Haptic Hybrid Rotations: Overcoming Hardware Angular Limitations of Force-Feedback Devices

Lionel Dominjon[1]
CPNI Laboratory
University of Angers

Anatole Lécuyer[2]
SIAMES Project
INRIA/IRISA

Jean-Marie Burkhardt[3]
EIFFEL Project
University of Paris 5/INRIA

Simon Richir[4]
CPNI Laboratory
University of Angers

ABSTRACT

This paper describes a new interaction technique called haptic hybrid rotations to overcome the physical angular limitations of force-feedback devices when manipulating virtual objects. This technique is based on a hybrid control of the object manipulated with the device. When approaching the angular mechanical stops of the device, the control mode switches from angular position-control to rate-control. The force-feedback of the device is used to simulate the use of an elastic device in the rate-control mode.

An experiment was carried out to compare this technique with two other common alternatives that are used when manipulating virtual objects with force-feedback devices: rotations scaling, and the clutching technique.

Our results showed that haptic hybrid rotations were both the fastest and the most appreciated technique for the proposed experiment.

CR Categories: H.5.2 [Information Interfaces and Presentation]: User Interfaces – *evaluation/methodology, haptic I/O, input devices and strategies, interaction styles, user-centered design*; H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems – *artificial, augmented, and virtual realities.*

Keywords: interaction technique, hybrid control, position/rate control.

1. INTRODUCTION

Object manipulation is a fundamental aspect of 3D interaction in Virtual Reality. Indeed, grabbing, moving, and orienting objects are basic tasks of most of virtual reality applications [3].

Numerous studies showed that using force-feedback when manipulating virtual objects can greatly enhance user's performance [2].

But force-feedback devices (more specially grounded-devices [4]) often have a limited physical workspace, especially concerning the angular motions. For this reason it is often impossible to achieve large movements in the virtual environment (VE) in a simple motion of the hand.

This issue has been widely studied regarding the translational component of manipulation, and some effective solutions have emerged [6, 7, 11]. But very few solutions have been proposed regarding rotations, due to the complexity of this issue. This problem becomes particularly important in VR applications where the user needs a full control over the object orientation, such as assembly simulation.

In the present paper, we describe a novel interaction technique to overcome this limitation when manipulating objects in a VE with a force-feedback device. This technique is based on a hybrid angular position/rate control of the object manipulated by the user in the VE. The force-feedback of the device is used to simulate the use of an elastic device in the rate-control mode. We also report on an experiment that we carried out to compare this technique with two other alternatives: rotations scaling and clutching. The task consisted in building a pyramid made of several cubic bricks with a force-feedback device. This was a complex task which required manipulation of virtual objects beyond the physical angular stops of the device.

Therefore, this paper starts with an overview of related work focusing on the problem of artificially extending the angular range of input devices. It is followed by a description of the design and implementation of haptic hybrid rotations. Then we report on the experiment that we conducted to evaluate this technique compared to the two aforementioned techniques. Finally, the paper ends with a general discussion on the results of the experiment and a conclusion on this study.

2. RELATED WORK

Due to the exponential diffusion of force-feedback interfaces in virtual reality applications, several techniques were proposed to overcome the physical constraints of such devices. The first technique which can be used is a "clutching" mechanism [18]. Picking up a computer mouse when it reaches the edge of the table and re-positioning it in the middle is a familiar example of clutching. It consists in temporarily suspending the mapping of the input device to the manipulated object: when the user reaches the boundaries of the workspace of the device, the object is de-clutched and then re-clutched in a comfortable position. For example, a clutching mechanism is directly integrated in the hardware controller of VIRTUOSE force-feedback devices from HAPTION [11]. De-clutching

[1]e-mail: dominjon@ingenierium.com
[2]e-mail: anatole.lecuyer@irisa.fr
[3]e-mail: jean-marie.burkhardt@inria.fr
[4]e-mail: simon.richir@gmail.com

and clutching are usually achieved by pressing and releasing an auxiliary button.

From some point of view, angular clutching behaves like a natural action for the user. Indeed, clutching preserves directional compliance between the user's motion and the manipulated object [16]. This means that when the user rotates the device, the virtual object rotates in the same direction (around the same axis). However clutching is also frustrating and can notably impair user performance. Indeed, Zhai pointed out that de-clutching and re-clutching processes take time to complete, which may significantly decrease user performance [20]. In addition, performing clutching operations may make the interaction seem unnatural, reducing the feeling of engagement [9]. Clutching also does not preserve nulling compliance since when the user rotates the device to its initial position, the manipulated object does not necessarily return to its initial position [16]. This may be an issue when using physical props at the tip of the device [12].

To reduce or cancel the need for clutching, non-isomorphic mappings may be used. This means that the user moves objects in ways that have no analog in the physical world [14]. Rotation scaling is an example of non-isomorphic mapping and was described by Poupyrev et al. in [16]. It is based on quaternion compositions, and may be organized in two categories: absolute and relative mappings. Absolute mapping consists in amplifying the global orientation of the device, whereas relative mapping consists in amplifying the rotation that occurred since the previous simulation step. The main issue with absolute mapping is probably the fact that they do not preserve directional compliance. Thus unpredicted rotations of the object may occur. Nevertheless, relative mappings are not a robust solution for extending the angular range of a device because they do not preserve nulling compliance with the device. This results in a drift of the initial orientation, which makes the scaling factor impossible to calibrate. On the contrary, absolute mappings do preserve nulling compliance, which makes possible to calibrate the device to map a given angular range onto the device angular range.

A third interaction technique that may be used to overcome the limitations of haptic devices with small workspaces is a hybrid position/rate control technique. De Boeck and Coninx use such a hybrid control to manipulate the viewpoint in a VE with a PHANToM device [17]. When the rotation exceeds a certain threshold around the ascendant axis, the camera automatically starts rotating. In addition to the visual feedback, an auditory feedback is generated to provide information about the camera velocity.

Hybrid position/rate control has also been used for haptic point-based interaction [5, 6]. In the Bubble technique, described by Dominjon et al. in [6], a spherical bounding volume – the "bubble" – is defined around the neutral position of the haptic device. The control mode of the manipulated object is switched when it crosses the surface of the bubble: when it is located inside, its motion is position-controlled (direct mapping of the user's motion onto the object's motion); when it is outside, the object is rate-controlled, and it may reach any location of the VE very quickly. The bubble is displayed both visually and haptically. The visual display consists in a semi-transparent sphere, looking like an actual "bubble", and the haptic display of the bubble is achieved by applying an elastic radial force as the object crosses the surface and goes outside the bubble. The Bubble technique was demonstrated to provide an accurate and fast mean to manipulate virtual objects out of the workspace of the device.

3. Design of Haptic Hybrid Rotations

3.1. Concept

The basic idea behind hybrid control is to detect when the user reaches the mechanical stops of the device, and continue his motion in the same direction automatically. Our aim is to design an efficient metaphor to adapt the concept of the Bubble technique described in [6] to rotations. Angular position-control is used around the neutral position of the device, i.e. while the device remains in a bounding volume centered on the neutral position, and switches to angular rate-control when approaching the mechanical stops of the device, i.e. when the extremity of the device gets outside the bounding volume.

3.2. Angular boundaries

Regarding translations, the effective workspace of a force-feedback device may be easily represented by haptically constraining the device inside a bounding volume – e.g. a sphere – and visually displaying this volume. But when it comes to rotations, finding an efficient metaphor to *visually* and *haptically* represent the mechanical stops of the device becomes a highly challenging issue. Indeed, rotation space is not a vector-space like translation space, but a closed curved-space that can be represented as a 4D sphere. Therefore, we chose to separate the 3 degrees of angular freedom and display yaw/pitch (2DOF) together and roll (1DOF) separately.

Regarding the roll component, we chose to bind this degree of freedom with two imaginary angular springs constraining the device between two given orientations (see Figure 1). When the device operates *between these two angular springs*, the roll of the manipulated object is *position-controlled*; *beyond* the springs, it is *rate-controlled*.

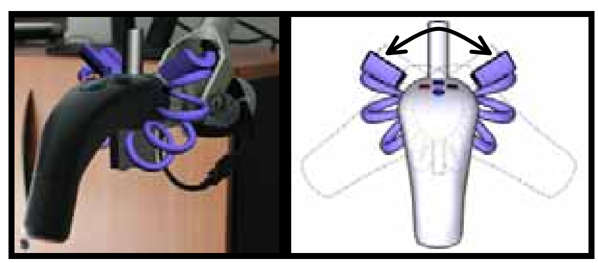

Figure 1. Roll control - between the virtual springs: angular position-control; beyond the virtual springs: angular rate-control.

Regarding yaw and pitch, the space contained between the mechanical stops would be bounded by a prismatic conic-like shape. For simplification and usability purpose, we chose to approximate this shape to a cone (see Figure 2). When the device operates *inside the cone*, yaw and pitch are *position-controlled*; *outside the cone*, they are *rate-controlled* (see Figure 7).

Figure 2. Yaw and pitch control - inside the cone: angular position-control; outside the cone: angular rate-control.

Of course, the axis of this cone is not constant and changes according to the position of the device. This is particularly visible on force-feedback arms using a serial architecture [8]. Yet, it is probably preferable for the cone to keep a constant orientation to avoid consistency problems. Indeed, seeing the cone rotating while moving the device in a translation-only motion could possibly lead to some kind of confusion for some users. Therefore, we chose to keep the axis of the cone parallel to the world-reference Z-axis (pointing to the user).

3.3. Bimodal display of the cone and springs

We propose to display the cone and the roll angular springs both haptically and visually. This choice was made to ensure a consistency between the visual and haptic spaces.

3.3.1. Haptic display

The haptic display is expected to supplement the visual display to help the user to distinguish between the two control modes – angular position-control and rate-control. It is also expected to improve the angular rate-control by simulating the use of a self-centring elastic device. Indeed, relations between the resistance mode of the device and the transfer function used in the interaction technique were studied by Zhai in [19]. He showed that, in general, elastic devices should be preferred for rate-control, due to the self-centring effect of the device. On the contrary, isotonic devices are usually more efficient for position-control. The force feedback of our apparatus is thus used to match Zhai's recommendations. When the device operates in the position-control zones, an isotonic device is simulated, i.e. no torque is applied except the contact torque, which corresponds to the contact between the manipulated object and the VE. When the device operates in the rate-control zone (i.e. outside the cone and/or outside the roll limits), a self-centring device is simulated.

The self-centring effect is achieved by applying a torque when the device crosses the surface of the cone or compresses the roll angular spring. The restoring torque we use is thus proportional to the angular penetration depth of the device into the angular rate-control zone. Equation (1) defines the torque applied on the device when it operates outside the cone, and equation (2) defines the torque applied when the device operates beyond the roll springs. When the device operates outside the cone and beyond the roll spring at the same time, $\vec{T_c}$ and $\vec{T_r}$ are summed and the torque applied on the device is calculated as in equation (3):

$$\vec{T_c} = -k_c \cdot (\alpha_d - \alpha_c) \cdot \vec{n} \quad (1) \qquad \vec{T_r} = -k_r \cdot (\theta_d - \theta_r) \cdot \vec{r} \quad (2)$$

$$\vec{T} = \vec{T_c} + \vec{T_r} \quad (3)$$

where k_c and k_r are constant parameters, α_d is the angle between the roll axis of the device and the axis of the cone, α_c is the cone half-angle, θ_d is the device roll, θ_r is the roll limit (see Figure 4), $\vec{r}$ is the main axis of the device (roll axis), and $\vec{n}$ is the normal axis, defined as the cross product between the main axis of the device and the cone axis.

The cone and the springs constrain the device in a comfortable workspace; they are comparable to software stops that somewhat restrict the actual physical angular workspace of the device on each axis. These software stops prevent the device from reaching the real physical stops. The main advantage of software stops over physical stops is that the device is allowed to operate slightly beyond the stop.

3.3.2. Visual display

In addition to the haptic display, the cone and the roll limits are displayed visually as well. An avatar of the device is also displayed to provide the user with hints regarding its orientation.

Visual display of the virtual boundaries.
The cone is visually displayed as a semi-transparent cone frustum (see Figure 3 and Figure 4). Its opacity depends on the device angle: the cone only appears when the device gets close to its surface. This avoids overloading the visual scene when not necessary. The roll limits are displayed as two curved springs (see Figure 3 and Figure 4).

Visual display of the avatar.
An avatar of the device handle is also displayed. It is constituted by a red spherical probe, a white cylinder representing the main axis of the device, and a another smaller white cylinder, perpendicular to the main axis and representing the roll index (see Figure 3). The probe is used to detect interferences between the avatar and the objects of the VE.

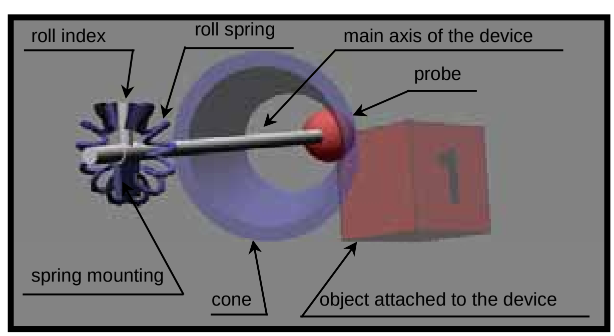

Figure 3. Visual display: cone, roll springs and avatar of the device.

The cone and the springs are deformed when compressed by the avatar of the device. This is supposed to improve consistency between haptic and visual displays, and help the user visualizing the location of incursion in rate-control zone. As a result, the avatar of the device never gets outside the *visual* cone, although it may get outside the cone used to switch from angular position to rate control (see Figure 7). Moreover, the color of the cone and springs continuously changes according to the stress applied by the user, from green (light pressure) to red (hard pressure).

3.4. Angular position and rate control

When the device operates in the angular position-control zone, i.e. inside the cone or between the roll springs, the angular motion of the device is directly mapped onto the manipulated object. This isomorphic mapping provides the user with natural and accurate manual interaction.

When the device crosses the surface of the cone or gets beyond the roll spring, the user's motion controls the angular velocity of the manipulated object (see Figure 7). The axis of rotation is orthogonal to both the cone axis and the device main axis, and the magnitude of the angular velocity is proportional to the penetration depth of the device in the rate-control zone. That is to say the velocity increases as the user approaches the physical stops. The center of the rotation is the center of the spherical probe of the avatar (see Figure 3).

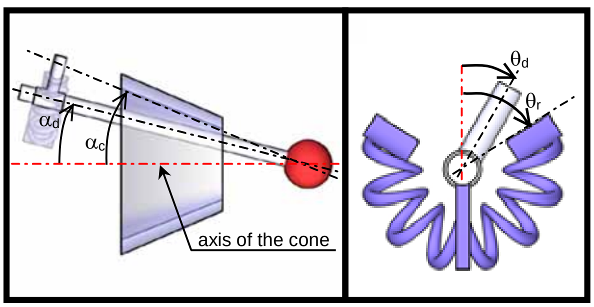

Figure 4. Definition of angles used in equations (1) to (6).

Equation (4) defines the angular velocity vector set to the object when the device operates outside the cone, and equation (5) defines the angular velocity vector set to the object when the device operates beyond the roll springs. When the device operates outside the cone and beyond the roll spring at the same time, $\vec{\Omega}_c$ and $\vec{\Omega}_r$ are summed and the velocity vector set to the manipulated object is calculated as in equation (6):

$$\vec{\Omega}_c = k_c' \cdot (\alpha_d - \alpha_c) \cdot \vec{n} \quad (4) \qquad \vec{\Omega}_r = k_r' \cdot (\theta_d - \theta_r) \cdot \vec{r} \quad (5)$$

$$\vec{\Omega} = \vec{\Omega}_c + \vec{\Omega}_r \quad (6)$$

where k_c' and k_r' are constant parameters, and α_d, α_c, θ_d, θ_r, $\vec{n}$, and $\vec{r}$ are the same as in section 3.3.1.

3.5. Torque applied to the user

In rate control, the torque applied to the user is the sum of the reaction torque of the VE on the manipulated object and the elastic torque generated by the haptic cone or spring (provided by Equation (1), (2) or (3)). Thus, when the manipulated object touches a static obstacle in rate control, the contact torque generated tends to rotate the device back into the angular position-control zone and thus stops the object's motion [13].

4. Evaluation

To evaluate the performance of haptic hybrid rotations, we conducted an experiment that consisted in building a pyramid made of several cubic bricks using a given interaction technique chosen among three different candidates (haptic hybrid rotations, scaling and clutching). Participants were asked to perform the task as precisely as possible. The performance of participants was recorded in terms of task completion time and quality of the final pyramid.

At the end of the experiment, a preference test was also proposed, in which participants had to test the three techniques and rank them according to several subjective criteria.

4.1. Participants

15 participants aged from 19 to 50 (mean=32, sd=8.8) took part in this experiment. Six of them were females. All of them, except two, were right-handed. None of them had known perception disorders, and all participants were naïve to the purpose of the present experiment.

4.2. Experimental apparatus

The haptic device we used for the experiment was a VIRTUOSE 6D35-45 from HAPTION [10]. 6 DOF object manipulation was simulated using Novodex SDK [15]. A virtual coupling with the force-feedback device was used to render contacts in the VE [1]. The frequency of the force-feedback was equal to 1kHz.

Visual feedback was displayed on a 21" CRT screen in monoscopic conditions. The framerate was equal to 60Hz. The visual display of the virtual environment consisted in a ground, six cubes laying in foreground at the beginning of the experiment, and a model of the pyramid to build on the top left corner of the screen (see Figure 5). The length of the edges of the cubes was equal to 4cm. Each cube held a number from 1 to 6 on one face in order to uniquely identify its orientation. The force-feedback device was represented in the VE by an avatar as described in section 3.3.2.

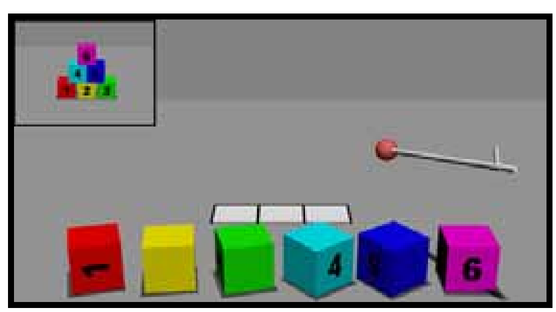

Figure 5. Visual display of the test application.

4.3. Compared techniques

Three techniques were implemented and compared during the experiment: rotations scaling, clutching and haptic hybrid rotations.

We intentionally did not mix several of these basic techniques. For example, using a clutching technique combined with a scaling factor could have reduced the need for clutching. But our intention was here to test and compare the possibilities of each "raw" technique (the technique as described in the literature) separately, in order to find out their main advantages and drawbacks distinctly.

The same technique was used to move objects in translation in all conditions: the isomorphic motions technique [18].

4.3.1. Scaling

The scaling technique (***Scaling***) was implemented as described in the literature [16]. An absolute mapping was used since nulling compliance is not preserved with relative mapping. The orientation of the object being manipulated was set through Equation (7) where q_{obj} is the quaternion representing the orientation of the manipulated object and q_d is the quaternion of the device. The scale factor was chosen to map the minimum effective joint angle of the device (≈45°) to a half-turn (180°). This resulted in a scaling factor equal to 4, according to Equation (8).

$$q_{obj} = q_d^{\,k} \quad (7) \qquad k = \frac{180}{minimum\_joint\_angle} \quad (8)$$

4.3.2. Clutching

Clutching (***Clutching***) was implemented as described in the literature [9]. When reaching one of the angular mechanical stops of the device, participants had to press a clutching-button (placed on the device handle) to de-clutch, move back to a more comfortable position, and release the clutching-button to re-clutch.

4.3.3. Haptic hybrid rotations

Haptic hybrid rotations (***Hybrid***) were implemented as described in section 3. To fit the VIRTUOSE angular workspace, we used a cone angle equal to 30° (α_c=15°). The roll limits θ_r were set to ±17°. Regarding the torque used to simulate an elastic device (equations (1) and (2)), we set k_c=2N.M.rad^{-1} for the cone and k_r=0.2N.M.rad^{-1} for the roll spring. Preliminary tests showed that these low values of angular stiffnesses avoided any stability issues. Regarding the angular velocity vector (equations (4) and (5)), we chose a constant gain k_c'=0.01s^{-1} for the cone and k_r'=0.001s^{-1} for the roll spring.

4.4. Procedure

Participants were standing in front of the screen (see Figure 6). The VIRTUOSE force-feedback device was placed on a stand in front of them, at a 1m height. The VIRTUOSE was grasped by its handle.

A learning phase was proposed, in which they were invited to read a set of instructions about the experiment and the apparatus. They were then demonstrated how to use the VIRTUOSE and how to manipulate the cubes. They had an unlimited period of time to get used to the technique and to the task before the evaluation actually started.

The experiment was then divided into two separate parts: one building test, and one preference test.

Figure 6. Experimental setup.

In the **building test**, participants had to build a pyramid with the 6 presented cubes. Participants were shown on a sheet of paper a model to reproduce, and this model was reproduced on the top left of the screen. Participants were instructed to build the pyramid as precisely as possible [18]. At the beginning of every trial, each cube was always placed at the same starting position (number 1 to number 6, from left to right), and in a random starting orientation. Cubes were grasped by intersecting the device probe with the desired object and clicking a grasping-button. The object was released by clicking again. Once released, the object remained static, like frozen in space. Participants had only one grasping per cube, i.e. re-grasping was not allowed. Indeed, as we stated in section 4.3, we did not want to mix the different techniques evaluated ; allowing re-grasping would have introduced a clutching component in every technique. All participants had to place the cubes in the same order (starting with number 1, ending with number 6). Once every cube was positioned, the pyramid disappeared and the cubes were restored in their initial conditions.

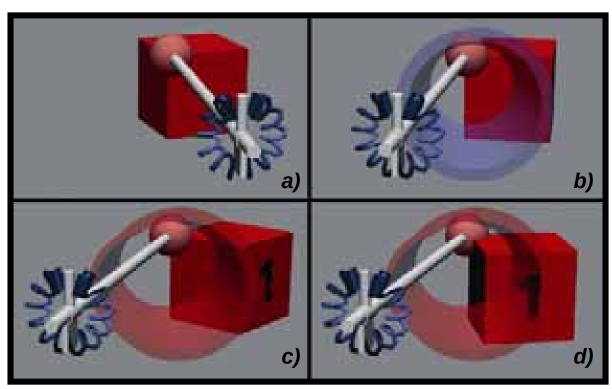

Figure 7.
a) inside the cone: angular position-control;
b) approaching the inner-surface of the cone: the cone appears;
c) and d) deforming the visual cone: angular rate-control.

Participants had to perform five successive trials, i.e. five pyramids. The 15 participants were divided into 3 groups. Each group used only 1 technique among the 3 possibilities (Scaling, Clutching or Hybrid). This decomposition implied that each interaction technique was used by 5 participants during the building test.

The **preference test** was passed immediately after the building test. It consisted in a free evaluation of the three possible interaction techniques. Participants tested the three techniques in an arbitrary order during one trial each. They were then allowed to re-test all the three techniques at their will.

The test ended with a subjective questionnaire in which participants had to rank the three techniques according to five subjective criteria: *global appreciation*, *cognitive load required*, *physical tiredness*, *estimated accuracy*, *and estimated speed*.

The global experiment lasted about 45 minutes including the learning phase and breaks.

4.5. Collected data

During the building test, recorded variables were the *task completion time* and the *accuracy of the building*.

The task completion time, measured in seconds, was equal to the time required to complete the whole task in each trial, i.e. the elapsed time from the grasping of the first cube to the release of the last cube.

The accuracy of the building, measured in degrees, was equal to the sum of the angular differences between the final user-defined orientation of the cubes and their target orientation within a completed trial.

After the preference test, the rankings of the three interaction techniques, according to the subjective criteria were also collected.

4.6. Results

4.6.1. How did the interaction technique affect performance of participants?

We computed a Multivariate Analysis of Variance (MANOVA) on two performance indicators: the *task completion time*, and the *accuracy of the building*. The between participants factor was the interaction technique used during the building test (Scaling vs. Clutching vs. Hybrid).

Task completion time.
There was a significant main effect of the interaction technique (Lambda Wilks=0.640; F(6,140)=5.826, p<0.0001). The subsequent ANOVA (analysis of variance) for each of the three indicators suggests that this effect was mainly related to total time to complete the task.

Indeed, the task was completed the quickest (see Figure 8) using haptic hybrid rotations (mHybrid=130.8s, sd=44) and then with the clutching technique (mClutching=216.6s, sd=107) and the scaling technique (mScaling=284.6s, sd=122). The ANOVA test was highly significant for the total time (F(2,72)=15.655, p<0.0001). Furthermore, post-hoc tests indicated a significant difference between each three techniques (corresponding Fischer PLSD tests from p<0.02 to p<0.0001).

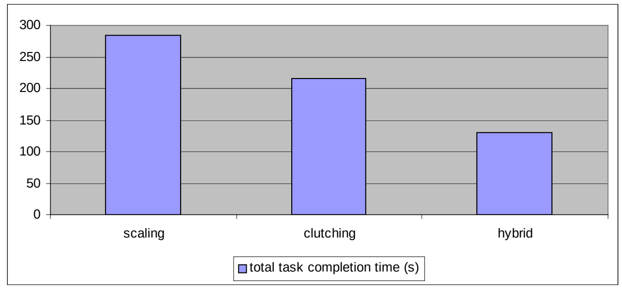

Figure 8. Results of the building test (task completion time).

Accuracy of the building.
Considering accuracy, the smallest angular distance was observed in the case of the scaling technique (mScaling=31.2°, sd=21). Then haptic hybrid rotations showed about 10° more than the scaling technique in terms of angular accuracy (mHybrid=41.3°, sd=58), corresponding on average to 1.6° more per cube, when compared to the scaling technique. The clutching technique performed slightly worse (mClutching=43.9°, sd=50), corresponding to 2.2° more per cube compared to the scaling technique. However, due to the high between-subjects variability, the ANOVA was not significant (F(2,72)=0.537, n.s.).

4.6.2. How did participants subjectively evaluate the different techniques?

Based on the total of rankings for each technique, we first verified that the evaluation was not affected by the technique used during the previous building test (Cramer V2=0.005; Khi2=4.632, DoF=4, n.s.). In other words, participants did not evaluate the technique differently depending on which technique they have just tested before. Then, we performed an ANOVA on each of the five subjective dimensions (criteria) used to ordinate the three proposed techniques. The five dimensions were: global appreciation of the technique, estimated cognitive overload, physical tiredness, estimated accuracy and estimated speed. The within-participants factors were the three techniques evaluated: Scaling, Clutching and Hybrid. The average rankings were treated as a score. Results are summarized as follows.

Haptic hybrid rotations were evaluated the best in terms of global appreciation (mHybrid=1.4) followed by clutching (mClutching=1.9) and scaling (mScaling=2.7). Statistical test was significant (F(2,42)=17.730, p<0.0001). Furthermore, post hoc tests showed that the three techniques were differently evaluated (all Fisher PLSD significant, p<0.05).

Haptic hybrid rotations were perceived as the easiest technique in terms of physical tiredness (mHybrid=1.4, sd=0.5), followed by the clutching technique (mClutching=1.8, sd=0.7) and finally by the scaling technique (mScaling=2.8, sd=0.6) (F(2,42)=22.750, p<0.0001). Post hoc tests showed that the scaling technique differed significantly from both haptic hybrid rotations and clutching (Fischer PLSD, p<0.0001), whereas haptic hybrid rotations and clutching did not differ (Fischer PLSD, n.s.).

The same scheme was found for the estimated accuracy and speed supported by the techniques. For both estimated accuracy and estimated speed, we found that haptic hybrid rotations were the best rated (mHybrid=1.5, sd=0.74) followed by the clutching technique (mClutching=1.9, sd=0.74) and the scaling technique (mScaling=2.7, sd=0.5). Differences were significant in both cases ($F(2,42)=12.511$, $p<0.0001$). Post hoc tests showed that the scaling technique differed significantly from both haptic hybrid rotations and clutching (Fischer PLSD, $p<0.002$ whereas hybrid and clutching did not differ in a significant way (Fischer PLSD, n.s.).

Finally, no significant differences were reported in terms of cognitive overload ($F(2,42)=1.943$, n.s.). Nevertheless, haptic hybrid rotations were once again better rated than clutching and scaling techniques (mHybrid=1.7, sd=0.9; mClutching=2.1, sd=0.8; mScaling=2.2, sd=0.6).

As shown on Figure 9, the haptic hybrid rotations technique was systematically preferred whatever the criterion, and whatever the technique used during the building test.

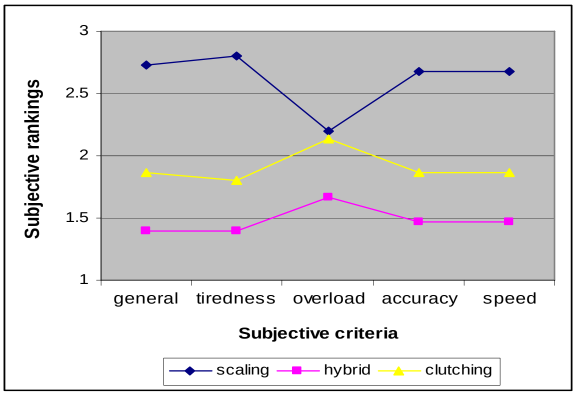

Figure 9. Results of the subjective evaluation.

4.7. Discussion

Our evaluation demonstrated that using haptic hybrid rotations allowed the participants to perform the experimental task 40% faster than using a clutching mechanism, and 53% faster than amplifying rotations (i.e. more than twice as fast) when precision was emphasized. On the contrary, we did not notice any significant effect of the interaction technique on the accuracy of rotations in this experiment, which is consistent with the instruction of maximum accuracy that the participants were given.

Concerning how participants subjectively appreciated the three techniques, haptic hybrid rotations were globally preferred to the other techniques. Indeed, regarding the global appreciation criterion, ranking differences were found to be significant. On the contrary, regarding the other criteria, haptic hybrid rotations were preferred but the differences with the other techniques were not significant.

One main observation that may be drawn from the experiment is that scaling was definitely not as appreciated as the two other techniques. The absence of directional compliance was really disturbing for most users, as expected from [16]. Some participants admitted they quickly gave up trying to understand the behavior of the object and performed random motions, hoping to stumble on the correct orientation. One participant described it as "as easy as driving a trailer backwards". In addition, the problem that was supposed to be solved using an absolute mapping instead of a relative mapping was not solved actually. Indeed, even if the scaling factor was calculated to map the device workspace on the full angular virtual workspace, participants often reached the mechanical stops anyway. This was mainly due to the lack of directional compliance, causing participants to get confused during manipulation.

The manipulation scheme using clutching was perceived as easier to understand. The direct 1:1 mapping used when clutched hardly required any learning, which made the technique effective very fast. However, two main drawbacks were pointed out during the experiment. First, the synchronization between the user's hand motion and the de-clutching mechanism was sometimes confusing for most participants. Second, the use of an auxiliary button to trigger the de-clutching mechanism sometimes resulted in a confusion with the grasp/release button.

Haptic hybrid rotations were perceived as a natural technique. The problem of visual overload that we expected did not seem to be disturbing for the participants. During a discussion after the whole experiment, one of the participants asked why the cone had been removed at the end of the experiment, whereas it had not. This suggests that the visual boundaries (the cone and the roll springs) could be removed without impairing the performance of the technique. Haptic hybrid rotations could be implemented with two modes: novice (with visual assistance), and expert (without visual assistance). Of course this needs to be confirmed by further experiments. On the contrary, the torque feedback used to simulate an elastic device is a special feature of haptic hybrid rotations that should not be removed. Indeed, according to preliminary tests, angular rate-control without torque-feedback (for example using a 3D mouse) seems very difficult to use – which is consistent with Zhai's recommendations [19]. Nevertheless, some further experiments are necessary to demonstrate that torque-feedback is absolutely necessary and provides haptic hybrid rotations with the best performances. Compared to the other techniques, we noticed that haptic hybrid rotations were the only technique which never led the user to an uncomfortable wrist/arm posture. Indeed, this technique inherently keeps the hand of the user in front of him, in a comfortable space. The main comment we received regarding this technique concerned the lack of angular amplitude. That is, the angular position-control zone was too small with respect to the whole angular workspace of the device. Further investigations are then needed to match the device workspace more closely.

5. Conclusion

This paper described a new technique to overcome the physical angular limitations of force-feedback devices for the manipulation of objects in virtual environments. This technique is based on a hybrid angular position/rate control and uses force-feedback to emulate an elastic device during rate-control. We carried out an experimental evaluation which showed that, in *our experimental conditions*, this technique was up to twice as fast as the other two techniques, without any significant loss of precision. Haptic hybrid rotations were also well appreciated by the participants, mainly regarding the global appreciation criterion.

Future work.
We would like to evaluate the performance of haptic hybrid rotations in the context of a "real" application, such as an industrial assembly simulation. We also would like to investigate the possibility to replace the software force-feedback used to simulate an elastic device by a hardware mechanism. With such a mechanism, we could use haptic hybrid rotations with passive (non force-feedback) devices and develop new concepts of interfaces. Last, we also would like to carry further evaluations with optimized techniques (e.g. clutching with a scaling factor slightly greater than 1) to define the optimal range of efficiency of every technique.

Acknowledgment.
The authors would like to thank Dr. Jérôme Perret from HAPTION for his valuable help during the development of the test application. We also would like to thank all the participants who took part in this experiment for their kindness and their patience.

REFERENCES

[1] P. J. Berkelman, R. L. Hollis, and D. Baraff, "Interaction with a Real-Time Dynamic Environment Simulation Using a Magnetic Levitation Haptic Interface Device", presented at IEEE International Conference on Robotics and Automation, 1999.

[2] S. J. Biggs and M. Srinivasan, "Haptic Interfaces", in *Handbook of Virtual Environments*, K. Stanney, Ed. London: Lawrence Earlbaum, Inc., 2002, pp. 93-116.

[3] D. Bowman, E. Kruijff, J. LaViola, and I. Poupyrev, *3D User Interfaces, Theory and Practice*, 2004.

[4] G. Burdea, "Keynote Address: The Challenges of Large-Volume Haptics", presented at Virtual Reality International Conferences, Laval, France, 2000.

[5] G. Casiez, "Contribution à l'étude des interfaces haptiques - le DigiHaptic : un périphérique haptique de bureau à degrés de liberté séparés." *PhD Thesis*. Lille, University of Lille, 2004.

[6] L. Dominjon, A. Lécuyer, J.-M. Burkhardt, G. Andrade-Barroso, and S. Richir, "The "Bubble" Technique: Interacting with Large Virtual Environments Using Haptic Devices with Limited Workspace", presented at World Haptics Conference (joint Eurohaptics Conference and Haptics Symposium), Pisa, Italy, 2005.

[7] A. Fischer and J. Vance, "PHANToM Haptic Device Implemented in a Projection Screen Virtual Environment", presented at 7th International Immersive Projection Technologies Workshop and 9th Eurographics Workshop on Virtual Environments, Zurich, Switzerland, 2003.

[8] P. Garrec, J.-P. Friconneau, and F. Louveau, "VIRTUOSE 6D: A new Force-Control Master Arm Using Innovative Ball-Screw Actuators", presented at ISR, 2004.

[9] C. Hand, "Survey of 3-D Interaction Techniques", *Computer Graphics Forum*, vol. 16, pp. 269-281, 1997.

[10] HAPTION, http://www.haption.com

[11] HAPTION, "VIRTUOSE API V2.0 Programming Manual", 2004.

[12] K. Hinckley, R. Pausch, J. Goble, and N. Kassell, "Passive real-world interface props for neurosurgical visualization", presented at SIGCHI conference on Human factors in computing systems, Boston, MA, US., 1994.

[13] R. L. Hollis and S. E. Salcudean, "Lorentz Levitation Technology: a New Approach to Fine Motion Robotics, Teleoperation, Haptic Interfaces, and Vibration Isolation", presented at International Symposium for Robotics Research, 1993.

[14] M. Mine, "Virtual Environment Interaction Techniques", University of North Carolina TR95-018, 1995.

[15] Novodex SDK, http://www.novodex.com

[16] I. Poupyrev, S. Weghorst, and S. Fels, "Non-isomorphic 3D rotational techniques ", in *Proceedings of the SIGCHI conference on Human factors in computing systems* The Hague, The Netherlands ACM Press, 2000 pp. 540-547

[17] SensAble Technologies, http://www.sensable.com

[18] C. Ware, "Using hand position for virtual object placement ", *Vis. Comput.* , vol. 6 pp. 245-253 1990

[19] S. Zhai, "Human Performance in Six Degree of Freedom Input Control", *PhD Thesis*, in *Department of Industrial Engineering*, University of Toronto, 1995.

[20] S. Zhai, P. Milgram, and W. Buxton, "The influence of muscle groups on performance of multiple degree-of-freedom input ", in *Proceedings of the SIGCHI conference on Human factors in computing systems: common ground* Vancouver, British Columbia, Canada ACM Press, 1996 pp. 308-315