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Evaluation of a Reconfigurable Tangible Device for Collaborative Manipulation of Objects in Virtual Reality

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Abstract

In this paper we introduce an evaluation of a Reconfigurable Tangible Device (RTD) for collaborative manipulation of objects in virtual environments. The considered RTD, called RTD-3, has a triangular shape that naturally provides three points of manipulation. The shape of the tangible triangle can be reconfigured at any time as its branches can be shrunk or stretched by users at will. Thanks to this simple shape the RTD-3 can be easily attached to any 3D virtual object and fully defines its virtual motion in 6 Degrees of Freedom. We have conducted an experiment to assess the potential of the RTD-3 and compare it with classical techniques used for collaborative virtual manipulation. Participants were asked to manipulate and assemble, in a collaborative manner, virtual parts. Our results suggest that the physical manipulation proposed by the tangible device is significantly preferred by participants in terms of immersion, realism of interaction and preparation to the real task. Although our approach is slightly slower than the other tested methods, it produces the fewest collisions.

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

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1. Introduction

Object manipulation is one of the most fundamental tasks of 3D interaction in Virtual Reality (VR) [BKLP04]. Collaborative manipulation of virtual objects by multiple users is a very promising area for Collaborative Virtual Environments (CVE) [BGRP01]. Collaborative manipulation 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 are expected to participate naturally and efficiently in the manipulation of virtual objects.

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, must be adapted for collaborative 3D virtual manipulation. This is why we have proposed a new physical device named Reconfigurable Tangible Device (RTD) [ADL10b] to enable collaboration on a shared virtual object through a tangible device and precise positioning of users' real hands. The RTD maintains the distance between users hands. Besides users can modify the shape of the RTD to better fit the virtual object they intend to manipulate.

We compared the RTD-3 (a tirangular RTD) with two classical techniques for manipulating collaboratively (with two users) virtual objects: the Mean technique and the Separation of Degrees of Freedom (DoF). The first technique simply averages translations and rotations applied by the two users. The second technique allows two users to make substantially different actions: one is controlling the orientation of a virtual object while the other applies translations.

This paper is structured as follows: first, we give an overview of related work in the field of collaborative interaction in virtual environments and the use of tangible devices in virtual reality. Second, we briefly describe the concept

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and implementation of our RTD-3. Third, we describe the evaluation of the RTD-3 and its comparison with the Mean technique and the Separation of DoF. The paper ends with a general discussion and a conclusion.

2. Related Work

Here we present a state of the art about metaphors and tangible devices for collaborative 3D interactions.

2.1. Two-Handed Object Manipulation

Several 3D interaction techniques have been proposed to manipulate 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], enable users to position and rotate virtual objects. The "grab-and-carry" technique [CFH97] is a 5 Degrees-of-Freedom (DoF) bimanual symmetric tool that enables users to carry and turn an object around with both hands. Object roll is not supported since it is not possible to determine rotation around the axis defined by the 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 enables users to use the non-dominant hand to position a virtual object while the dominant hand rotates this object around its center.

In our opinion, these techniques are not very representative of real world interactions considering users' movements. In addition, they could probably not be used to simulate interactions with large or cumbersome objects that a user cannot manipulate alone.

2.2. Multi-User Object Manipulation

Several approaches are suitable to combine two users' movements to obtain the final movement of a virtual object [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 seems ideal. Indeed, the intersection technique is the more relevant when the two users have to perform a very similar action, whilst the average technique is preferred when users have to perform different tasks [RSJ02].

The Bent-Pick-Ray [RHWF06] metaphor enables several users to simultaneously co-manipulate a virtual object. This technique merges users' inputs according to the amount of hand movement a user does with one input device. Rotations are computed with a spherical linear interpolation (Slerp) [Sho85], while the translations are interpolated using only offset transformations.

The SkeweR technique enables multiple users to simultaneously grab any part of a virtual object through special points called "crushing points" [DLT06]. To determine the translation and the rotation of a grabbed object, SkeweR considers positions of those points. A problem remains for determining the rotation along the axis linking the two crushing points. 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. 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 [GMMG08]. In [SJF09], Salzmann *et al.* use two optical markers to let two users manipulate a windshield. Authors also use the simple averaging of translation and rotation to move the virtual windshield.

Another kind of collaborative manipulation consists in splitting the task among users [PBF02]. 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 one is limited to translation. This can be compared to the Two-Hand "trackball" technique [CFH97].

The concept of a 3-Hand Manipulation Technique has been introduced in [ADL09]. It 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 placed on the surface of this object. These manipulation points can be used by three different "hands" of two or three users.

2.3. Tangible Devices for Object Manipulation

A tangible device (or prop) is a real object that users can hold to move a virtual object and feel a passive tactile feedback. Such tangible interfaces are often preferred by people over non-physical interfaces [SJF09]. However, several studies show that they do not always lead to better performance [HTP*97] [WR99]. Nevertheless, passive tactile feedback can be used to increase presence and improve training effectiveness in virtual environments [IMWB01].

Many *adhoc* tangible interfaces have been proposed to mimic real objects in a virtual world. In this case, users may have to hold a scale model for interaction with the virtual environment as in [HPGK94]. If some tangible interfaces let users use both hands, to our knowledge usual tangible interfaces are generally limited to single-user interactions.

Tangibles interfaces can also be designed for helping people to coordinate their movements during a collaborative manipulation. In [SJF09], Salzmann *et al.* propose a prop for two-user manipulation that maintains the users' hands at the same distance. As such, the prop acts as haptic link between them. As position and orientation are given by only one optical marker on the top of the prop, this technique is limited to one point of manipulation. The shape of the prop also restricts its use to cases where users use only one of their hands or keep their two hands very close.

Some tangible interfaces can be re-designed and modeled, such as MERL bricks [AFM*99] or the ActiveCubes [WIA*04] where users can assemble several tangible blocks that the system would later match with 3D virtual models. Other approaches consist in deforming a malleable TUI [STP08] or balance between malleability and rigidity such as the Senspectra TUI [LPI07] or the Glume TUI [PLI06]. However, none of these reconfigurable tangible devices are rigid enough to be shared by several users.

2.4. 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 software solution has been proposed to naturally apply a motion to a co-manipulated object.

While tangible interfaces may be interesting for better collaboration between users, a lack of a universal tangible device for collaborative manipulation is apparent: to the authors' best knowledge no previous work has been done in the area of reconfigurable tangible user interfaces to find a good balance between easy reconfigurability and rigidity for the purpose of collaborative object manipulation in VR.

We assume that coupling collaborative interaction techniques with a rigid reconfigurable tangible device can improve the overall collaboration and provide a haptic passive link for collaborative manipulations between users. This will be addressed in the following sections with the evaluation of the Reconfigurable Tangible Device.

3. The Reconfigurable Tangible Device

The Reconfigurable Tangible Device (RTD) has been introduced in [ADL10b]. Its aim is to propose a universal physical interface that can match the shape of any virtual object. Besides RTD has been designed to let at least two users interact together with the same virtual object, and to let them precisely place their hands on the virtual object to grab it. Toward this goal, the RTD provides stretchable physical links between physical handles. Each of these handles matches one virtual handle in order to obtain a virtual object that is somehow "embodied" in the RTD.

3.1. A Reconfigurable Triangle for Three-Point Manipulation

In this paper, we use the instance of the RTD that is based on only three points: the RTD-3. This choice has been inspired by the 3-Hand Manipulation technique which has been introduced in [ADL09]. This technique determines the position and orientation of a virtual object through only positions of three non-aligned manipulation points placed on it. More generally, the RTD-3 could enable to grab any part of an object to manipulate even if it is in an inner or outer part of the virtual object. As a result, two or three users can move, resize or reshape a virtual object thanks to this device.

The RTD-3 is made up of three branches connected together by a pivot. Each branch can be shrunk or stretched (see Figure 1) by users by pulling a button to unblock/block a branch. When users want to attach the device to an object, they start to set the relevant branch lengths. Then they move the three virtual points associated with the device in order to touch the virtual object to manipulate. After selecting the object, users can begin to manipulate it.

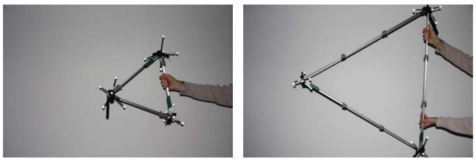

Figure 1: *Minimal and maximal configurations of the Triangular Reconfigurable Tangible Device (RTD-3).*

Varying branch lengths and using many angles let users obtain small or large triangles with arms length varying from 38 cm up to 95 cm and with angles varying from 20 degrees up to 130 degrees as a result. Users are able to grasp not only flat objects but also long, round or cubic objects. Objects can be grasped horizontally or vertically.

3.2. Implementation

The Reconfigurable Tangible Device has been evaluated within a virtual reality centre involving an ART optical tracking system. The infrared cameras were placed around a large screen facing users to track positions and orientations.

Optical markers are placed at each corner of the RTD-3. Three virtual pointers are associated with the positions of these markers, they are used to point and touch the manipulated object to begin the manipulation. Our implementation uses ray-casting coming from one pointer to add a manipulation point where the ray hits the virtual object.

To manipulate the RTD-3, one user can put one hand on one corner while the other user puts their hands on the two remaining corners. They can move the triangle seamlessly together by applying movements to the device. The beginning of the manipulation is triggered by an external button click. Buttons could also be incorporated directly on the RTD-3 to activate/release each virtual pointer individually.

4. Evaluation

The objective of our evaluation was to compare the RTD-3 with two classical techniques for collaborative virtual manipulation: the Mean and Separation of DoF techniques. The proposed task is a “pick-and-place" task involving two users in the manipulation of a virtual car hood described in [ADL10a]. We collected task completion time, number of collisions, distance covered by the virtual hood, distance covered by the users’ hands, and a questionnaire on users’ subjective preferences. Preliminary results of this evaluation about subjective preferences have been briefly presented in [ADL10b]; here, we now evaluate the results in full detail.

4.1. Three Interaction Techniques to Compare

We now analyse three different interaction techniques, with each technique covered in a separate section.

4.1.1. Technique 1: the Reconfigurable Tangible Device (RTD-3)

The RTD-3 was implemented as previously described. One user supports two corners of the RTD-3 with his hands while the other user supports the remaining corner (Figure 2). Before the selection, users can adjust the shape of the RTD-3 to fit the shape of the virtual object. When the manipulation has begun, users are not allowed any longer to modify the shape of the RTD-3.

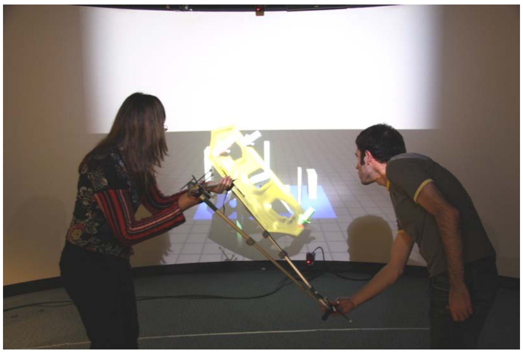

Figure 2: *Use of the RTD-3 technique.*

4.1.2. Technique 2: Averaging Users’ Actions (Mean)

The Mean technique [RSJ02] combines user’s actions by averaging positions and orientations that they provide. In our implementation [ADL10a], this technique is only concerned with users’ movements and not absolute positions. So 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 marker (Figure 3).

The result of interaction will be as follows: If users do opposite movements then the virtual object will remain almost stationary. If one user stays inactive then the other user must move excessively to apply motion. If users do almost the same movements at the same time then the car hood will move similarly. Users do not have to point to the hood before selecting it, instead they have to ask an operator to initiate the manipulation.

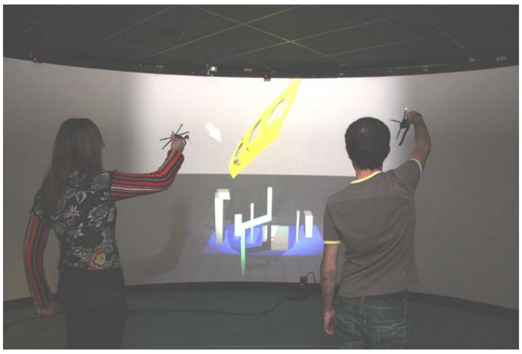

Figure 3: *Use of the Mean technique. Users are standing in a similar way since they have to synchronize their gestures to optimize the task.*

4.1.3. Technique 3: the DoF Separation (Separation)

The Separation of DoF splits the control of the degrees of freedom of the motion among users [RSJ02]. In our implementation, this technique shares common aspects with the Mean technique for placement and movement of users since people act through their movements, rather than absolute positions in space. Actions of users are separated: one is restricted to manipulating translations whilst the other one is bounded to rotations (Figure 4).

As seen with the Mean technique, each user holds only one optical marker and users do not need to select the hood before manipulating it. One marker is dedicated to translations and the other is dedicated to rotations.

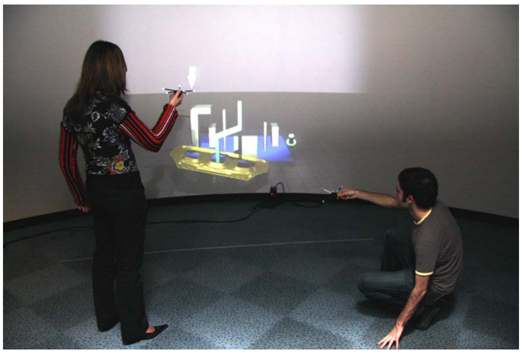

Figure 4: *Use of the DoF separation technique. The user standing on the left is orientating the hood. The other participant is translating it.*

4.2. Method

We now describe the method behind the experiment in terms of apparatus required, procedure carried out and the experimental plan.

4.2.1. Apparatus

Users were staying in front of a large screen with stereoscopic images (3 m large and 2 m height). The tracked area for the ART infrared cameras was 4 x 4 m. Users wore shutter glasses and they shared the same point of view (heads were not tracked).

The simulation used Bullet for physics and Ogre3D for 3D graphics. We provided a virtual moving camera that was following the car hood such that users did not have to move their body out of the tracked area. Thus, users had to walk a maximum of two steps in front of them during the simulation to achieve the task.

No sound was provided but yellow particles were emitted visually during virtual collisions. They were triggered when two objects collided. Shadows were provided to help users to perceive the scene depth.

4.2.2. Procedure

24 volunteers to participated in our study (20 male, 4 female). Their average age was 26.7 years old. Few users had experience with 3D interaction. Most of the users were computer science students, software engineers, computer science researchers or teachers.

The task to complete is described in Figure 5. When manipulation starts, users have to move the virtual car hood outside a Z-shape. For users, this shape forces them to frequently rotate the hood to pass the Z-shape. Therefore, users have to coordinate their movements to translate and rotate the object.

Once the virtual car hood is out of the Z-shape, users have to walk one or two steps in front of them to place the hood on the final virtual support. This support is also an abstract shape but made up 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 few minutes to practice the technique before doing the measured task. They were free to ask any question of 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 6.

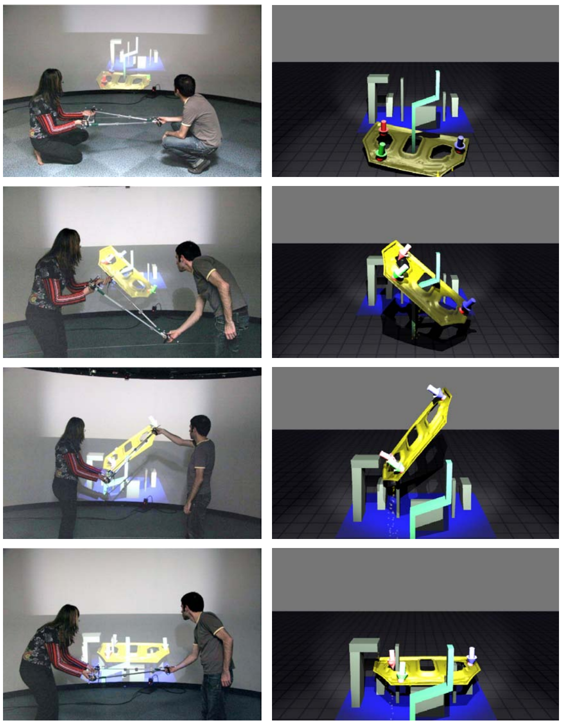

Figure 5: *Experimental task. Column on the left: two users are achieving the task with the RTD-3. Column on the right: movements of the virtual car hood. Steps are as follows: 1) initial position, 2) passing the “elbow" of the “Z-shape", 3) passing between the “T-shape" and a stem, 4) reaching the final position.*

4.2.3. Experimental Plan

Experiments were conducted with 12 pairs of users. Each pair of users tested the three techniques. Six groups of user corresponding to the 6 orders of presentation of the 3 techniques participated. Two virtual scenes were available: one being the “mirror” of the other. The type of the scene was selected randomly. Each pair of users had to pass 4 times each technique, which gives a total of 12 trials. The total duration of the experiment was 40 minutes.

For each technique and each trial, we measured the time needed to complete the task and the number of collisions between the manipulated virtual object and the other objects of the world. We also measured the distance covered by the virtual car hood and by the users’ hands. For each pair of users and each technique, we recorded the 2 best attempts of the users in terms of time spent to complete the task. We also collected the answers of participants to the subjective questionnaire.

For each criterion, we have performed a global single factor ANalysis Of VAriance (ANOVA) to compare the three

Figure 6: *Real-world task: manipulation of a "real" hood made of cardboard.*

techniques, and three other single factor ANOVA have been performed to compare couples of techniques.

4.3. Results

Table 1 shows the time spent (in seconds) to complete each task with each technique, and the number of collisions between the car hood and the other objects of the virtual world. Table 2 shows the distance covered by the car hood and the users' hands during the task with each technique.

4.3.1. Task Completion Time

A global single factor ANOVA revealed a significant main effect of the technique used on the completion time of the task ($F(2,69) = 4.9$, $p = 0.0102$). The difference was highly significant between RTD-3 and Mean ($F(1,46) = 9.63$, $p = 0.0033$), but not between RTD-3 and Separation ($F(1,46) = 2$, $p = 0.1639$) nor between Mean and Separation ($F(1,46) = 3.1$, $p = 0.0848$). The preliminary conclusion about task completion time is that RTD-3 seems significantly slower than Mean.

	Time (in seconds)		Number of collisions	
	Mean	SD	Mean	SD
RTD	26.22	$\sigma = 9.7$	151.88	$\sigma = 38.59$
Mean	18.34	$\sigma = 7.38$	166.38	$\sigma = 51.63$
Separation	22.44	$\sigma = 8.39$	227.54	$\sigma = 59.03$

Table 1: *Average time spent (in seconds) and number of collisions to complete the task in the virtual environment.*

4.3.2. Collisions

A global single factor ANOVA revealed a significant main effect of the technique used on the number of collisions during the task ($F(2,69) = 14.57$, $p < 0.0001$). The difference was not significant between RTD-3 and Mean ($F(1,46) = 1.16$, $p = 0.28$), but it was highly significant between RTD-3 and Separation ($F(1,46) = 26.48$, $p < 0.0001$) and between Mean and Separation ($F(1,46) = 13.99$, $p = 0.0005$). The preliminary conclusions about collisions is that RTD-3 and Mean seem significantly more precise than Separation.

4.3.3. Distance Covered by the Car Hood

A global single factor ANOVA revealed a significant main effect of the technique used on the distance covered by the hood during the task ($F(2,69) = 5.5$, $p = 0.0061$). The difference was significant between RTD-3 and Mean ($F(1,46) = 5.13$, $p = 0.0283$) and between Mean and Separation ($F(1,46) = 0.71$, $p = 0.0032$), but it was not significant between RTD-3 and Separation ($F(1,46) = 1.34$, $p = 0.2525$).

	Hood		Hands	
	Mean	SD	Mean	SD
RTD-3	3.78	$\sigma = 0.46$	6.37	$\sigma = 0.9$
Mean	3.46	$\sigma = 0.49$	5.78	$\sigma = 0.91$
Separation	3.96	$\sigma = 0.59$	5.78	$\sigma = 0.5$

Table 2: *Average distance (in meters) covered by the car hood and the users' hands.*

4.3.4. Distance Covered by the Users' Hands

For the RTD-3, we considered the three hands involved in the manipulation, for the Mean we considered the two hands involved in the manipulation, and for the Separation we considered only the hand of the user who was translating the car hood. Here again, a global single factor ANOVA revealed a significant main effect of the technique used on the distance covered by the hands during the task ($F(2,141) = 8.52$, $p = 0.0003$). The difference was significant between RTD-3 and Mean ($F(1,118) = 12.2$, $p = 0.0027$) and between RTD-3 and Separation ($F(1,94) = 9.09$, $p = 0.0033$), but not between Mean and Separation ($F(1,70) = 0$, $p = 0.97$).

4.4. Subjective Ratings

We recall here the subjective results that have already been presented in [ADL10b]. At the end of the experiment, each user was asked to fill a questionnaire with subjective ratings (using a 7-point Likert scale) for the 3 techniques according to the following criteria: training for the same task in the real world (Training), realism of the manipulation (Realism), feeling of presence in the virtual environment (Presence), fatigue during the manipulation (Fatigue), and how much they liked the technique (Like). Table 3 shows the results of the questionnaire.

	RTD-3		Mean		Separation	
	Mean	SD	Mean	SD	Mean	SD
Training	5.83	$\sigma = 1.37$	4.54	$\sigma = 1.32$	4.00	$\sigma = 1.72$
Realism	5.88	$\sigma = 0.99$	4.42	$\sigma = 0.88$	3.63	$\sigma = 1.64$
Presence	5.71	$\sigma = 1.12$	4.88	$\sigma = 0.85$	4.54	$\sigma = 0.83$
Fatigue	4.79	$\sigma = 1.64$	4.88	$\sigma = 1.45$	5.13	$\sigma = 1.68$
Like	4.96	$\sigma = 1.49$	5.04	$\sigma = 1.57$	5.08	$\sigma = 1.47$

Table 3: *Absolute rating of the techniques using a 7-point Likert scale.*

An Analysis of Variance (global ANOVA) revealed that the technique used had a significant effect on the rating of the **Realism** rating ($F(2,69) = 22.45$, $p < 0.00001$). For this criterion, the RTD was found significantly better rated than the Mean technique ($F(1,46) = 29.02$, $p < 0.00001$), and than the Separation ($F(1,46) = 35.71$, $p < 0.00001$). The ANOVA also revealed that the technique used had a significant effect on the **Presence** criterion ($F(2,69) = 9.72$, $p = 0.0002$). For this criterion, the RTD was again found significantly better rated than the Mean technique ($F(1,46) = 8.41$, $p = 0.0057$), and Separation ($F(1,46) = 16.73$, $p = 0.0002$). Last, the ANOVA also revealed that the technique used had a significant effect on the **Training** criterion ($F(2,69) = 9.71$, $p = 0.0002$). For this criterion, the RTD was again found significantly better rated than the Mean technique ($F(1,46) = 11.06$, $p = 0.0017$), and Separation ($F(1,46) = 16.66$, $p = 0.0002$). No significant effects were found for the other criteria: **Fatigue** ($F(2,69) = 0.03$, $p = 0.85$) and **Like** ($F(2,69) = 0.04$, $p = 0.9584$).

5. Discussion

Our evaluation aimed at assessing the potential of the RTD-3 and comparing it with other classical interaction techniques used for collaborative virtual manipulations. From our results we can first stress that the subjective questionnaire of participants turns strongly in favor of the RTD-3. These results complement findings of Salzmann *et al.* [SJF09] wherein users tend to prefer prop-based interactions over pure virtual interactions. On top of that, the RTD-3 is a good candidate for training people to work on two-user manipulation tasks as our users tend to feel themselves more prepared for a real task when using it. In [SJF09], participants were manipulating a windshield.

The RTD-3 seems to be more realistic mainly for the user who can use two hands. In his point of view, the two hands move in a very realistic way to move an object: raising one hand while lowering the other one rotates a virtual object. We think that this gesture is also responsible for the feeling of a better preparation for the real task. All the same, the user using only one hand still feels him involved in the interaction because of the haptic link of the prop.

Althought the distance covered by the hood is nearly the same with the three techniques, the distance covered by the users' hands is significantly more important with the RTD-3. It is not a surprise because users have to move their hands in opposite ways to make the hood rotate. This leads to more body movements, so it can explain that the RTD-3 can be slower than the two other techniques and that it can also be more tiring. Nevertheless, these large movements also provide a better precision during the manipulation.

We observed that users were very concerned about achieving the correct movements with the RTD-3. Usually, users were helping each other with verbal exchanges. Unrealistic movements with the Mean technique favored it. By contrast, the RTD-3 provides many precise ways to orientate a virtual object while the Mean technique can act seamlessly only when both users are coordinated. So the RTD-3 aims at letting each user interact with the same capabilities, and the Mean technique leads to a compromise solution. In fact, some users described the Mean technique as a kind of low-pass filter. Salzmann *et al.* [SJF09] found that a pure virtual technique takes longer to complete a manipulation task than a prop-based technique. This may be explained by the chosen implementations of the Mean technique. The implementation of [SJF09] averages users' positions while our implementation averages users' movements. Perhaps our implementation lets users adopt a more confortable posture since they were not constrained to remain close each other. We note however that Salzmann *et al.* [SJF09] observed that some pairs of users were able to reach times comparable to the prop manipulation with their implementation of the Mean technique.

Finally, results suggests that the RTD-3 provides users with a better feeling of training, realism and presence than the Separation technique. Indeed, this last technique carried the most mixed users' opinions in the reporting questionnaire and during informal discussions with them. Some pairs of users were acting in a very mechanical fashion: one user was translating the hood whilst the other was turning it exactly at the right time. For other pairs, one user was faster than the other and thus provided help with vocal orders to the second. With such pairs of users and no help to coordinate their gestures, the Separation technique could lead to difficulties for someone who is unable to anticipate his partner's gestures.

6. Conclusion

The Reconfigurable Tangible Device (RTD) is a universal physical interface that can match many shapes of virtual objects in collaborative virtual manipulations. The RTD-3 is an instance of the RTD device that uses the translation motions of three manipulation points to fully determine the resulting 6 DoF motion of the manipulated object.

We conducted an experiment to compare the RTD-3 with classical collaborative interaction techniques: the Mean of interactions and the DoF Separation. Objective results show that the RTD-3 ends with slower task completion time than the Mean technique probably due to the complex movements of the two-handed user, and that the RTD-3 is as precise as the Mean technique. Subjective results show that our technique provides a better sense of immersion and better realism. According to users, the RTD-3 provides a better knowledge transfer to the real world.

The evaluation suggests that the RTD-3 could be used in many collaborative applications such as for training people in virtual environments to do assembly or maintenance tasks in a collaborative manner.

7. Future Work

We have constructed an instance of RTD with four coplanar points to enable each user to use two hands in a symmetric way, we must now conduct new evaluations to compare it to the RTD-3. We have also constructed another instance of RTD with four non-coplanar points that draw a tetrahedron which could better match complex 3D shapes. We could also construct other instances of RTD with more points, for example to allow more than two users to interact with the same virtual object. We also plan to use the RTD for dynamically resizing or reshaping virtual objects.

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