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Abstract This paper compares three interactive techniques for two-user collaborative manipulation in virtual environments. The first technique averages positions and orientations provided by users (Mean technique). The second technique (DOF separation) splits degrees of freedom of the manipulated object among users. The third technique is a tangible device grasped simultaneously by the two users. We have conducted an experiment where participants were asked to manipulate and assemble, in a collaborative manner, virtual parts. Our results suggest that the mean technique leads to faster completion time probably due to smaller physical motions. However, the tangible device seems globally preferred by users in terms of immersion and realism of the task.

Keywords Virtual Reality · Collaborative Interaction · 3D Interaction · Tangible Device

1 Introduction

Object manipulation is one of the most fundamental tasks of 3D interaction in Virtual Reality (VR) [3]. Collaborative manipulation of virtual objects by multiple users is a very promising area for Collaborative Virtual Environments (CVE) [2]. Collaborative manipulation seems indeed necessary in many different applications of VR such as virtual prototyping, training simulations or assembly and maintenance simulations [11]. In such virtual collaborative tasks, all the users are expected to participate naturally and efficiently to the manipulation of objects in the VE.

In this paper, we compare three techniques for virtual collaborative manipulation: the Mean technique, the Separation of Degrees of Freedom (DoF), and a Collaborative Tangible Device. The first technique averages translations and rotations provided by two users. The second technique allows two users to make substantially different actions: one controls orientation of the virtual object while the other applies translations. The third technique provides a collaborative tangible device (CTD) that links physically the users using a rigid triangular shape.

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2 Related Work

Several approaches are suitable to combine two users' movements to obtain the final movement of a virtual object.

A first approach consists in averaging the two motions [11]. SkeweR lets multiple users simultaneously grab any part of a virtual object through special points called "crushing points" [4]. To determine the translation and the rotation of a grabbed object, SkeweR considers positions of those points. However, a problem remains for determining the rotation along the axis determined by the two crushing points. A similar technique seems to be used to construct a virtual gazebo [10]. Two users manipulate a beam by grabbing its extremities. But no solution is proposed for the sixth DoF. This beam manipulation has been reproduced by using two virtual hands but simply using their average position in order to provide a position for the manipulated virtual beam [5]. In [12], Salzmann *et al.* use two optical markers to let two users manipulate a windshield by simply averaging the translations and rotations provided by the users. However, these techniques only let both users to use one hand. The 3-Hand Manipulation Technique [1] is a 3D interaction technique for 6 DoF multi-user collaborative manipulation of 3D objects. It enables the determination of virtual object position and orientation through only positions of three non-aligned manipulation points on the surface of this object. These manipulation points form a triangular shape that can be used naturally by three different hands of two or three users.

Another approach consists in adding the two motions of the users [11] (asymmetric integration of movements), generally by splitting the task among users [9]. In this case, the number of DoF that each user can access and control is limited: one user controls rotation of the object while the other is limited to translation.

A tangible device is a real object that can be used to move a virtual object in order to provide users with passive tactile feedback [6]. Such tangible interfaces are often preferred by people over non-physical interfaces. Moreover, passive tactile feedback can be used to increase presence and improve training effectiveness in virtual environments [8]. However, several studies show that they do not always lead to better performance [7][14]. Tangibles interfaces can be also designed for helping people to coordinate their movements during a collaborative manipulation. In [12], Salzmann *et al.* propose a tangible device for two-user manipulation: users hold a tangible device that maintains their hands at the same distance. The user standing on the right uses left hand while the user standing on the left uses right hand to hold the tangible device. As such, the tangible device acts as haptic link between them. Finally, position and orientation are given by only one optical marker on the top of the tangible device. In addition, an evaluation is also provided but it only compares the tangible device with one purely virtual technique.

3 Evaluation

The objective of our evaluation was to compare three promising techniques: the Mean, the Separation of DoF and a Collaborative Tangible Device. The proposed task is a “pick-and-place” task involving two users in the manipulation of a virtual car hood. We collected task completion time and users’ subjective comments.

3.1 Three Interaction Techniques to Compare

3.1.1 Technique 1: averaging users’ actions (Mean)

The Mean technique [11] combines movements of the users by averaging their changes in position and orientation.

In our implementation, this technique is only concerned with users’ movements and not absolute positions. Users are free to place themselves anywhere in the tracked area and (for instance) to stand far from their counterpart. Each user holds only one optical marker. Positions and orientations of markers are periodically received from the used optical tracking system. Position of the object is denoted as p_{obj}. Orientation is given by the quaternion q_{obj}. From positions and orientations provided by two users, p_n and q_n for user n, we compute:

$$p_{obj} = \frac{\mathbf{t_1}+\mathbf{t_2}}{2} + p_{obj} \qquad \text{with } \mathbf{t_n} = p_n - p_{n,prev} \tag{1}$$

$$q_{obj} = slerp(q_1, q_2, \frac{1}{2}) \qquad \text{with } q_n = (q_n \cdot q_{n,prev}^{-1}) \cdot q_{obj} \tag{2}$$

The slerp function achieves spherical linear interpolation between two quaternions [13].

3.1.2 Technique 2: DoF separation (Separation)

The Separation of DoF splits the control of the degrees of freedom of the motion among users [11]. In our implementation, this technique shares common aspects with the Mean technique for placements and movements of users since people act through their movements, rather than absolute positions in space. Actions of users are separated. One user is manipulating translations only whilst the other one is responsible for rotations. As with the Mean technique, each user holds only one optical marker. One marker is dedicated to translations and the other one is dedicated to rotations.

3.1.3 Technique 3: Collaborative Tangible Device (CTD)

This technique is based on the 3-hand manipulation technique [1] with the 3 physical handles rigidly linked together, in the same manner Salzmann *et al.* propose to use a tangible device for two-user collaborative interactions [12]. Here, the shape of the tangible device is a triangle, and each handle represents one virtual hand. The size of the tangible device made up of the 3 handles matches the virtual triangle drawn by the 3 virtual hands. One user supports two corners of the CTD with the hands while the other user supports the remaining corner (Figure 1).

3.2 Method

3.2.1 Apparatus

Users were staying in front of a large screen with stereoscopic images. A Barco projector was displaying images at a resolution of 1400 x 1050 on the screen (3 m large and 2 m height). Five ART infrared cameras for optical tracking were running at 48Hz while the framerate of the screen was 48Hz per eye. The tracked area for infrared cameras was 4 x 4 m. Users wore shutter glasses and they shared the same point of view (heads were not tracked).

We provided a virtual moving camera that was following the virtual hood such that users did not have to move their body out of the tracked area. Thus, users had to walk maximum two steps during the simulation to achieve the task.

3.2.2 Procedure

24 participants volunteered to participate in our study (20 male, 4 female). Their average age was 26.4 years old. Few users had experience with 3D interaction. Most of the users were computer science students, software engineers or computer science researchers or teachers.

The task to complete is described in Figure 1. When manipulation starts, users have to move the virtual hood outside a Z-shape. This shape forces users to frequently rotate the hood to pass the Z-shape. Therefore, they have to coordinate their movements to translate and rotate the object.

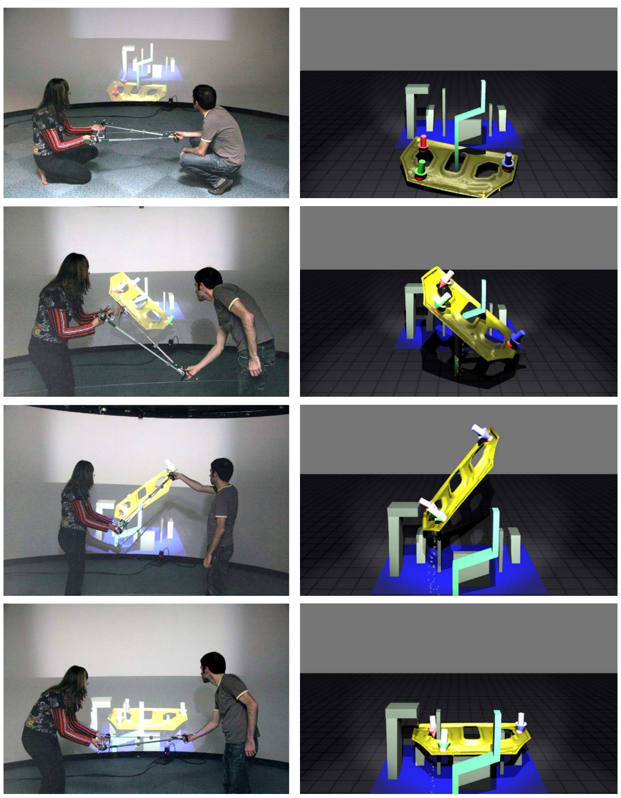

Fig. 1 Experimental task. Column on the left: two users are achieving the task with the CTD. Column on the right: movements of the virtual hood. Steps are as follows: 1) initial position, 2) passing the "elbow" of the "Z-shape", 3) passing between the "T-shape" and a stem, 4) reaching the final position. For the sake of clarity, pictures are provided with monoscopic display.

Once the virtual hood is out of the Z-shape, users have to walk one or two steps towards the virtual support to place the hood on it. This support is made of two stems that have to be aligned with the holes of the virtual hood. Furthermore, a T-shape is placed on one side of this support to force users to 1) orientate the virtual hood almost vertically, 2) align the hole of the virtual hood with the stem at the same side than the T-shape, 3) move the virtual hood towards the ground, 4) at the same time continuing to translate the virtual hood and orientate it horizontally.

For each technique, users received explanations about how it works. Then users had a few minutes to practice the technique before doing the measured task. They were free to ask any question to the instructor during the practice.

An experimental task in the real world was also proposed to help users in understanding the usefulness of practicing in the virtual world before trying to make a similar task in the real world. This "real-world task" is illustrated Figure 2.

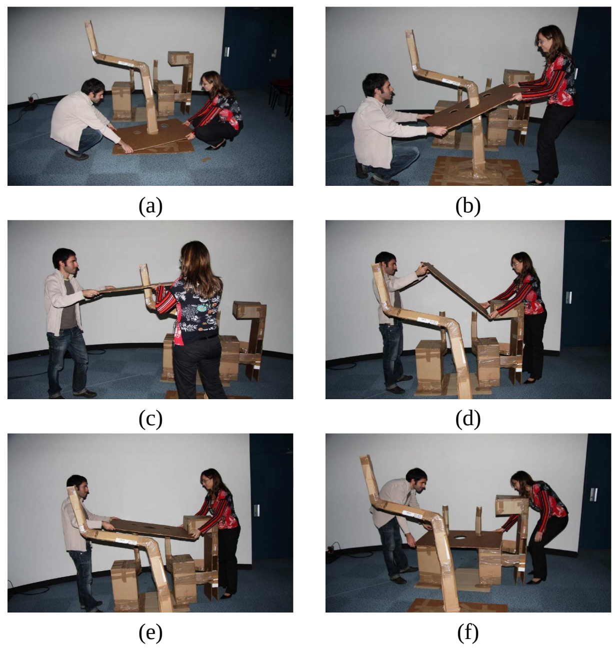

Fig. 2 Real-world task: manipulation of a "real" hood made of cardboard.

3.2.3 Experimental Plan

Experiments were conducted with 12 pairs of participants. Each pair of participant tested the 3 techniques. Participants were divided into 6 groups of users corresponding to the 6 orders of presentation of the 3 techniques. Two virtual scenes were available: one being the "mirror" of the other. Each pair of participant had to pass a total of 3 techniques x 2 virtual scenes x 2 trials = 12 trials. The global duration of the experiment was 40 minutes.

3.3 Data Collected

For each technique and each trial, we measured the time needed to complete the task.

3.4 Results

The average time spent (in seconds) to complete the experimental task with each technique is shown in table 1.

A global single factor ANOVA on the task completion time was performed for the three techniques, and three other single factor ANOVA were performed to compare pairs of techniques.

The global ANOVA indicated that the Technique factor is significant for the task completion time ($F(2,141) = 4.6$, $p = 0.0116$). This difference was highly significant between CTD and Mean ($F(1,94) = 8.47$, $p = 0.0045$), but not between CTD and Separation ($F(1,94) = 2.06$, $p = 0.155$) nor between Mean and Separation ($F(1,94) = 2.73$, $p = 0.1015$).

The preliminary conclusions about task completion time are thus that: 1) Mean is significantly faster than CTD, 2) we cannot affirm that Separation is significantly faster than CTD, or that Mean is significantly faster than Separation.

Table 1 Time needed to complete the task in the virtual environment.

Mean	23.92	$\sigma = 13.58$
Separation	28.17	$\sigma = 11.48$
CTD	31.68	$\sigma = 12.52$

3.5 Users' comments

During experiments, many users felt the CTD as a realistic technique. One user said: "the strategy for the real world is close to the technique with the triangle" and another: "we try to mimic what we do in the real world". But realism comes at a price and one user noted that sometimes he was "fighting for the movement against the other user". With the Mean technique, some users pointed out that since it acts like a low-pass filter it can slow them down or help them by damping wrong movements. Finally, users' opinions about the Separation were mixed up as only some users preferred to interact separately. The CTD was clearly preferred by our participants in terms of immersion and realism of the task.

4 Conclusion

We have conducted an experiment to compare three collaborative techniques in virtual environments: the Mean of users' motions, the DoF Separation, and a Collaborative Tangible Device (CTD). The results show that the Mean technique is faster than the other techniques, which is probably due to less body movements of the users. However, most participants found the CTD as a more realistic technique, suggesting that the CTD is a good candidate for training people to work on two-user manipulation tasks.

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