EUROVR 2017

Usability of Natural Interaction Input Devices in Virtual Assembly Tasks

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Received: date / Accepted: date

Abstract We investigate the usability of different natural interaction input devices in demanding bi-manual virtual assembly tasks. Our use case is the assembly of a spacecraft including a functionality test. We performed a user study to empirically measure the performance and additionally, we used a questionnaire to measure the user's experience. We tested three different input devices: a pair of cybergloves and a Leap Motion Tracker, both allow the tracking of arbitrary finger and hand movements, and the HTV Vive controllers that are restricted to pre-defined gestures. Our results show that the HTC Vive controllers performed best in our bi-manual assembly task and moreover, they were rated best with regard to immersion.

Keywords Virtual reality · Assembly · Usability · Immersive · 3D · Input Devices

1 INTRODUCTION

Virtual prototyping (VP) and virtual assembly (VA) in particular have changed the product development lifecycle significantly during the last years. Instead of the time-consuming building of expensive physical prototypes, VP enables engineers to directly create and change *virtual* prototypes which lead to an enormous saving of time and money [12]. Typical tasks during the assembly of such virtual prototypes are the selection, movement and manipulation of parts in a 3D environment. Traditional input devices like mouse and keyboard are not very well suited for these tasks. Hence, more intuitive interaction metaphors are necessary. In the real world, our hands are the most versatile tools and we use them every day to perform tasks like grasping and moving objects. Consequently, interaction metaphors relying on the natural interaction of the human hand are a very intuitive metaphor for the assembly of virtual prototypes.

There exist several hardware devices that support such natural interactions: traditional cybergloves are the oldest product on the market. The Leap Motion

*This work was not supported by any organization
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enables bi-manual hand tracking without the need of wearing bulky gloves using a depth camera. Finally, current consumer oriented virtual reality (VR) systems are delivered with special devices, like the Vive Controllers or the Oculus touch, that allow an almost natural interaction by supporting several gestures. Even if they do not cover a complete finger tracking, their expressiveness is sufficient to support typical assembly operations like grasping and movements of parts.

In this paper, we have investigated the performance and the usability of these different devices for natural bi-manual interaction in VR assembly simulations. To do that we have created a virtual assembly environment with support of a head mounted display (HMD) and room-scale user tracking. We chose a practically relevant assembly task that is closely related to real-world assembly simulations. More precisely, the task is the assembly of a spacecraft of several parts like sensors, actuators, power units, communication devices, etc. We performed a user study to investigate the user's experience based on the "Presence Questionnaire"[15] and the "NASA TLX"[7]. Our results show that, surprisingly, the most limited but also the most inexpensive device, the HTC Vive controllers, performed best both in performance as well as with respect to the users' ratings.

2 RELATED WORK

Interaction metaphors for virtual assembly simulations as well as natural interaction in virtual environments are relatively well studied fields.

[16] use single-handed 2D virtual assembly on a 3-DOF haptic device with dynamic haptic guidance to improve user performance. They used a standard display instead of an immersive display, such as a head-mounted display (HMD). [13] introduce a tool with haptic feedback that is designed to increase user performance and acceptance in single-handed virtual assembly tasks.

Similar to the goal of testing different input devices to compare their performance in a virtual reality environment, [10] tested how useful virtual reality is for learning how to perform a laparoscopy. The conclusion is that virtual reality is beneficial in the sense that time is saved, that the simulation could be used without a real-world subject and that skills can be trained in a safe environment. This conclusion is confirmed by [4].

In [2], the authors also investigated the potential of VR for training of assembly tasks. They compared VR, AR and conventional methods like 2D drawing. The study shows that VR leads to improved performance over the conventional 2D drawing.

[6] incorporate large stationary haptic devices in their assembly task for single-handed interaction and compare them to other input devices such as bi-manual gesture recognition gloves in addition to an HMD for immersion. They come to the conclusion that both approaches have advantages and that a combination of both would be ideal.

[9] develop a wearable haptic device that can be used in corporation to an HMD for single-handed interaction in virtual environments and compare it to a stationary haptic device with an ordinary display. However, all of these approaches uses only single handed tasks.

Actually, there already exist works that have successfully incorporated bi-manual interaction in virtual assembly tasks to improve user performance and experience.

[3] introduced novel interaction techniques of the Pinch Gloves for virtual environments. They explored what was possible in the early ages of VR, although not all interactions are very intuitive, easy to learn and remember back then, some of these techniques are still used in todays applications. [5] implemented a training system with virtual bi-manual assembly to teach users specific assembly tasks, similar training is performed in physical form. Their results show that virtual bi-manual assembly in addition to visual colorization can have an equal learning effect compared to physical assembly.

Another publication on virtual bi-manual assembly introduces a self built electrotactile grasping device that improves the users' performance as well as the user experience [8].

[11] investigate the differences in user perception between physical and virtual bi-manual assembly. Their results suggest that haptic feedback is the most important factor that will improve the user experience. However, none ot these works used the natural interaction metaphor.

To the best of our knowledge there is no prior publication that dealt with the user experience when performing virtual bi-manual assembly with different input devices and the natural interaction metaphor.

3 OUR USE CASE

We have developed a virtual reality environment for our expriments with different input devices. For the real time stereoscopic graphics rendering we used is the Unreal Engine. The virtual environment is displayed to the user by a HMD, the HTC Vive. The HMD is tracked by the HTC Vive optical tracking system in a large 5m by 5m area, where the users are allowed to move freely.

3.1 Task

Our task models a practically relevant assembly simulation in an aerospace context. The goal is to equip a spacecraft with various parts, e.g. senors, power engines, etc.

In our scene, the user is placed on a virtual asteroid with the base of a spacecraft in front of him. The spare parts (see Figure 1) are placed on the ground. These parts can be grabbed, moved, mounted and dismounted, respectively from the base of the spacecraft. We did not include a real physically based simulation of the assembly but instead we kept the mounting of parts be as easy to perform as possible. The reason for this is mainly the limited gesture support of the Vive controllers. Thus, we developed a reliable snapping mechanism for the mounting task. A preview of the snapped to position is rendered in a blue shade (see Figure 2). Moreover, we did not include gravity simulation: in case of the user releases a part, it will stay at its' position and not fall down to the ground. This interaction metaphor faciliates the change of the grip. The bi-manual assembly allows the user to grasp spare parts with their right hand and rotate the spacecraft base

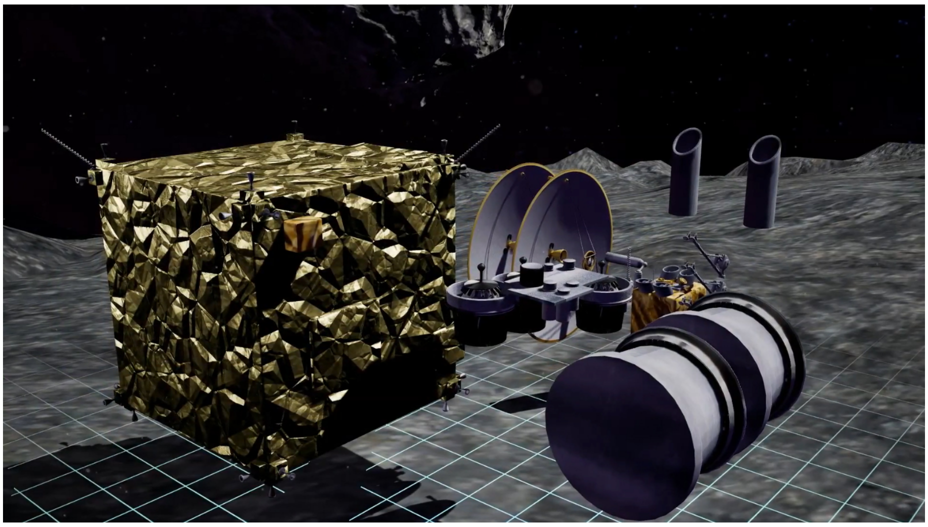

Fig. 1 Spare parts, which can be grabbed, moved, mounted and dismounted on the spacecraft.

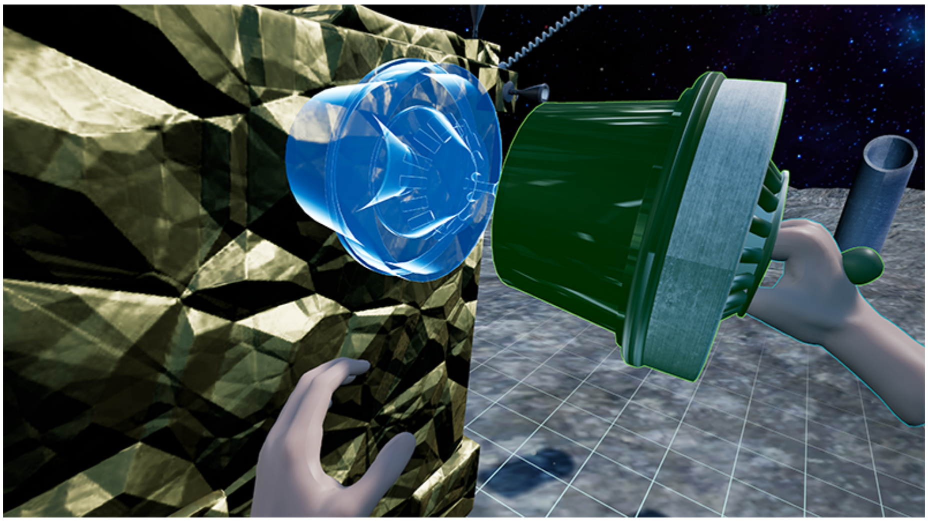

Fig. 2 Bi-manual assembly in our virtual reality environment. The blue shaded part shows a projection of where the part will be mounted to, when released.

with their left hand. Obviously, we included a left-handed mode where the roles of the hands are switched.

In order to avoid a complicated training phase, we provide the user with a blueprint of how the spare parts have to be assembled. It is displayed during the complete assembly simulation. This also diminishes the influence of the user's spacial ability.

3.2 Devices

Our system supports different bi-manual natural interaction devices, namely, a pair of cybergloves, a Leap Motion tracker and the HTC Vive controllers.

The Vive controller supports a grasping gesture by pressing a button with the index finger while holding the thump down on top which is recognized by a sensor. The global position and orientation tracking of the controllers is done wirelessly with the HTC Vive optical tracking system.

The Leap Motion is basically a depth sensor with the specialization in hand tracking. It is delivered with a hand tracking SDK that offers support for the Unreal enging. The work space of this device is relatively small and not applicable to room-scale tracking. Hence, we mounted the device on top of the front panel of the HMD. This allows the user's hand to be recognized in the field of view and the tracking can be automatically aligned with the HMD's tracking data. However, this device requires a cable to the PC.

Finally, we integrated a pair of cybergloves from CyberGlove Systems. The challenge is the global tracking of the hands because they do not support the HTC Vive optical tracking system. Instead, we use an electromagnetical Polhemus Fastrak tracking systems for the gloves. We initially have to match the coodinate systems of the Polhemus and the HTC Vive tracking with support of the HTC Vive controllers. In our current system, we used a wired CyberGlove I with 18 sensors for the right hand and a wireless CyberGlove III with 18 sensors for the left hand. Our Polhemus tracking requires additional cables for the sensors that are directly mounted on the gloves.

4 USER STUDY

We used our VA system described above to investigate the influence of the controller on the user's performance and experience in typical VA tasks. The main questions of our user study were to evaluate the usability including the ease of use of the respective input method.

4.1 Participants and Protocol

24 subjects participated in our user study. 70,83% of our subjects were male, 29,17% female. All of the subjects were in an age range between 20 and 30, except one participant who was 63. 66,67% of all 24 subjects reported to never have used a VR headset before this study. Six of the subjects already came in contact with some of our input devices. Six have already used the HTC Vive Controller in the past, three reported to have used the Leap Motion and one subject has used the CyberGloves prior to our user study.

The participants entered the laboratory with the experimental setup one after another. They were given a short verbal introduction about the task, the experiment, and the special properties and features of the devices by the instructor. As described above, the task was to assemble a spacecraft consisting of eight parts following a pre-defined template that was displayed during the complete experiment (see Figure Figure 2). The participants were given a one minute training phase for each device, however, during this time they were not able to pick up or move the parts.

Each participant performed the task three times, i.e. once with each of the three different input devices. We varied the order of the devices randomly ensuring, that each order is applied equally. Since we had three devices this results in 6 permutations of the order. With 24 participants we get overall 4 runs per order.

After finishing a task with a particular device, the participant was asked to fill a questionnaire. We used questions from the standardized "Presence Questionnaire"[15] and the "NASA TLX"[7] about the usability, the intuitiveness of controll, and so on. For each question we used a 20 points scale with 1 point steps, ranging from "very low" (1) to "very high" (20). This allows a suitable symmetry and equidistance for the use of parametric analysis. Additionally, we measured the time that the participant nedded to complete the task. Finally, after finishing all three tasks, the participants were asked to give additional comments on the experiment and the devices.

5 RESULTS

In the following we will present and analyze the results of our experiment including the objective measurements and the users' ratings.

First, we manually recorded the time to completion for each user with respect to each input device in order to have objective data on our participants performance. Our statistical analysis shows that our participants completed their task highly significantly faster (p¡0.001) when using the Vive controller compared to both other devices (N=24; Vive: M=1m; SD=0m25s; Leap: M=3m10s, SD=1m02s; Gloves: M=2m42s SD=1m12s). The CyberGloves show faster completion times than the LeapMotion on average, however the difference is not significant (p=0.181).

Second, to measure the participants subjective experience when using each device we conducted a NASA TLX questionnaire after each task.

Figure 3 shows a boxplot for the given answers per input method for all questions of the NASA TLX. The results for the questions are grouped by three (For each input method we assign one color. Blue: HTC Vive Controller, orange: LeapMotion, green: CyberGloves). A one-way within subjects ANOVA was conducted for every question to compare the effect of different input devices on the outcome of the NASA Task Load Index. Significances were evaluated using Paired Samples T-Test.

For the mental demand, we found the Vive controller to be high significantly less mentally demanding (p¡0.001) than both other devices by a large margin (N=24; Vive: M=19.38, SD=17.65; Leap: M=58.96, SD=26.21; Gloves: M=40, SD=22.78). The Leap Motion had the worst result and was significantly worse (p¡0.001) than the CyberGloves.

The physical demand was perceived very similarly by the users, rating the Vive to be least physically demanding (N=24; Vive: M=22.08, SD=17.67; Leap: M=52.5, SD=29.53; Gloves: M=47.5, SD=26.46). Again, Leap Motion and cybergloves are singificantly worse (p¡0.001) by a similarly large margin. However, this time there was no significant difference in the perceived physical demand between Leap Motion and cybergloves (p=0.464). One possible explanation for the bad

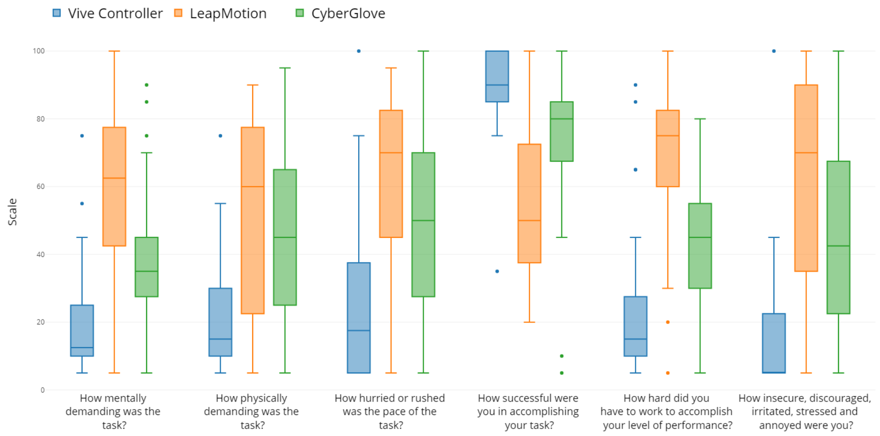

Fig. 3 This plot shows the average rating and the standard deviation of each input method per question. There is a visible pattern, in which the Vive controllers are the easiest to use, the Leap Motion the hardest, with the cybergloves being in between.

results of the cybergloves could be the heavy cables that needed to be dragged along, explaining the increased physical demand.

The next question checks how hurried or rushed the subjects felt while performing the task. The subjects reported to feel significantly less rushed when using the HTC Vive controllers compared to the Leap Motion (p¡0.001) as well as the cybergloves (p¡0.001) (N=24; Vive: M=25.83, SD=26.40; Leap: M=61.67, SD=25.74; Gloves: M=48.33, SD=25.26). Between cybergloves and Leap Motion is a weak significant difference on the feeling of being rushed (p¡0.05).

The pattern that is expressed through the numbers becomes obvious when taking a look at Figure 3. This pattern continuous in the next question "How successful were you in accomplishing your task?". The subjects reported their performance to be significantly better when using the Vive controller compared to the Leap Motion (p¡0.001). However the participants reported a weak significant difference to the cybergloves (p=0.008) (N=24; Vive: M=88.54, SD=13.79; Leap: M=55.41, SD=22.11; Gloves: M=72.70, SD=24.45).

When the users were asked to rate the effort that it took them to complete the task, there was a clear consensus. The Vive controller was preceived to require significantly less (p¡0.001) effort than both other devices, followed by the cybergloves, which are rated to require significantly less (p¡0.001) effort than the Leap Motion (N=24; Vive: M=25, SD=25.58; Leap: M=67.50, SD=24.32; Gloves: M=43.96, SD=20.59).

Finally, users were asked to rate the level of frustration they perceived while using the respective input devices. Again, the HTV Vive is perceived to be significantly less frustrating to use compared to both other devices (p¡0.001) (N=24; Vive: M=15.63, SD=20.76; Leap: M=62.91, SD=30.31; Gloves: M=46.87, SD=29.47). Leap Motion and cybergloves show a waek signifit difference (p¡0.05) in terms of causing frustration in our subjects.

These results mirror in the previously shown time each subject needed to accomplish the given task.

To summarize, the Vive controllers were perceived better and they performed better than the other two input devices. This is surprising because the interaction seems to be less intutitive than a direct manipulation using the hand as we do it every day. Actually, multiple persons reported that the controllers themselves felt unnatural in their hands, however, the majority found them to be convenient. The reason for the best results could be the simplicity of the operations (picking, moving, assembly), that does not require versatile finger movements.

The Leap Motion has the worst rating and performance, this is presumably due to the fact that the Leap Motion has a limited range and the hands always need to be kept in a boundary to maintain tracking, i.e., the users have to hold the hands in front of their face. While some subjects claimed that they felt very natural and intuitive, the majority had issues with inconsistent hand tracking.

Surprisingly, the cybergloves got significantly worse ratings than the Vive controllers. This is probably the case because of the cables attached to them, which increase the physical load. Even more, the electromagnetic tracking sometimes got very noisy which resulted in tracking errors and finally, the cybergloves require and initial calibration for each user which could be annoying.

6 CONCLUSION AND FUTURE WORK

We have presented the first comparison of three different devices for bi-manual natural interaction tasks in virtual assembly. Our results show that the cheapest, the HTC Vive controllers, performed best in both performance and users' experience. However, in our experiment we investigated only the very basic operations for VAs, i.e. picking and movement of parts and a simple docking task that was additionally supported by an automatic snapping mechanism. More versatile tasks, like an accurate turning of a screw, may require a higher degree of realism for the fingers' movement. Even more, the noisy and wired electromagnetical tracking disturbed the user experience with the cyberglove and the limited field of view that for the Leap Motion device. Hence, future devices with an improved tracking may produce different results.

Another explanation of better results for the Vive controllers could be that people prefer to have something in their hands during assembly tasks. This could be an argument for the inclusion of haptics into assembly simulations, even if we did not even turn on the force feedback of the Vive controllers. We will further investigate this in the future, e.g. by combining the cyberglove with a CyberGrasp or CyberForce system. Another possibility would be a test with more common devices like keyboard and mouse or a gamepad [1], in addition to the CyberGloves and the HTC Vive controllers. Or the use of mobile devices like [14] suggests.

Finally, in this experiment we focused on the different input devices and how they compare to each other and we kept the training phase very short and our participants had only very few VR experience. A further experiment could test the learning ability when using these devices, i.e. how much participants improve with an increasing experience.

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