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Abstract

In this paper we introduce a new 3D interaction technique called "3-Hand Manipulation", for multi-user collaborative manipulation of 3D objects. The 3-Hand Manipulation relies on the use of three manipulation points that can be used simultaneously by three different "hands" of two or three users. Interestingly, the three translation motions of the manipulation points can fully determine the resulting 6 degrees of freedom motion of the manipulated object. We describe the implementation of the 3-Hand Manipulation, its graphical representations and an illustration of its use by two or three users on an insertion task in immersive virtual environment. This technique could be used in various applications of collaborative VR such as for virtual prototyping, training simulations, assembly and maintenance simulations.

Categories and Subject Descriptors (according to ACM CCS): H.5.1 [Information Interfaces and Presentation (e.g. HCI)]: Multimedia Information Systems—Artificial, augmented, and virtual realities; I.3.6 [Computer Graphics]: Methodology and Techniques—Interaction techniques

1. Introduction and Related Work

Object manipulation is one of the most fundamental tasks of 3D interaction in Virtual Reality (VR) [BKLP04]. Due to new 3D input devices becoming widely available even for the general public, research in new 3D user interfaces is more relevant than ever [BCF*08]. Furthermore, the collaborative manipulation of virtual objects by multiple users is a very promising area for Collaborative Virtual Environments (CVE) [BGRP01]. Collaborative manipulation of objects seems indeed necessary in many different applications of VR such as virtual prototyping, training simulations or assembly and maintenance simulations [RSJ02]. In such virtual collaborative tasks, all the users should participate naturally and efficiently to the motion applied to the object manipulated in the VE.

Although most collaborative systems support simultaneous manipulation of different objects by different users, generally only one user at a time can manipulate a virtual object. Interaction metaphors that are usually used for single-user 3D interaction, such as virtual hands, virtual rays or virtual 3D cursors, have to be adapted for collaborative 3D virtual manipulations.

1.1. Two-Hand Object Manipulation

Some 3D interaction techniques have been proposed in the field of manipulation of virtual objects with the two hands of a single user [HPPK98], but only a few of them such as "grab-and-carry", "grab-and-twirl" and "trackball" techniques [CFH97] allow users to position and rotate at the same time virtual objects.

The "grab-and-carry" technique [CFH97] is a 5 Degrees Of Freedom (DOF) bimanual symmetric tool that allows users to carry and turn an object around with both hands. Object roll lacks since it is not possible to determine rotation around the axis defined by positions of the two hands. The "grab-and-twirl" technique extends the "grab-and-carry" technique, adding the sixth DOF using either the left hand's roll, the right hand's roll, or a combination of both. The "trackball" technique is a bimanual asymmetric tool that allows users to use the non-dominant hand to position a virtual object while the dominant hand rotates this object around its center.

These techniques seem to have two main restrictions. First, they are not very representative of real world inter-

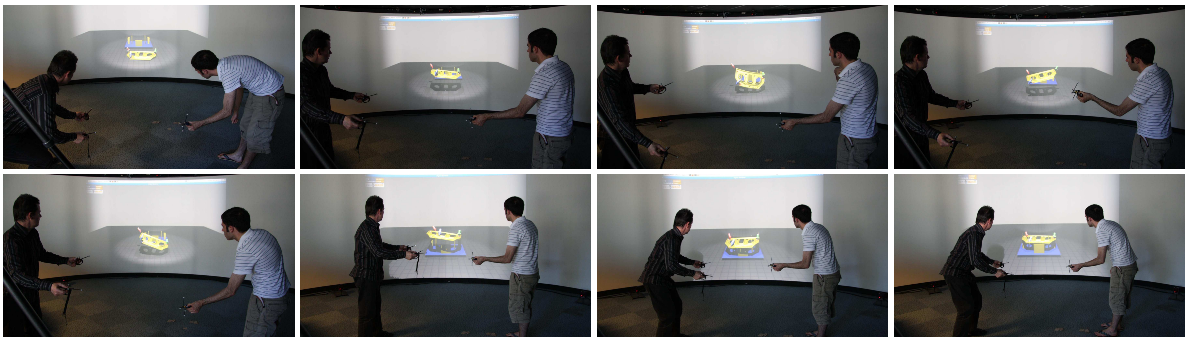

Figure 1: *3-Hand Manipulation of a virtual hood by two users.*

actions. Second, it is likely that they would not be used to simulate real interactions with large or cumbersome objects a user cannot manipulate alone.

1.2. Multi-User Object Manipulation

Several approaches are suitable to combine two users' movements to obtain virtual object's final movements [RSJ02]. A first approach consists in adding the two motions (asymmetric integration of movements). A second approach is to average the two motions. A third approach aims at keeping only the common part (intersection) of the two motions (symmetric integration of movements). But none of these combinations is ideal. Indeed, the intersection technique is the more relevant when the two users have to perform a similar action, whilst the average technique is preferred when users have to perform different tasks.

The Bent Pick Ray [RHWF06] metaphor allows several users to co-manipulate simultaneously a virtual object. This technique merges users' inputs according to the amount of hand movement a user does with her input device. Rotations are calculated with a spherical linear interpolation, while the translations are interpolated using only offset transformations, in order to move the object incrementally. Results may be close to those of the average technique.

The SkeweR technique lets multiple users simultaneously grab any part of a virtual object [DLT06]. To determine the grabbed object's translation and rotation, SkeweR considers positions of those "crushing points". A problem remains for determining the rotation along the axis determined by the two crushing points, and even with more clues, these points cannot be used in a very natural or realistic way. A similar technique seems to be used to construct a virtual gazebo [RWOS03]. Two users manipulate a beam by grabbing its extremities but no solution is proposed for the sixth DOF.

Another kind of collaborative manipulation consists in splitting the DOF task among users [PBF02]. In this case, the number of DOF that each user can access and control is limited: one user controls object's rotations while the other one controls object's translations. This can be compared to the Two-Hand "trackball" technique.

1.3. Conclusion

Separate motions of several users' inputs (from several hands or users) can be used to define the final motion of a virtual object. However, due to the complexity of current VR interfaces, no universal collaborative solution has already been proposed to naturally apply a motion to a co-manipulated object. Therefore, we propose to extend these techniques by adding a third manipulation point for the collaborative manipulation.

2. The 3-Hand Manipulation Technique

2.1. Concept

We propose a new 3D interaction technique for 6 DOF multi-user collaborative manipulation of 3D objects. Our technique 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 can be used naturally, in a realistic way, by three different "hands" of two or three users.

2.2. Manipulation and Graphical Feedback

Hands are represented by pointers. When a hand is close enough to the object to manipulate, ray-casting from the hand gives an intersection point with the object. This point is called a *manipulation point*. A manipulation point differs from a SkeweR "crushing point" and should rather be considered as a hand position. If a user starts a manipulation, a virtual ball is added to display the location of the manipulation point. In addition, a rubber band is added between the virtual ball and the hand to avoid any ambiguity concerning its owner and to display the distance between the hand and the manipulation point (Figure 3). A screenshot of the virtual

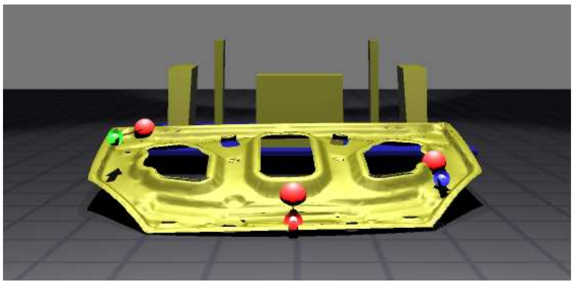

Figure 2: *Screenshot of a 3-Hand Manipulation of a virtual hood.*

environment with three hands manipulating a hood is given in Figure 2.

The rubber band drawn between a hand and its manipulation point is elastic and its color varies according to the distance between the hand and the manipulation point. The rubber band uses a green-yellow-red code: the farther a hand is from its associated manipulation point, the more the rubber band becomes redder. With such a feedback, users' hands are expected to remain close to their manipulation point to avoid instabilities during the manipulation.

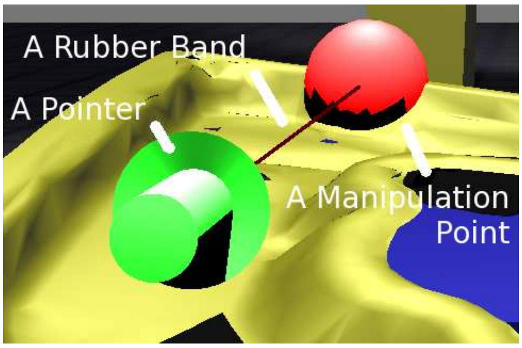

Figure 3: *A rubber band between a pointer and a manipulation point.*

2.3. Computation of Manipulated Object's Motion

The manipulated object motion can be computed in different ways using input motions of the three users' hands. One solution consists in making the manipulation points stay as close as possible to the hands. At the beginning of the manipulation, hands positions H_1, H_2, H_3 correspond to positions of their contact points P_1, P_2, P_3 with the manipulated object. These contact points are the manipulation points and are illustrated in Figure 4.

When users move their hands to H'_1, H'_2, H'_3, the $\vec{T}$ translation to apply to the initial position P_c of the manipulated

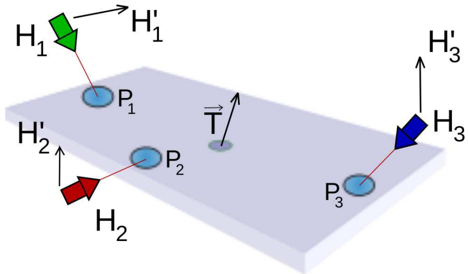

Figure 4: *Computation of virtual object's motion ($\vec{T}$) given the three hand's motions.*

object is computed as follows:

$$H_0 = \frac{H_1+H_2+H_3}{3};\ H'_0 = \frac{H'_1+H'_2+H'_3}{3};\ \vec{T} = \overrightarrow{H_0H'_0}.$$

To compute the rotation difference with the initial plane orientation, the first step consists in computing the rotation $(\vec{R_1}, \alpha_1)$ that transforms $\vec{i}$ into $\vec{i'}$ (see Figure 5):

$$\vec{i} = \overrightarrow{H_0H_2};\ \vec{j} = \overrightarrow{H_0H_3}\ \ ;\ \vec{i'} = \overrightarrow{H'_0H'_2};\ \vec{j'} = \overrightarrow{H'_0H'_3}$$

$$\vec{R_1} = \vec{i} \times \vec{i'}\ \ ;\ \alpha_1 = \arccos\left(\frac{\vec{i}\cdot\vec{i'}}{\|\vec{i}\| * \|\vec{i'}\|}\right).$$

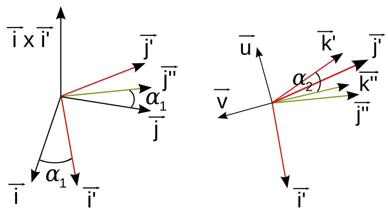

Figure 5: *Rotation* $(\vec{R_1}, \alpha_1)$ *and rotation* $(\vec{i'}, \alpha_2)$.

This rotation transforms $\vec{j}$ into an intermediate vector $\vec{j''}$:

$$\vec{j''} = (\vec{R_1}, \alpha_1) * \vec{j}.$$

The second step consists in computing the rotation $(\vec{i'}, \alpha_2)$ that transforms $\vec{j''}$ into $\vec{j'}$. After constructing a new 3D orthogonal basis $(\vec{u}, \vec{v}, \vec{i'})$, this angle is calculated as follows:

$$\begin{aligned} \vec{k''} &= (\vec{j''}\cdot\vec{u}) * \vec{u} + (\vec{j''}\cdot\vec{v}) * \vec{v} \\ \vec{k'} &= (\vec{j'}\cdot\vec{u}) * \vec{u} + (\vec{j'}\cdot\vec{v}) * \vec{v} \\ \alpha_2 &= \arccos\left(\frac{\vec{k''}\cdot\vec{k'}}{\|\vec{k''}\| * \|\vec{k'}\|}\right). \end{aligned}$$

The difference between the current and the initial orientation of the object is then obtained by combining these two rotations: $(\vec{i'}, \alpha_2) * (\vec{R_1}, \alpha_1)$.

If the first triangle, defined by the three hands' positions, and the second triangle, defined by the three initial positions of the manipulation points, do not keep the same shape then the roll angle (rotation around the axis orthogonal to these triangles) is the best possible approximation, otherwise this roll angle value is exact.

Another solution for implementation is to use three "point-to-point" constraints of a physics engine like Bullet [Bul] or PhysX [Phy]. A constraint is dynamically added between a hand and a manipulation point. Here, if the triangles do not keep the same shape, there can be some small inconsistencies for the roll angle.

In both cases, the use of a colored rubber band can help users to keep their hands close to the manipulation points.

3. Implementation

The 3-Hand Manipulation technique was implemented in a virtual reality center involving ARTracking markers [ART]. The five ART infrared cameras placed around a large screen were tracking hand positions in 3D space. Users were located in front of this large screen.

Two or three people could manipulate simultaneously a virtual hood to place it on a support. This hood had holes that users had to align with the support. This task is inspired by an assembly task faced in automative industry.

Figure 6: *Three users manipulating a virtual hood with the 3-Hand Manipulation technique.*

Physics and collisions in the virtual environments were implemented using the Bullet physics engine. Hands were manipulating objects through Bullet constraints.

First observations. During the manipulation, we observed that people needed to communicate a lot: to start or end the action, and to decide where to move the hood. All users found the 3-Hand Manipulation technique natural. During a 2-user manipulation, one user had notably the impression that "he was moving his hands in the air as he would have done with a real object".

4. General Conclusion and Perspectives

We have presented a new 3D interaction technique for multi-user collaborative manipulation of virtual objects called "3-Hand Manipulation". This technique relies on the use of three manipulation points that can be used simultaneously by three different "hands" of two or three users. The three translation motions of the manipulation points fully determine the resulting 6 DOF motion of the manipulated object.

The considered task consisted in assembling a virtual hood on a support. Different configurations were tested with two or three users. First user feedback suggests that the technique is suitable for collaborative manipulation, and further work is now necessary to evaluate and compare our approach to other existing techniques involving many users.

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