"A^4": A Technique to Improve Perception of Contacts with Under-Actuated Haptic Devices in Virtual Reality

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Abstract

The objective of this paper is twofold. First, it aims at positioning the performance of under-actuated haptic devices as compared to fully-actuated haptic devices and unactuated devices (i.e. input devices) in virtual reality. Second, it proposes a technique - called "A^4" - to improve the perception of contacts when using an under-actuated haptic device in virtual reality. This technique focuses on point-based haptic exploration. When a contact occurs in the simulation, we suggest to rotate the virtual scene in order to align the contact normal with the direction of the actuated axis (or axes) of the haptic device. With this technique, the virtual scene moves itself automatically to provide a more "realistic" sensation of contact. An experimental evaluation showed first that the performance of under-actuated force-feedback was located between the no-haptic condition (worst performance) and the full-haptic condition (best performance). Second, the use of the A^4 technique decreased strongly the "penetration" inside virtual objects, and thus globally improved the performance of the participants in situation of under-actuation.

1. Introduction

Due to the current cost and weight of haptic actuators, most haptic devices – and more especially wearable haptic devices – have today less actuators than sensors. This condition of haptic "*under-actuation*" implies that the haptic device can "sense" many motions of the user but, unfortunately, can not send efforts in enough directions to constrain all these motions. Recently, Barbagli and Salisbury [2] provided a theoretical framework describing these situations of under-actuation and the problems they generate. When the number of actuators is not sufficient, the simulation seems to "react" strangely, attracting or repulsing the user for no reason. Barbagli and Salisbury concluded that "specific haptic rendering" should be proposed to cope with these problems. Actually, as for today, there is a need for two kinds of investigation about the use of under-actuated haptic devices:

1. Evaluation of under-actuated devices in terms of both performance and subjective preference as compared to the use of fully-actuated haptic devices and unactuated device (i.e. input devices).
2. Development of new types of haptic rendering and interaction techniques in order to improve the perception of force-feedback, when using an under-actuated haptic device.

In this paper, we provide partial answers to these two questions. A technique is first proposed to improve sensations of contact in situation of under-actuation, in virtual reality. Then we report on an experimental evaluation conceived both for evaluating the proposed technique, and for positioning more globally the performance of under-actuated haptic devices as compared to the use of fully-actuated haptic devices and of unactuated devices.

2. Related Work

The benefit of using haptic feedback was first demonstrated in robotic applications. It is well-known that the presence of force-feedback can significantly improve the performance of an operator during a teleoperation task [8] [12]. In virtual reality, several studies also showed that using a haptic feedback can significantly improve the performance [10].

A haptic device is said to be under-actuated when its number of actuators (na) is smaller than its number of sensors (ns) [2]. In this situation, the perception of efforts is degraded and the user may get confused. Wang and Srinivasan [13] found that the performance of locating an object in a Virtual Environment (VE) decreased when using a 6 DOF haptic device which does not provide the user with the three torque feedback. Situations of under-actuation were well illustrated by Barbagli and Salisbury [2] in a sensor/actuator asymmetry framework. They conducted an experiment in which the participants manipulated one point in 2D using a haptic device with only one actuated axis (na=1 and ns=2). The manipulated point was put in contact with a virtual wall. When the normal of the wall was aligned with the actuated axis of the haptic device, the participants estimated that their sensation of contact was "realistic". When the virtual wall was rotated by 90° and its normal became perpendicular to the actuated axis, the sensation of contact was judged "unrealistic". The limit found by the authors for a "quite realistic" sensation of contact corresponded to an angle between the normal of the plan and the actuated axis of 30° [2].

To cope with the lack of actuators (i.e. of active DOF) of under-actuated haptic devices, researchers have already proposed several solutions. The most radical solution is the sensory substitution, which translates haptic information using another sense [1]. For instance, Massimino and Sheridan substituted the haptic information of contact force by using a modulated auditory feedback [8]. Another solution consists in using metaphors to simulate the missing haptic information. Lécuyer et al. [7] proposed a haptic metaphor to simulate torques using a device that provided only force feedback. The rotations and translations of virtual objects were treated separately. In the rotation mode, the virtual objects were rotated through the use of a virtual trackball (a "Virtual Haptic Sphere") which enabled the user to "feel" torques as if he/she was manipulating a lever [7]. Koutek and Post [5] proposed another technique using spring-based tools to manipulate virtual objects. They displayed properties such as forces, inertia, or friction "visually", by using the extension and compression of a visual spring attached to the manipulated object. Thus, they could feel contacts using a simple tracker, i.e. without any force-feedback. Last, Lécuyer et al. [6] have proposed the concept of "pseudo-haptic" feedback which uses the combination of passive haptic information and visual feedback to give "haptic illusions" and simulate properties such as friction or stiffness.

3. The "A^4" Technique

3.1. Hypotheses

We restricted our framework to two specific cases. Future work will be necessary to extend our results to the cases that are not enclosed here.

- First, we only considered point-based interaction. Point-based interactions are found in many painting or sculpture softwares, and in most haptic API [11] [9]. This implies that rotations (in input) and torques (in output) were not considered.
- Second, we focused our study on Cartesian haptic devices. This encloses devices in which actuators and sensors are aligned with the axes of the orthogonal frame.

3.2. Concept

In situation of contact between the manipulated object and another object of the virtual environment, a rotation of the entire virtual scene is performed. Each contact is characterized by one contact point (here the manipulated point) and one contact normal. The rotation of the scene is used to align the normal of contact with the actuated axis (or axes) of the haptic device. We thus propose an Automatic Alignment with the Actuated Axes of the haptic device: A.A.A.A or "A^4" technique.

Figure 1 displays the concept of the A^4 technique in the canonical case of Barbagli and Salisbury [2] (see related work). In this case, the user manipulates one point in the 2D horizontal plane. Axis A2 is the only actuated axis of the haptic device. Axis A1 is not actuated. On Figure 1a, the point collides with a static object. The contact normal (N) is perpendicular to the surface of the object. Since the contact normal is not aligned with the actuated axis, the virtual scene is rotated around A3 (Fig. 1b), until the two vectors N and A2 become co-linear (Fig. 1c). Thus, the situation turns progressively to a "realistic" situation of contact, as a reference to Barbagli and Salisbury framework [2].

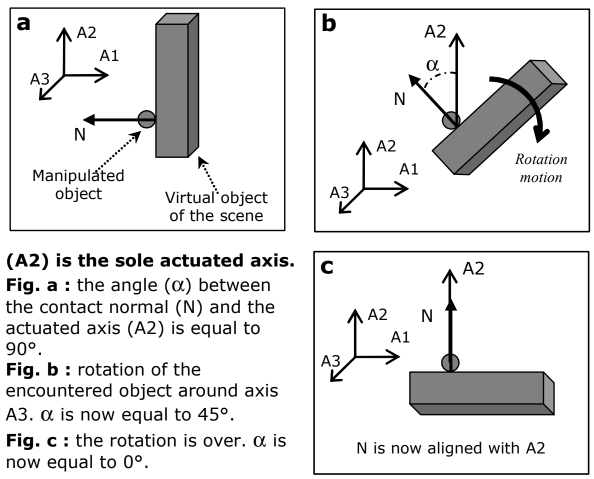

Figure 1 – Concept of the A^4 technique.

3.3. Implementation

The algorithm of the A^4 technique encloses six successive actions, launched at each time step of the main simulation loop:

1. **Get user's motion**. Measure the input motion of the device along the three Cartesian axes (translation Tu).

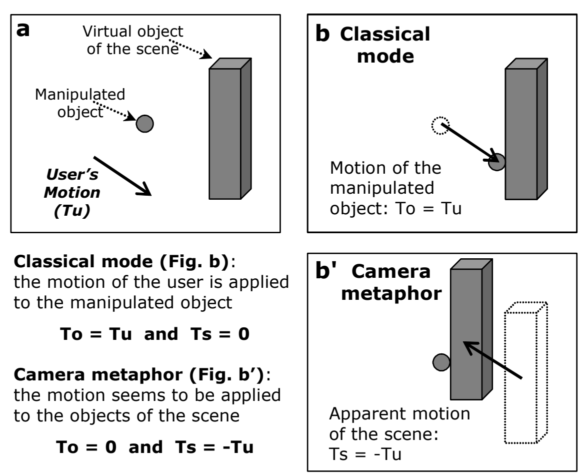

Figure 2 – Use of the camera metaphor.

2. **Apply motion.** Apply the translation motion to the manipulated object, using the "camera metaphor" or "eyeball-in-hand" technique [4]. In this mode, the

translation motion of the user is also applied to the camera used to display the virtual environment (see Figure 2). The manipulated object is thus always displayed at the center of the screen. This technique prevents objects from getting out of the field of view when rotated (especially with long objects and when the contact occurs in a corner of the screen).

3. **Detect collision.** Check if the manipulated object is in contact with one or multiple objects of the VE.

4. **Get contact normal**. Compute the normal of contact. In case of multiple contacts, the contact normal is the average of all elementary normals of contact.

5. **Compute theoretical rotation.** Compute the rotation which aligns the contact normal (N) with the actuated axis (or axes) of the haptic device. This rotation aims at projecting (N) on the actuated axis (or axes) of the haptic device. It is defined by one axis of rotation (A) and one rotation angle (α). Table 1 provides computations of (A) and (α) according to three cases of under-actuation.

UaH Case:	Case 1	Case 2	Case 3
Num. of Sensors	2 (on axes A1 and A2)	3 (A1, A2, A3)	3 (A1, A2, A3)
Num. of Actuators	1 (on axis A1)	1 (A1)	2 (A1, A2)
Rotation Axis	- A3	N ∧ A1	(N.A1).(N∧A1) + (N.A2).(N∧A2)
Rotation Angle	Acos (N.A1)	Acos (N.A1)	Acos ((N.A1)^2 + (N.A2)^2)

Table 1 – Computation of rotation axis (A) and rotation angle (α) as a function of the contact normal (N) in the Cartesian frame (A1, A2, A3), according to three cases of under-actuation. (*Note: the number of actuators (Na) is always strictly smaller than the number of sensors (Ns). Cases in which Na=0 are not relevant. Vectors are all normalized)*.

6. **Apply elementary rotation**. Apply an elementary rotation to the virtual scene depending on the time step (Dt). This elementary rotation is defined by the rotation axis (A) and an angular speed (S) which varies as a function of angle α. For high values of α (α>30°) the angular speed is set to its maximum (see Figure 3). For lower values of α, the rotation motion does not need to be fast and the speed is smaller (see Figure 3). The angle of this elementary rotation is equal to the product of the angular speed and the time step (Dt*S).

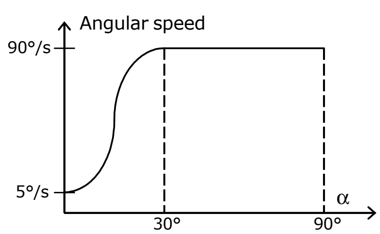

Figure 3 – Profile of angular speed used.

4. Experimental Evaluation

The objective of the evaluation was twofold. First, we wanted to evaluate the use of the A^4 technique in situation of under-actuation. Second, we also wanted to compare more globally the use of an under-actuated haptic device with the use of a "fully-actuated" haptic device as well as with an unactuated device.

Figure 4 – Experimental set-up.

The evaluation was focused on the canonical case described by Barbagli and Salisbury [2]. We considered a point-based exploration. The sole authorized motions were in 2D, in the horizontal plane. The chosen task consisted in following the contour of a virtual object. The participants had to achieve this task with different virtual objects, as precisely and as fast as possible. Three possible levels of *haptic actuation* were used: no-haptic, full-haptic, and under-actuated haptic feedback. These conditions were combined with two *rotation* conditions, i.e. with or without a rotation of the virtual scene.

4.1. Participants

Ten young adults aged between 22 and 27 passed this experiment (Mean=23.6, SD=1.7). There were nine men and one woman. The participants had no known perception disorders and were unaware of the purpose of the experiment.

4.2. Experimental Apparatus

The VIRTUOSE 35-40 device from Haption [3] was used to "simulate" a Cartesian device. The VIRTUOSE is a 6 DOF force-feedback arm. Using the force-feedback of the device, the handle of the VIRTUOSE was forced to remain on the horizontal plane. The orientation of the handle was also forced to remain aligned with the vertical axis. The remaining motions of the handle were thus the two translations on the 2D horizontal plan. The force-feedback of the VIRTUOSE was sent back to the participants at a frequency of 1000Hz.

The visual display used was a simple SGI 17" computer screen in monoscopic conditions and with a frame rate of 40Hz.

4.3. Procedure

The participants were standing in front of the computer screen (see Figure 4). They grasped the extremity of the haptic device with the dominant hand and could only manipulate it on the horizontal plan.

The visual display of the computer screen corresponded to a top-view of the 2D plan in which the participants manipulated the haptic interface. In this 2D virtual environment, the participants manipulated a small pink ball which was always located at the center of the screen, due to the use of the camera metaphor (see Figure 2). When manipulating the pink ball, the participants could explore the environment and enter in contact with a large yellow virtual object. Two semi-transparent spheres were displayed at the surface of the virtual object. The first sphere (green) corresponded to a starting position. The second sphere (red) corresponded to an ending position. The participants were asked to collide and maintain contact between the manipulated pink ball and the virtual object. They were asked to follow the contour of the virtual object, beginning by touching it at the level of the green sphere, and following its surface until the red sphere was reached. They were asked to make the full turn of the object as fast as possible and always trying to maintain contact with the object. The trial ended when the red sphere was reached. The next trial was then automatically launched.

A long learning phase was initially proposed to the participants during which they were taught with the characteristics of the experimental apparatus. They had also to perform one complete series of trials, which was not taken into account in the data processing. The whole experiment lasted about 90 minutes, including the learning phase and breaks.

4.4. Experimental Conditions

Levels of Haptic Actuation

In all conditions, a 3D green frame was used graphically to display the extremity of the VIRTUOSE in the virtual environment. When in contact, the green frame could penetrate inside virtual objects, but the manipulated pink ball was forced to stay at the surface of objects, such as in the God-Object method proposed by Zilles and Salisbury [14]. The participants were asked to always maintain a small distance between the green frame and the pink ball. Three ordinal levels of haptic actuation were then used to manage contacts between the manipulated ball and the encountered virtual objects:

- **No Haptic Feedback (NoH).** No force was sent back to the user in the horizontal plane. The manipulated sphere remained visually at the surface of the virtual object, but the user could "penetrate" inside the object, in the haptic space.
- **Full Haptic Feedback (H).** A contact force was sent back to the user along the direction of the contact normal, in 2D. This force was computed using a classical virtual coupling [12] - made of one spring and one damper in parallel - between the extremity of the haptic device and the manipulated virtual object.
- **Under-Actuated Haptic Feedback (UaH).** A force was sent back in one direction of the horizontal plane. One coordinate of the contact force (computed as in the previous case) was taken into consideration while the other one was set to zero. Force-feedback could constrain the user's motions along the sole forward-backward axis.

Rotation Conditions

In case of contact between the manipulated ball and the virtual object, two modes were possibly used:

- **Rotation Mode (R).** The virtual scene was rotated in order to align the contact normal with the forward-backward axis of the haptic device (vertical axis of the visual display). The rotation was achieved as described in case 1 of Table 1.
- **No Rotation Mode (NoR).** The virtual scene was not rotated and thus the orientation of the visual display remained always identical.

Virtual Objects

Four different virtual objects were used (see Figure 5). These four objects were: a "star" (O1), a "labyrinth" (O2), an "inverted" labyrinth (O3) and a "lock" (O4).

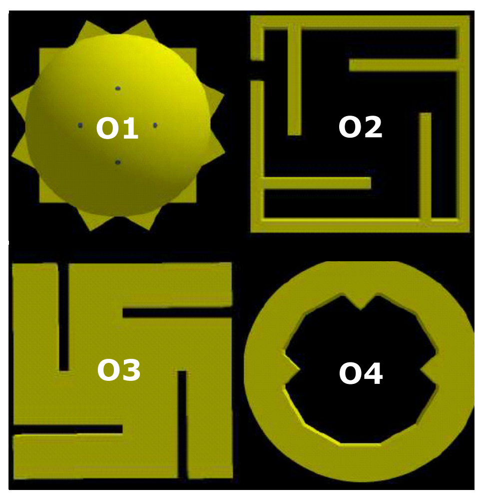

Figure 5 – Virtual objects used.

Experimental Design

There were 24 experimental conditions obtained by the combination of: 3 Haptic conditions (H, NoH, UaH), 2 Rotation conditions (R, NoR) and 4 virtual Objects (O1, O2, O3, O4). The 24 tests were randomized within one block of tests. There were 3 consecutive blocks of tests for a global amount of tests of 24*3=72 tests.

4.5. Recorded Data

Three performance indicators were gathered for each participant and trial: the total time (*total time*) needed to achieve the contour of the virtual object (in seconds), the number of times the participant lost contact with the virtual object (*losses of contact*), and the average "penetration" (*penetration*) inside the virtual object, which corresponded to the average distance of penetration of the user inside the surface of the virtual object in the haptic space when in contact, in dm. The penetration corresponded to the distance between the green frame and the pink ball (see part 4.4).

Furthermore, we also measured the average value of angle α (*contact angle*), which corresponded to the angle between the contact normal and the actuated axis of the haptic device in case of under-actuation (see Figure 1). This indicator is used to control the effect of our technique. The contact angle is indeed expected to decrease in presence of the A^4 technique.

4.6. Results

We performed a Multivariate ANalysis Of VAriance (MANOVA) on the three performance indicators: Total Time, Losses of Contact, and Average Penetration inside the virtual object. The Within participants conditions were the $Haptic_3$, $Rotation_2$, $Object_4$ and $Trial_3$.

We found that the four main effects are significant: the level of Haptic actuation (Lambda Wilks=.236; F(6,1292)=228.207, p<.0001), the absence or provision of Rotation of the scene (Lambda Wilks=.925; F(3,646)=17.486, p<.0001), the shape of virtual Objects (Lambda Wilks=.110; F(9,1572)=257.433, p<.0001) and the repetition related to Trials (Lambda Wilks=.925; F(6,1292)=8.590, p<.0001). Furthermore, we observed the following significant higher level interactions: Rotation and Haptic (Lambda Wilks=.911; F(6,1292)=10.271, p<.0001), Object and Haptic (Lambda Wilks=.868; F(18,1828)=5.227, p<.0001), Object and Rotation (Lambda Wilks=.934; F(9,1572)=4.964, p<.0001).

Let us begin by assuming that any further detailed analyses of Object's and Trial's main effects would be of no interest here, since such significant tests merely state that the participants' performance depended on the object's shape and on the repetition of trials. In contrast, Haptic and Rotation main effects must be further analyzed since they are the central issue of our work: this is done in the following part. In the same way, the specific two-way interaction between Rotation and Haptic must be detailed. Indeed, this interaction shows specifically the influence of the A^4 technique on the performance of the participants.

Level of haptic actuation: effect on the performance?

Subsequent ANalyses Of VAriance (ANOVA) demonstrated that the level of Haptic actuation have a significant effect on the *total time* required to perform the task (F(2,648)=12.141; p<.0001). When Haptic actuation was optimal (i.e. fully-actuated force-feedback), we found that participants were more efficient since they needed on average 25s (sd=13) to perform the task. Their performance was worst when no haptic axis was actuated in the horizontal plan (mean for NoH=mNoH=29s; sd=15). The performance of the under-actuated condition (UaH) is found logically between the two previous values: participants needed 27,5s (sd=15) when only one axis was actuated. Post-hoc tests suggested that the time needed was significantly different between each of the three conditions (all Fisher PLSD comparisons at p <.05).

Haptic actuation had also an effect on the number of *losses of contact* (F(2,648)=19.139; p<.0001). Indeed, when the level of actuation increased from no-haptic to full-haptic feedback, we observed that the number of losses of contact decreased (mNoH=24, sd=11; mUaH=22, sd=11; mH=21, sd=10). Post-hoc tests suggested that the three conditions differed significantly (all Fisher PLSD comparisons at p <.04).

The level of haptic actuation had again a strong and significant effect on the performance in terms of *penetration* inside the virtual objects (F(2,648)=836.377, p<.0001). When no haptic actuation was provided in the horizontal plan, the average penetration was around 0,101dm (sd=0,031) whereas it was of 0,068dm (sd=0,023) when only one axis was actuated, and 0,031dm (sd =0,008) when the haptic device was fully actuated. Post-hoc tests showed that the three conditions differed significantly (all Fisher PLSD comparisons at p <.04).

Rotation of the scene: effect on the performance?

Providing the participants with a rotation of the virtual scene significantly increased the *total time* needed to perform the task (mNoR=25,14s; sd=12,041; mR=29,15s; sd=15,972; F(1,648)=29.674, p<.0001). The virtual Rotation also affected significantly the number of *losses of contact* (F(1,648)=22.389, p<.0001): we indeed observed slightly fewer losses of contact when the rotation of the scene was not performed (mNoR=22, sd=10; mR=23, sd=12). However, the participants *penetrated* on average slightly less with a rotation of the scene (mR=0,066dm, sd=0,038) than without (mNoR=0,067dm, sd=0,035). However, this effect was not significant (F(1,648)=0,845, n.s).

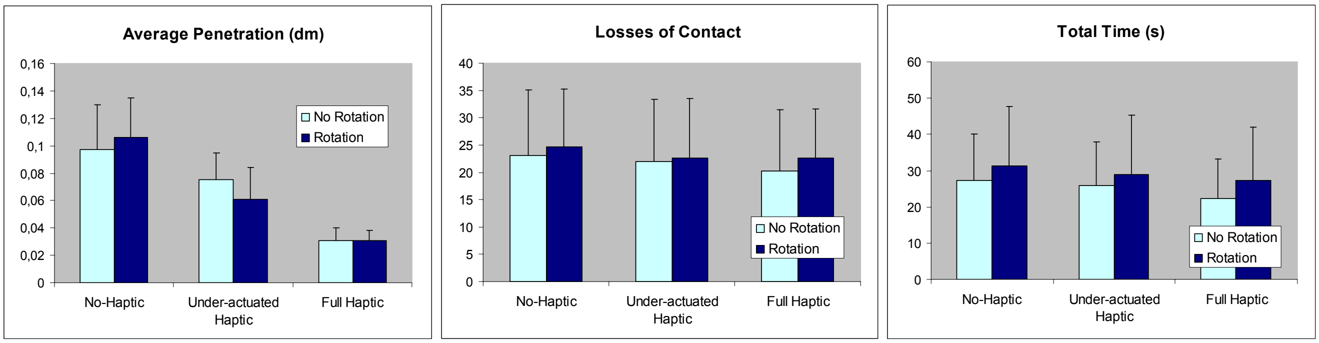

Figure 6 – Rotation x Haptic interaction.

Haptic and rotation interaction: does the A^4 technique improve the performance?

The MANOVA previously demonstrated a significant two-way interaction between the level of Haptic actuation and the presence of a Rotation of the scene. This implies a global effect of A^4 on the performance of the participants.

Subsequent analyses of variance (ANOVA) show more specifically that the interaction was strongly significant for the average *penetration* inside the virtual object ($F(2,648)=22.859$; $p<.0001$) (see Figure 6). A similar but non significant trend was found for the number of *losses of contact* ($F(2,648)=2.608$; $p<.07$). Last, the two-way interaction between Haptic and Rotation was not found significant for the *total time* needed to perform the task ($F(2,648)=.433$, n.s.).

Contact angle: does the A^4 technique maintain an optimal contact angle?

We ran a repeated-measure model of ANOVA on the contact angle data. The Within participants factors were the $Haptic_3$, $Rotation_2$, $Object_4$, and $Trial_3$.

The average contact angle between the contact normal and the actuated axis was significantly smaller ($F(1,9)=162{,}31$, $p<.0001$) with a Rotation of the scene than without (mNoR=49.4°, sd=3 ; mR=32.1°, sd=5). Thus, the contact angle decreased strongly when a rotation was performed to the virtual scene (see Figure 7). The contact angle reached a value close to the limit found by Barbagli and Salisbury [2], i.e. 30°.

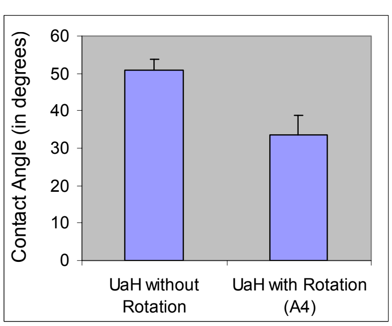

Figure 7 – Contact angle in under-actuated situations.

5. General Discussion

Our results showed first that the performance with under-actuated feedback is inferior to the performance when using a “fully-actuated” haptic device. This is probably due to the strange behavior of the manipulated device in situation of under-actuation. Indeed, under-actuated force-feedback attracts or repulses the user sometimes very strongly and very strangely.

However, our results also showed the benefit of using an under-actuated haptic device, as compared to no force-feedback at all. Since they were more guided at the surface of virtual objects, the participants were more efficient in following the contour of virtual objects with under-actuated force-feedback than with no force-feedback at all. This suggests that under-actuation is still of interest as compared to the use of input devices.

The presence of a rotation of the virtual scene slightly impaired the global performance of the participants in terms of task completion time. The rotation of the virtual scene somehow distracted the users during their main task, implying probably changes of orientation in their reference frame, and changes in their mental models. It was also probably more difficult to follow the contour of the virtual object when it was constantly moving.

However, in the under-actuated situations, this rotation tended to align the direction of the contact force with the actuated axis of the haptic device. Indeed, the average contact angle (angle between the contact normal and the direction of the actuated axis) decreased and reached a value close to 30°. This value of 30° was found to be the limit for a “quite realistic” sensation of contact by Barbagli and Salisbury [2]. Therefore, the rotation made the situation evolve toward a “more realistic” simulation of contacts, closer to the fully-actuated condition.

Thus, we logically found an effect of the rotation on the performance of the participants in situation of under-actuation. The presence of this rotation (i.e. the use of the A^4 technique) decreased strongly the penetration inside the virtual objects, and then globally improved the performance of the participants.

Taken together our results suggest a trade-off between the performance and the sensation of contacts. The A^4 technique seemed indeed to have a positive impact on the subjective perception of contacts but, in the same time, the presence of the rotation of the scene tended to slightly impair the performance in terms of task completion time.

Therefore, if the designer of a virtual environment using under-actuated haptic devices wants to focus on the performance, then he/she should maybe stay in the "normal" situation, i.e. without using the proposed A^4 technique. However, if he/she prefers to focus on the haptic perception of the user, then he/she could use the A^4 technique.

6. Conclusion

We have proposed a technique called A^4 (Automatic Alignment with the Actuated Axes of the haptic device) to improve the user's perception of contacts in situation of haptic under-actuation in virtual reality. This technique is based on an automatic rotation of the virtual scene, in order to align the contact normal with the available actuated axis (or axes) of the haptic device.

An experimental evaluation of the A^4 technique was conducted. It first enabled to position the use of under-actuated devices, showing that an under-actuated haptic feedback is more efficient than no force-feedback at all, but still remains less efficient than a complete ("full") haptic feedback. The use of the A^4 technique was globally found to influence the performance of the participants positively in situation of under-actuation, since it brings the situation closer to the use of a fully-actuated haptic device.

Designers of virtual environments with under-actuated haptic devices – and especially with wearable haptic devices – could use the A^4 technique in applications where the haptic perception of users is the most fundamental aspect to preserve.

Future work. First, we would like to extend our results to 6DOF manipulation and uses of non-Cartesian devices. Second, we would like to study the use of the A^4 technique when interacting with usual objects and several levels of complexity (a pen, a car, a house, or a landscape). It might be more difficult and disturbing to use A^4 when interacting with large and halo-centered objects. Third, the rotation modifies the viewpoint of the user on the virtual scene. We would like to investigate whether this modification could help or disturb the user, in several contexts of application. Fourth, we would like to study new kinds of device or interaction technique based on our approach. For instance, we could imagine a haptic device with only 1 active DOF to probe the VE in 3D, making a full use of a technique such as A^4.

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References

[1] P. Bach-y Rita, J.G.Webster, W.J. Thompkins, and T. Crabb, "Sensory substitution for space gloves and for space robots", *Workshop on Space Telerobotics*, Vol. 2, pp. 51-57, 1987.

[2] F. Barbagli and K. Salisbury, "The effects of sensor/actuator asymmetries in haptic interfaces", *Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, 2003.

[3] Haption Company. http://www.haption.com

[4] K. Hinckley, R.F. Pausch, J.C. Goble, and N.F. Kassell, "A Survey of Design Issues in Spatial Input", *ACM Symposium on User Interface Software and Technology,* pp. 213-222, 1994.

[5] M. Koutek and F.H. Post, "Spring-based manipulation tools for virtual environments", *Symposium on Immersive Projection Technology and Virtual Environments*, pp. 61-70, 2001.

[6] A. Lécuyer, S. Coquillart, A. Kheddar, P. Richard and P. Coiffet, "Pseudo-Haptic Feedback: Can Isometric Input Devices Simulate Force Feedback?", *IEEE International Conference on Virtual Reality*, pp. 83-90, 2000.

[7] A. Lécuyer, A. Kheddar, S. Coquillart, L. Graux, and P. Coiffet, "A Haptic Prototype for the Simulations of Aeronautics Mounting/Unmounting Operations", *IEEE International Workshop on Robot-Human Interactive Communication*, 2001.

[8] M.J. Massimino and T.B. Sheridan, "Sensory Substitution for Force Feedback in Teleoperation", *Presence*, Vol.2, Num. 4, pp. 344-352, 1994.

[9] Reachin Technologies. http://www.reachin.se

[10] P. Richard, G. Birebent, P. Coiffet, G. Burdea, D. Gomez, and N. Langrana, "Effect of Frame Rate and Force Feedback on Virtual Object Manipulation", *Presence*, Vol. 5, Num. 1, pp. 95-108, 1996.

[11] SensAble Technologies. http://www.sensable.com

[12] B.J. Unger, A. Nicolaidis, P.J. Berkelman, A. Thompson, S.J. Lederman, R.L. Klatzky, and R.L. Hollis, "Virtual Peg-in-Hole Performance Using a 6-DOF Magnetic Levitation Haptic Device: Comparison with Real Forces and with Visual Guidance Alone", *Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pp. 263-270, 2002.

[13] S. Wang and M.A. Srinivasan, "The role of torque in haptic perception of objet location in virtual environment", *Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, 2003.

[14] C. Zilles and J.K. Salisbury, "A Constraint-based God-Object Method for Haptic Display", *IEEE International Conference on Intelligent Robots and Systems*, 1995.