Small Objects Manipulation in Immersive Virtual Reality

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Abstract: In this pilot study, we analyze how the user approaches the manipulation of small virtual objects using different technologies, such as the HTC Vive controllers, the Leap Motion, and the Manus Prime haptic gloves. The aim of the study is to quantitatively assess the effectiveness of the three devices in a pick-and-place and simple manipulation task, specifically the assembling of a three-dimensional object composed of several mechanical parts of different shapes and sizes. 12 subjects perform the proposed experiment in a within-subjects study. We measured the total time to complete the entire task, the partial timing and the errors as the number of objects lost, to understand which are the most difficult actions. Moreover, we analyze the user feelings with the User Experience Questionnaire (UEQ), and the System Usability Scale (SUS). Both timing measurements and user experience reveal the weaknesses of the gloves, which suffer from problem in correctly tracking the thumb, thus in allowing grasping actions. Controllers are still a good compromise, though some fine tasks could not be correctly performed. The vision-based solution of the Leap Motion is appreciated by users, and it is stable enough to perform the given task.

1 INTRODUCTION

The field of Virtual Reality (VR) has approached a huge step further in these last years thanks to the recent improvement of VR technologies and low-cost head-mounted displays (HMDs). With its widespread success, the development of embodiment and new interaction techniques for immersive simulation using the latest technologies available is being requested. Indeed, today the controllers are the standard tools for interacting in the virtual world, but their use is still a subject of discussion: on one hand, we are used to them and they provide a stable and effective interaction with objects; on the other hand, they represent a physical link between the real and virtual world that could break the illusion of being in VR. Also, they do not provide a naturalistic interaction behavior since the user needs to press a button to perform an action in VR. Other types of technologies were studied to find a valid alternative. For example, the Leap Motion [1], a non-wearable hand tracking device, with several limitations such as occlusion, environment condition, and limited field of view (Weichert et al., 2013; Potter et al., 2013). Much more cumbersome solutions, such as gloves with haptic feedback (as Manus Prime haptic gloves [2]), were developed with a high cost for purchasing that ensure high tracking quality and realistic hands models. Newest solutions include gloves with force feedback such as Dexmo [3] or the Teslasuit gloves [4].

A different number of interactions can be performed in a VR environment (e.g. navigation, travel selection, manipulation and system control (Frohlich et al., 2006)), and in this paper we focus on manipulation, which corresponds to modifying an object's position, orientation, scale, or shape. In particular, we address the problem of manipulating small objects, which is one of the steps necessary to perform manual assembling tasks in industrial contexts (Hoedt et al., 2017; Eriksson et al., 2020), or to perform complex actions in medical and surgical simulation systems (Girau et al., 2019; Mao et al., 2021).

Manipulation of small virtual objects recalls the concept of dexterous manipulation (DM) that is an area of robotics in which the fingers cooperate with the aim of grasping and manipulating an object (Okamura et al., 2000). In this context, one challenge is

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[1] https://www.ultraleap.com/

[2] https://www.manus-vr.com/

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

[4] https://teslasuit.io/

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to accurately capture the motion of the human hand configurations and fine control of the fingertips to perform stable grasps and inside-hand manipulation (Mizera et al., 2019).

In this study, we aim at comparing three straightforward approaches, i.e. the HTC Vive controllers, the Leap Motion, and the Manus Prime haptic gloves. Even if HTC Vive controllers do not provide fingers tracking as the other two technologies, we decided to keep it in consideration since it is one of the most used type of controllers. The considered tasks consist in picking several small virtual objects (models of Meccano [5] components) and positioning them to create a given three-dimensional structure. The total time to complete the task, the partial times (corresponding to picking and correctly positioning the single objects) and the errors as the number of objects involuntary lost by the users during the task are measured. Moreover, user experience is assessed with the User Experience Questionnaire, the System Usability Scale, and open-ended questions to collect the feelings of the users. The considered task has different layers of complexity, ranging from a standard pick-and-place task, to more complex manipulation actions, like rotating a washer around a screw. The goal of this study is to analyze the strengths and weaknesses of the three solutions in a quantitative way, opening a further discussion towards the implementation of systems where natural and ecological interaction and manipulation are possible.

2 RELATED WORKS

To manipulate objects in VR in a similar way to what happens real in world, it is necessary to capture and track the position of the hands' joints in real-time and with the highest possible accuracy. This could become a challenging task when manipulation involves small objects since positioning errors could become relatively consistent.

Many methods in the literature are based on kinematic Gesture-Based approaches, based on predefined gestures used to perform some actions. Common gestures include circle, swipe, pinch, screen tap, and key tap gestures. One popular example is the Microsoft HoloLens (Avila and Bailey, 2016). While this approach is valid for certain VR interactions and environments, it does not simulate a physically accurate pinching or grasping interaction with an object, thus not sufficient for direct object manipulation.

Heuristic-Based approaches are based on a priori information about the hands and objects, thus objects interaction is only possible for a set of predetermined object-hand configurations. This significantly limits the practical application of such an approach in unconstrained environments with unknown objects, where this a priori information is not available (Oprea et al., 2019).

It is worth noting that in the real world, our ability to interact with objects is due to the presence of friction between the surfaces of the objects and our hands. The physics-based approaches simulate forces involved in object grasping to obtain more naturalistic hand interaction in VR. This kind of approach is very accurate but usually computationally expensive, which limits its applicability in VR where real-time performance is required. Recently, an efficient physics-based approach is implemented in (Höll et al., 2018).

When dealing with interactions in VR, several studies can be found that focus on different aspects of this fundamental action. Some focus their attention on the importance of the size of the hands (Lin et al., 2019) and how they affect the interaction also considering hands appearance (Van Veldhuizen and Yang, 2021) and fingers configurations (Sorli et al., 2021). Some others focus on the feedback we can provide to the user such as audio and visual feedback as in (Blaga et al., 2020) where they show how visual thermal feedback had an influence on grasp aperture, grasp location and grasp type. Furthermore haptic and force feedback can be considered using gloves or developing new techniques and technologies (Yoon et al., 2020). Others focus also on normal-sized objects considering the differences between real and virtual grasping and the level of presence in the environment, adding in some cases also a self-avatar of the user (Viola et al., 2021).

This parallel line of research studies the effect of the hand representation on the level of presence and on the embodiment of the VR user usually reimplementing in several ways the so called rubber hand illusion experiment. In (Argelaguet et al., 2016; Lougiakis et al., 2020), the authors pointed out that different hand models can have an impact on both the sense of ownership and the performances. For this reason, we decided to use the same robotic hand model for each technology to not influence in any ways the proposed task.

Considering the methods and devices to track the users' hands and fingers, there are works in the literature aiming to compare the different technological solutions.

In (Masurovsky et al., 2020; Gusai et al., 2017; Fahmi et al., 2020; Viola et al., 2021) performed a

[5]https://www.meccano.com/

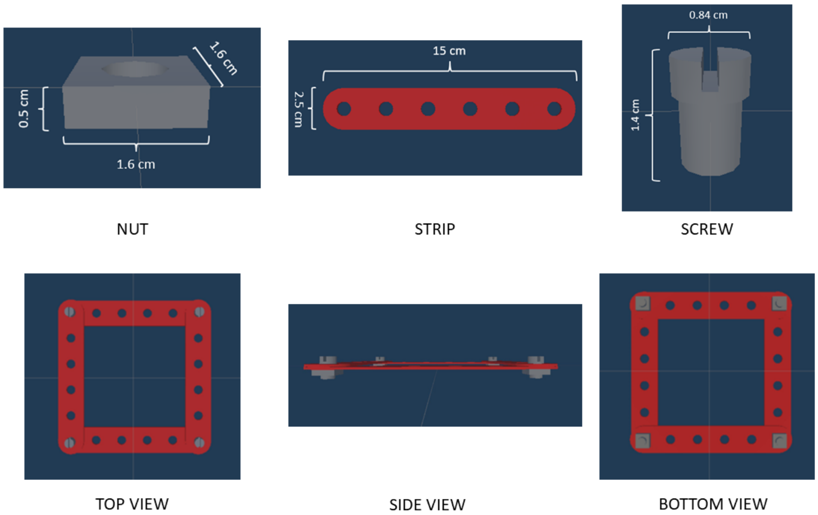


Figure 1: Top: the Meccano parts. Bottom: the final object.

comparative analysis of consumer devices, by considering grasping and pick-and-place tasks. Neither of these studies considered the manipulation and the interaction with small objects.

3 MATERIAL AND METHODS

3.1 Hardware Components

The device used for displaying Virtual Reality is the HTC Vive Pro [6]. The headset has a refresh rate of 90 Hz and a 110 degree field of view. The device uses two OLED panels, one per eye, each having a display resolution of 1440 × 1600 (2880 x 1600 combined pixels). To manage the data flow from the different devices simultaneously, we used the following machine: a PC equipped with an NVIDIA GeForce 3080 graphic card, an AMD Ryzen 9 5900x processor, 32 GB of RAM, and Microsoft Windows 10 Home 64 bit as the operating system.

For the detection and tracking of the hands and the fingers, we used the Vive Controllers, the Leap Motion, and the Manus Prime haptic gloves.

- The Vive controllers use the Lighthouse tracking system with 24 sensors, they have a multi-function trackpad and a dual-stage trigger. In this experiment, we do not use the haptic feedback.
- The Leap Motion [7] is a non-wearable device that acquires the hands with two cameras and fits the data with a model of the hands. Then it computes the 3D position of each finger and of the center of the hand. It has a field of view of 140°× 120°. As with any vision-based device, it has some limitations such as occlusions and noise due to illumination and image processing. In our setup, we attached the Leap Motion device to the headset with a 3D printed support designed for the HTC Vive Pro [8]. The version of the SDK is Orion 4.1.0, the Unity plugin version is 4.8.0.
- The Manus Prime haptic gloves [9] tracks the users' hands and fingers by combining the measurements of an HTC Vive tracker (attached on the back of the hand), and the inertial measurements of sensors attached on the fingers. The gloves could provide haptic feedback transmitted by linear resonance actuators on the fingertips, but in our setup, we did not consider it.

3.2 Software Components

The virtual environment has been implemented in Unity 2019, with the following plugins: SteamVR tool, so that our software is compatible with all the supported HMDs, Virtual Reality Toolkit (VRTK), the Leap Motion Unity module, and the Manus plugins for Unity, to implement the interaction with the virtual objects. The same 3D model of a robotic hand has been used for all the three methods to remove possible influences of the predefined models of each technology.

[6] https://www.vive.com/us/product/vive-pro-full-kit/
[7] https://www.ultraleap.com/datasheets/Leap_Motion_Controller_Datasheet.pdf
[8] https://www.thingiverse.com/thing:3119186
[9] https://www.unipos.net/download/ManusVR-Prime.pdf

3.3 The Interaction Task

The task consists in building a square using the provided strips, bolts and nuts. They are part of a standard Meccano set, their shape and real size are shown in Figure 1(top). The final square to be assembled is shown in Figure 1(bottom). Meccano set was chosen due to the freedom of creating either simple or complex objects from small parts.

All the virtual objects have two Unity component attached, a rigid body that simulates a real-world scenario (i.e. use gravity is set to true and its kinematics set to false) and a box collider with its shape and set to trigger.

To pick-and-place the objects we use the same hands model for all the interaction devices. It is worth noting that the virtual hands are the visual feedback of the interaction also for the HTC controllers.

When an object is in its final position, highlighted by a green light of the shape of the object during the grasping (see Fig. 2), we constraint the rigid body's position and rotation and we set its kinematics to true. In each scene, both strips and bolts use a lerp (linear interpolation) function to slowly move to the correct position and rotation when they are closer enough to the green area in Fig. 2. Since the rotation of the nuts involves the use of the fingers, and it is not easy to be implemented with the HTC Vive controllers, we implemented it in the following way:

- HTC Vive Controllers: We use gestures to detect if the controller is rotating counterclockwise or clockwise in order to move the nuts in the correct position. This is actually the common way of implementing this type of interaction in industrial applications.
- Leap Motion/Manus Gloves: The user uses his index finger to rotate the nut through colliders. We then detect if the nut is rotating counterclockwise or clockwise and move it up or down consequently.

4 EXPERIMENT

4.1 Participants

To compare the three devices in the proposed task, we performed a within-subjects experimental session and collected data from 12 subjects (10 males, 2 females). The participants, aged from 24 to 54 (30.25 ± 8.65) and with normal or corrected-to-normal vision, were all with low to medium experience with VR and the used technologies. Each subject performed all the experimental conditions in a randomized order to avoid learning or habituation effects.

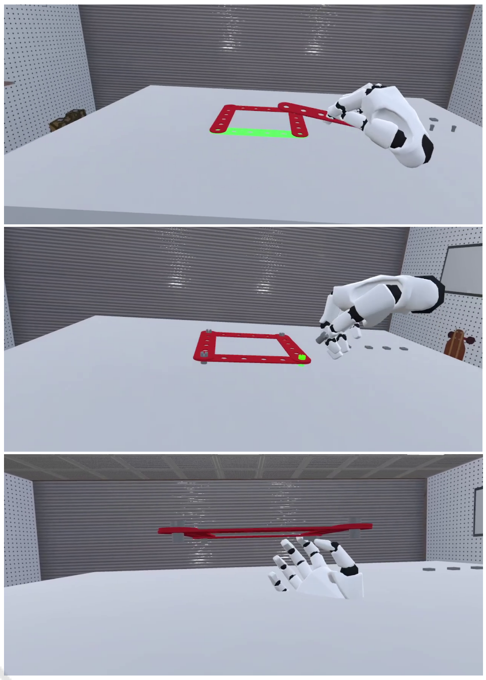


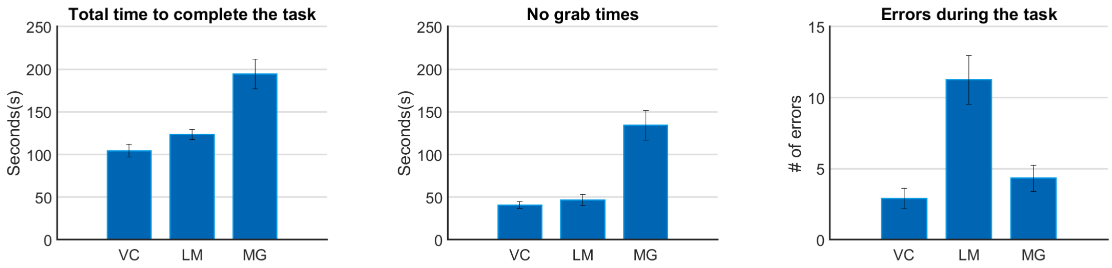
Figure 2: Three snapshots of the assembling task. Top: positioning of a strip. Center: positioning of a screw. Bottom: positioning of a nut. The final positions are highlighted in green.

4.2 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 explains the task. The user has to complete the assembly task that consists of interacting and grabbing pieces of the Meccano game such as strip, bolt, and nut, with the aim of building a square. The simulation starts when the user presses a button on the table in front of him. At this point, the user should grasp the appeared pieces, and put them in the highlighted areas. The task ends when all the pieces are correctly positioned. At the end of the assembly task, the user removes the HMD and they are asked to fill the questionnaires.

4.3 Measurements

During the task, both the total time to completion (TTC) and the partial time of each piece were recorded. Also, the number of time a piece falls from the user's hands were saved to compute the errors' number.



(a) (b) (c)

Figure 3: (a) Time (seconds) to complete the task. (b) Time (seconds) without a grabbed object. (c) The number of errors. Values are averaged across participants and the standard error of the mean is shown. VC: Vive Controllers, LM: Leap Motion, MG: Manus Gloves.

After each trial of a device, the users compile the User Experience Questionnaire (UEQ) (Laugwitz et al., 2008), and the System Usability Scale (SUS) (Lewis, 2018).

The UEQ consists of 26 statements, to be evaluated by the users with a score from 1 to 7. The statements are then analyzed with respect to 6 domains which are attractiveness, perspicuity, efficiency, dependability, stimulation, and novelty. In this paper, we used the tools provided by the developers and available in the official website [10].

The SUS consists of a 10-item questionnaire with five response options for respondents: from Strongly agree to Strongly disagree, or viceversa. The analysis is performed by averaging the answers (subtracting 5 to the ones with the opposite order), summing the results, and multiplying by 2.5. The state-of-the-art reports that the average score of the SUS is 68. Systems that obtain a score higher than 68 are above the average. In particular, systems above 80 are highly recommended, while systems under 51 must be carefully checked before use.

5 RESULTS

Figure 3(a) shows the total time to complete the task with the three devices. The Vive Controllers (VC) and the Leap Motion (LM) have similar performance, while with the Manus Gloves (MG) users need almost a double time to complete the task (ttest confirmed the statistical difference with $p < 0.01$). It is interesting to note in Figure 3(b) that the difference is due to the fact that most of the time spent in the MG condition is without grabbing any object. This is confirmed by the observation of the experiment: with the Manus Gloves users experienced many problems in grabbing the objects. This is due to a specific malfunction of the gloves that may happen during the experiment. Indeed, it is often impossible to close the thumb and to do a real pinch action. For this reason, people spent a big amount of time trying to grab the objects. After objects are grabbed, the position and all the other actions are very easy to be completed.

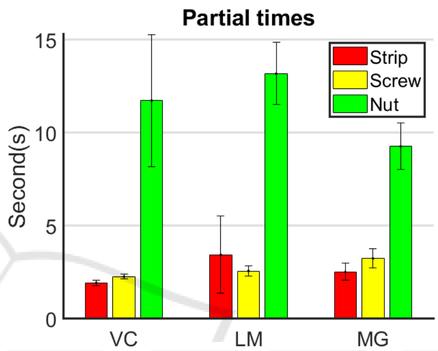


Figure 4: Partial time (in seconds, averaged across participants, with standard error of the mean) to put in the correct position the three considered objects. VC: Vive Controllers, LM: Leap Motion, MG: Manus Gloves.

By considering the errors, i.e. the number of objects lost by the users during the action, the performance of the Vive Controllers and of the Manus gloves are similar. Indeed, they use the same tracking technology, and errors are mainly due to tracking instability, which mainly affects the Leap Motion.

The experiment has been designed to consider the manipulation of three objects with different features. The positioning of the strip is a simple pick-and-place task, performed with a quite big object. The three devices have similar performance (see Fig. 4 red bars). Also the positioning of the screw is a pick-and-place task, though the objects are considerably smaller. Again, the three devices perform similarly (see Fig. 4 yellow bars). The correct positioning of the nut requires more time (see Fig. 4 green bars), and for this specific task performances of the Manus Gloves are better than the other devices. In all the

[10] https://www.ueq-online.org/

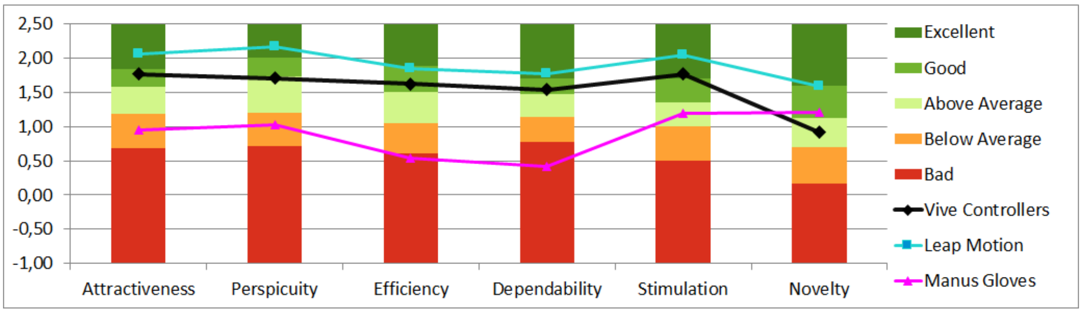


Figure 5: User experience evaluation with the UEQ questionnaire for the three considered devices. Mean values, averaged across all the participants, are plotted on the visualization scales provided by the official website.

cases, variability among users is very high, indicating a subjectivity in using the devices and performing the task.

The user experience evaluation with the UEQ questionnaire reported good results in terms of attractiveness, perspicuity, efficiency, dependability, and stimulation for the Vive Controllers. For the same aspects, the Leap Motion obtained an excellent evaluation. Users found the Leap Motion better in terms of novelty. The Manus Gloves are in general below average for all the evaluation domains, except for stimulation and novelty. In Figure 5, it is possible to see the mean values, averaged across all the participants, plotted on the visualization scales provided by the UEQ official website.

Similar results are obtained with the SUS questionnaire. Both the Vive Controllers and the Leap Motion are above the threshold. In particular, the controller obtained a score of 77 and the Leap Motion a score of 84. The Manus Gloves obtained a score of 54, resulting in below the threshold.

6 CONCLUSION

In this paper, we have analyzed three consumer devices for tracking the users' hands and fingers, thus interacting in VR environments, by taking into consideration an assembling task with small objects.

This work is motivated by the fact that one of the main application domains of immersive VR is training, e.g. in industrial contexts.

The 12 participants were all able to complete the required task, but the analysis of the timings shows that with the Manus Gloves almost a double-time is necessary. Further analysis shows that the main problem of the gloves is the fact that the thumbs are not tracked correctly, thus hampering the grasping actions. This is also reported by almost all the users in a post-experiment interview, and it affects the user experience evaluation performed with the UEQ and the SUS. It is worth noting that commercial gloves are available in several sizes and need an ad-hoc calibration for each user (Caeiro-Rodríguez et al., 2021). We performed the calibration for each user, but our gloves are of a standard size, thus fitting may not be ideal for all the users. Actions not involving the use of the thumb were performed correctly and quickly (e.g. the assembling of the nuts). The Vive Controllers have similar performance compared with the Leap motion, in terms of timing (both total time, time without a grabbed object, and partial times). The vision-base technique of the Leap Motion makes the device less robust in terms of number of errors. When the tracking is too noisy, object could fall down. Nevertheless, users appreciate this device.

The lesson learned from this experiment is that none of the considered devices may allow us to interact in an ecological way in virtual environments. Indeed, the task was simplified by adding visual hints (highlighting in green the final position of the objects) and by moving the objects in the final position when getting close to it. It would be interesting to remove such hints, and to investigate interaction in more complex tasks and with smaller objects.

It is worth noting that researchers are now pursuing physically-based approaches, thus improving grasping capabilities of small and complex objects in VR (Delrieu et al., 2020).

Finally, the naturalness of actions in VR should be analyzed with more complex metrics, e.g. by looking at the users' behaviour, as in (Ragusa et al., 2021).

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