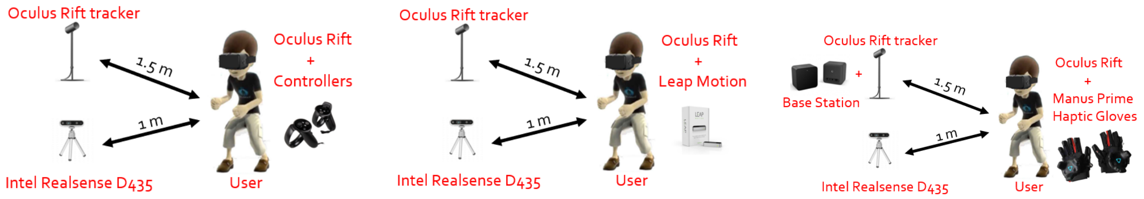
[4] https://www.ultraleap.com/datasheets/Leap_Motion_Controller_Datasheet.pdf

[5] https://manus-vr.com/.com/

[6] https://github.com/pushrax/OpenVR-SpaceCalibrator/



(a) (b) (c)

Figure 2: Arrangement of sensors with the 3 hand and fingers detection system. (a) Oculus Rift controllers. (b) Leap Motion attached to the headset. (c) Manus Prime haptic gloves, which needs the HTC Vive base stations.

ence aspects (originality, stimulation). IPQ is a scale for measuring the sense of presence experienced in a virtual environments.

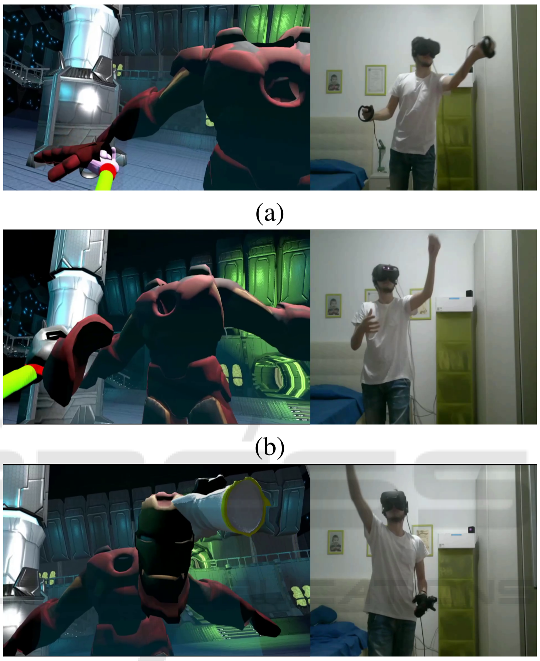
Conditions. We have implemented three different setups, depending on the interaction device utilized: controllers, Leap Motion, and Manus gloves. For each interaction device, we considered two conditions, one in which the full avatar is displayed, the other one in which only the hands are displayed. A problem of compatibility has emerged while using the Manus gloves with the avatar systems. In fact, the gloves are not stable if used with an RGB-D camera based on infrared light. The problem is caused by the IR light of the RGB-D camera that interferes with the Vive trackers. Therefore, the calibration lead to a bad alignment of the avatar and furthermore it is hard to complete the task. Thus, we decided not to take in consideration this condition, but only to use the gloves without the RGB-D camera, i.e. without the avatar. Figure 2 shows the arrangement of the sensors in the environment for the three conditions with avatar. The user stands in front of the RGB-D camera at a distance of about 1m wearing the HMD. The user is free to move over an area of about 1.5m^2 to interact with the 3D objects in the virtual environment.

In total, we tested 5 conditions: ControllersAvatar (Fig. 3(a)), ControllersNoAvatar, LeapAvatar (Fig. 3(b)), LeapNoAvatar, ManusNoAvatar (Fig. 3(c)).

5 RESULTS

Figure 4 shows the results of the UEQ. The average value of each scale (range between -3 and 3) and the associated standard deviations are shown for the 5 experimental conditions. To understand the results, we need to separately analyze each scale:

- *Attractiveness:* Due to the ease of interaction, the subjects seem to prefer the Controllers (mean score 2.53 both with and without avatar), then the Manus Prime haptic gloves (mean score 2.14) and then the Leap Motion (mean score 1.72 with avatar, 1.61 without).



(a)

(b)

(c)

Figure 3: Snapshots of 3 (out 5) experimental conditions, ControllersAvatar (a), LeapAvatar (b) and ManusNoAvatar (c). For each figure, on the left the first-person view of the VR scene, on the right the external view of the user in the real environment.

- *Perspicuity:* As expected, the Controllers are easier to learn (mean score 2.75 with avatar, 2.92 without avatar), than the Leap Motion though with a high standard deviation (1.63 ± 1.35) and the Manus Prime haptic gloves (1.46 ± 1.26).
- *Efficiency:* Due to the different types of interaction the three technologies provide, the task is solved easily by using the Controllers rather than with the Leap Motion (again with a high standard deviation 1.46 ± 1.39) and the Manus Prime haptic gloves.

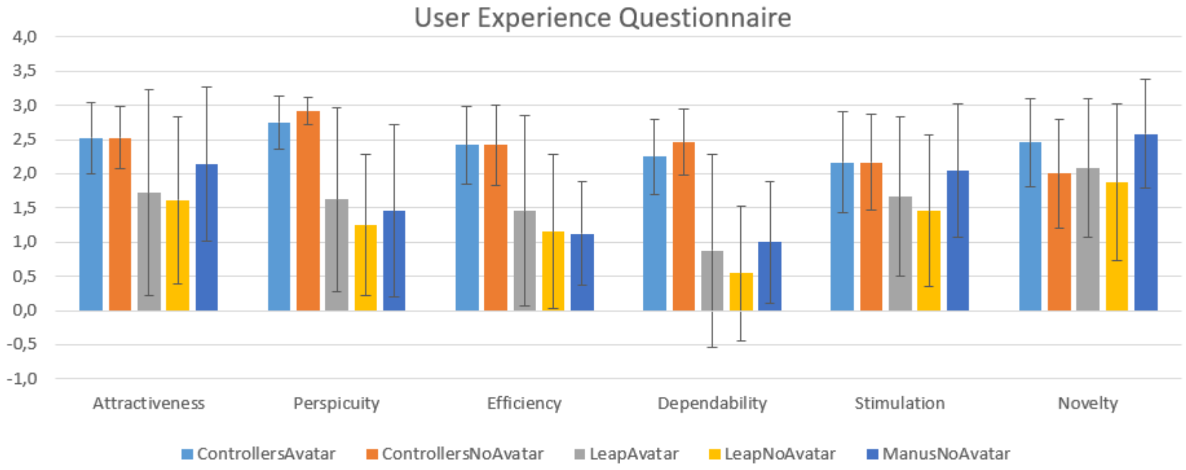


Figure 4: Results of the UEQ: mean values and standard deviations on a scale from -3 to 3.

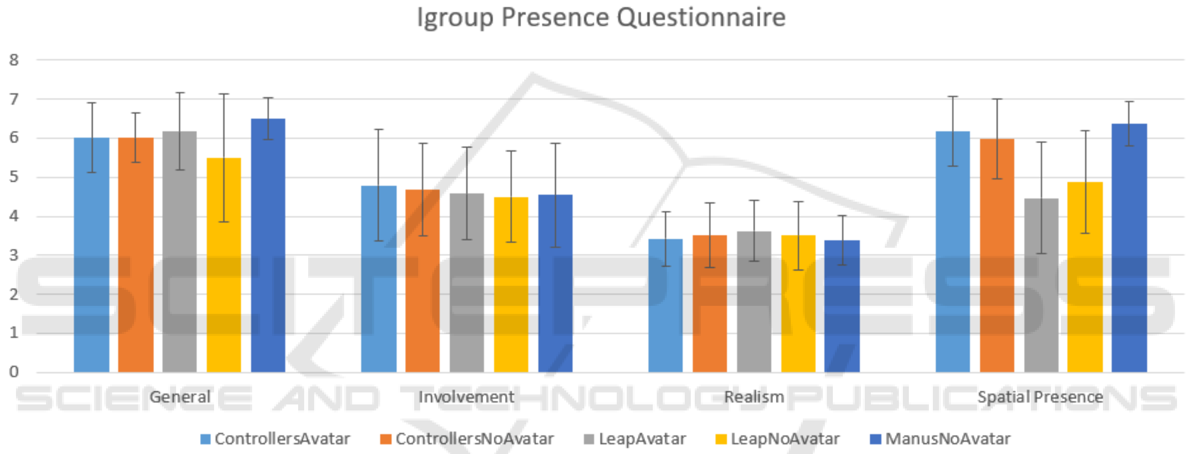


Figure 5: Results of the IPQ: mean values and standard deviations on a scale from 1 to 7.

- *Dependability:* The subjects seem in control of the interaction in case he/she uses the controllers, while in case he/she uses the Leap Motion or the Manus Prime haptic gloves the value is not high as expected (mean scores 0.88 and 0.54 for the Leap Motion with and without avatar, 1.00 for the Manus gloves).
- *Stimulation:* The subjects provide similar scores to this category. It seems that the five solutions excite and motivate the subjects in an equal way.
- *Novelty:* For this category, the higher value is for the Manus Prime haptic gloves (2.58 ± 0.80). Then, the Controllers and the Leap Motion with the avatar have higher values with respect to the ones without the avatar.

Figure 5 shows the results of the IPQ, the mean values of each category (range between 1 an 7) and the associated standard deviations, for the 5 experimental conditions, are reported.

The answers of the subjects show that the Manus Prime haptic gloves allow us to achieve a higher General sense of ”being there” (6.50 ± 0.55) and Spatial Presence (6.37 ± 0.57) with respect to, in particular, the Leap Motion cases, in which the worst type of interactions with complex objects reduces these two aspects (6.17 ± 0.98 and 4.47 ± 1.43, respectively, with the avatar). While the values for the Involvement and the Realism are very close one from the other. For what concerns the comparison between the avatar and no-avatar solution while using the same technology, the results show that the use of avatar is slightly better in all the categories of the IPQ. No appreciable differences for the UEQ.

In Figures 6 and 7 the bar graphs representing the mean values of the TTC an the error rate (and the related standard deviations), for the 5 experimental conditions, are shown. The results show that the Controllers are the easiest interaction device (mean TTC with avatar 77.93 ± 25.57 seconds and 0.33 ± 0.82

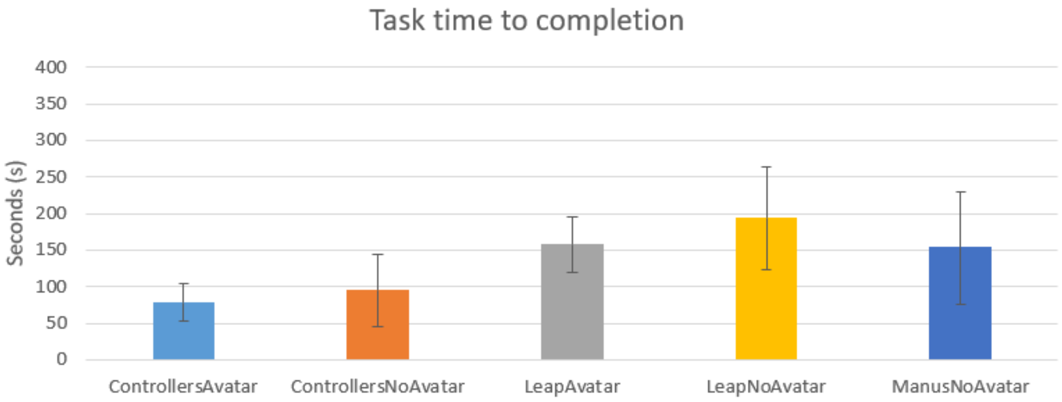


Figure 6: Total time to completion TTC for the five experimental conditions.

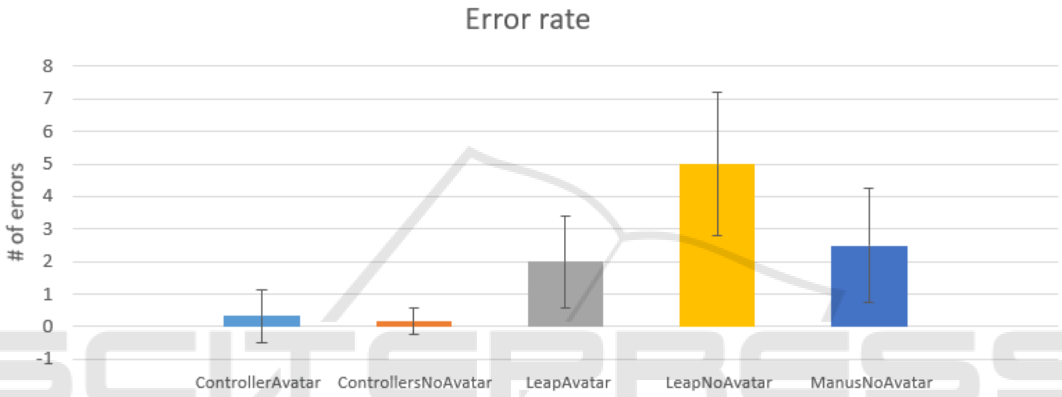


Figure 7: Error rate for the five experimental conditions.

errors), while the Leap Motion (mean TTC without avatar 193.87 ± 70.24 seconds and 5.00 ± 2.19 errors) is the hardest and the Manus Prime haptic gloves are the middle ground (mean TTC without avatar 152.65 ± 77.39 seconds and 2.50 ± 1.76 errors).

6 CONCLUSIONS

In this paper, we have presented a framework based on sensor fusion to build a self representation inside VR (i.e. an avatar of the user). The main goal of the proposed approach is to use off-the-shelf and low cost devices, and to be easily extended to any tracking and interaction device.

Starting from the developed approach, we have implemented three different setups that use the Oculus Rift as a VR device, together with three different interaction technologies, which allow us to represent the hands and the fine movement of the fingers: the controllers of the headset, the Leap Motion and the Manus Prime haptic gloves. Furthermore we have used an RGB-D camera, the Intel Realsense d435, to track the user body, and thus to create the avatar and to replicate the movement of the user. To further analyze the role of the self representation, we have devised an assembling experiment and tested it in 5 conditions: the 3 interaction devices, and with or without the presence of the entire user avatar (we had to remove the ManusAvatar condition for compatibility issues).

In this paper, we have presented the results of a preliminary evaluation, conducted with a small number of participants, but it allows us to draw some preliminary conclusion. For what concerns the interaction, the results we obtained from our experiment suggest that the Controllers is the preferred solution due to the simplicity of the interaction, even if the model of the hands is not precise and the movement of the fingers depends on their position on the controllers and not on the real one. Instead, the Leap Motion is the hardest technology to deal with. The problems are that the user always need to have the hands in front of the sensors and also that complex objects affect negatively the type of interaction. At the end, the Manus Prime haptic gloves are the middle ground solution that gives a precise model of the hands and a detailed movement of the fingers. Furthermore, the haptic module adds, on top of these, the sensation of touch through the vibration of the fingers. The role of the haptic feedback in interaction should be further analyzed. The main drawbacks of our solution are caused by the problems of the RGB-D camera, which interferes with the HTC Vive tracking system, thus hampering the use with the Manus gloves. Based on these findings, our next works will investigate on adding a mesh to the avatar and solving the different issues we faced during the development of our systems that are mainly caused by the RGB-D camera. First of all, we will try to re-implement the Manus Prime haptic gloves with the avatar case by exploiting the skeleton provided by standard RGB cameras such that the gloves are not disturbed by the IR light anymore. Then, it would be interesting to try to overcome the occlusion problem by using one more RGB-D camera (or multiple RGB cameras) placed behind the user and fuse the data coming from the two RGB-D cameras before the alignment phase to obtain a much more stable system that could better mimic other solutions for the avatar reconstruction, such as motion capture suit or Inverse Kinematics.

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