# Haptic motion: Improving Sensation of Self-Motion with Force Feedback

Category: Research

**Abstract**

We present a new haptic method for user interaction with virtual worlds called haptic motion. It allows the user to feel an important sensation of displacement of his body by applying a force on his hands. This force is coherently produced together with a visual 3D environment. We designed two experiments that evaluate haptic motion. In the experiment one, results demonstrate that haptic motion significantly improves the sensation of self-motion and the realism of the virtual experience. In the second experiment, we found that the sensation of self-motion is more important when subjects received a force in the hand proportional to the 3D acceleration vectors of the visual scene.

## 1 Introduction

Virtual reality technologies target realistic sensation of immersion. When the scene is in displacement, meaning that the point of view of the user is supposed to move, it is critical to have an accurate rendering of inertial cues. Indeed, it is well-known that inertial cues can be helpful to navigate. It will be not immersive nor realistic in egocentric navigation to have a feeling that the scene is in displacement but not our body (in this scene).

In this work we propose a new method called haptic motion to induce a sensation of self-motion which compared to others bring many benefits. This technique uses mechanical devices, and more precisely haptic force feedback.

The most usual manner to immerse people in a virtual world is to use visual cues alone. For instance, watching a large screen to cover the most important part of the field of view, or wearing a head mounted display is usual. These kind of technology can induce immersion and one of his component can be vection. Vection is a well-known illusion of self-motion. Many people had experienced at least one time, in a train, a visually induced illusion of self-motion, caused by the optic flow of another train which starts. In this situation people have the sensation to move in the direction opposite to the optic flow while they are steady. Vection can be circular (i.e product by a rotational optic flow) or linear (product by a linear optic flow) [1, 12, 5, 15]. Visual methods are limited because vision is adapted to detect velocity but not acceleration [12]. It means that some other cues can be useful to enhance the sensation of self-motion and thus immersion.

They are several mechanical approaches that give the sensation of motion in a virtual environment. Among them we can quote three major mechanical designs: hexapod, rails and vibrotactile actuators.

Stewart platform (also called Hexapods) and its variants are widely used in simulators. The main principle underlying this technology is to move the platform in six degrees of freedom (3 rotations and 3 translations) with six hydraulic cylinders (hexapod). Classical Hexapod are very limited in workspace. It is one of the the reason Hexapod on rails was invented.

Platforms on rails give the possibility to have a bigger range of linear acceleration. Good examples is the Ultimate Platform developed by Renault [6] and the Toyota driving simulator [14] (X and Y displacements).

Another mechanical technique is vibrotactile actuators. The most used vibrotactile actuators in simulators are characterized by a narrow frequencies's range of activation.

All of these technologies suffer of intrinsic limitations. The first that we can quote is in the case of rails, and to a lesser extent the hexapod, is the important volume. This problem limits the access to these technologies to individual customers at home. In the same way individual customers, usually, cannot pay the high price inherent in these technologies. These problems slow the spreading of this technology outside of large organizations like global companies or government agencies.

Another limitation is related with the matching between the visual scene and the information that can be send by mechanical actuators. Indeed, usual vibrotactile devices do not give a specific information related with the acceleration profile. The information can be seen as a bit of information: active or not. We understand why this kind of device is limited to give an accurate sensation of motion.

In the case of tilting device it was shown that people can distinguish between tilting (gravitational acceleration) and linear displacement (inertial acceleration). It means that, to produce an illusion of self-

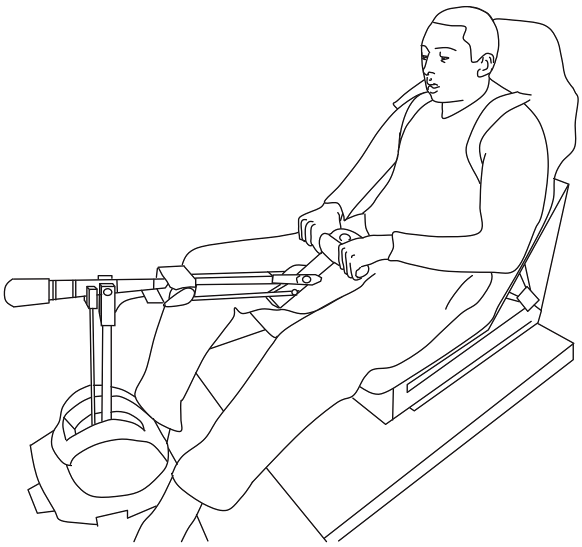

Figure 1: Experimental apparatus: subject grasping the 6DOF haptic devices. Subject had to put their thumb of their dominant hand on the button during the trials. And they grasped the haptic device with two hands in a symmetric manner. Subjects were strapped on the chair to mainly avoid torso and head movements. The subject was in an immersive room in front of a screen surrounded by curtains.

motion, a tilting method can be used but only for very fast variation of acceleration and not for long time acceleration. The same problem occurs with the rail technology because of the limitation of the rails length, it is impossible to have an acceleration during a long period. These rails and tilting platforms are also difficult to control and complex subthreshold movements (under the threshold of perception) have to be done to stay in the workspace of the platform.

We propose a new method to overcome these limitations. This method is based on haptic feedback. The use of forces to give a sensation of self-motion.

## 2 RELATED WORKS

Sensation of self-motion is a multimodal perception. It means that many sensorial canals are combined to give a unique sensation of self-motion [10]. These canals can be visual [1, 11, 15], tactile [16, 17], proprioceptive [8], vestibular [1] and even acoustic [9].

In a psychophysic study, Mergner et col. [8] showed that it was possible to induce an illusory sensation of rotation of the head by only rotate the trunk, in the dark. This could be considered as an illusion of self-motion induced by proprioception only.

Another study related to disorientation in an aircraft showed that tactile cues can be used to control the self-motion illusion [2]. The aim of this work was to determine whether a vibrotactile stimulation of the torso of a subject who pilots an aircraft can limit the disorientation. Their hypothesis of a disambiguating role of vibrotactile actuators was confirmed by the experiments.

Here, we will focus on haptic display. Haptic stimulation can be considered to give proprioceptive and tactile cues. Some previous works suggest that haptic feedback can enhance the sensation of self-motion. In a prior study, in a virtual environment, a virtual tunnel was visually displayed. The task of the subjects was to determine the angle of the tunnel's turn with (or without) a haptic device that rotated the same angle [7]. The results of the study was a not significant tendency in favor of the haptic condition to evaluate the angle turn. But these former results were sufficiently encouraging for beginning to design a new method of haptic stimulation which enhances self-motion in virtual worlds.

## 3 CONCEPT

We propose a dramatic change in the usage of haptic devices. Usually, haptic feedback was used to interact with some objects in a virtual environment. Haptic devices serves to give the sensation of touching or moving given objects, to feel their weight or their texture. The radical change in our concept is that haptic feedback can be used to produce the illusion to the user that all his body is moving. The key idea of our approach is to send a force to the user which is proportional and in the same orientation than the inertial acceleration vector. Simply by applying this force on hands it is possible to give a sensation of whole-body self-motion.

A schema block (figure 2) describes the pipeline of process, that represent the implementation for our concept. A physics engine determine the acceleration of the vehicle. The multimedia is defined here as visual and acoustic information produced in parallel to haptic force-feedback. In this study, we were restricted to visual information. We computed the 3D force and we send it synchronized with the 3D visual scene. This means that visually the user was submitted to a visual acceleration proportional to the 3D force and in the same direction.

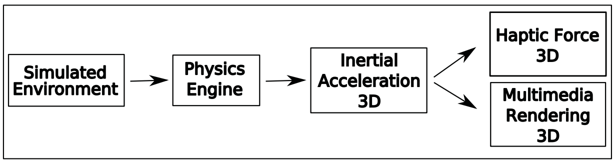


Figure 2: Simulation pipeline. Simulated environment corresponds to the virtual world that we design and the characteristic of the vehicle that we used. The physics engine deduces from this virtual world and from the initial state the dynamic of motion of the vehicle and particularly the inertial acceleration (translation and rotation). The multimedia rendering corresponds to the production of a 3D visual scene and 3D sound.

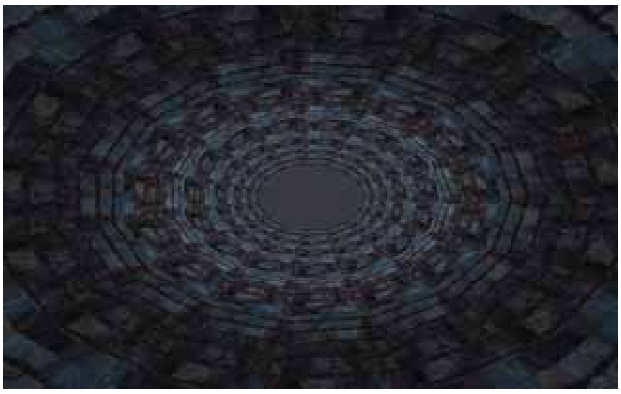

Figure 3: A simple textured cylindrical tunnel

## 4 Experiment 1: Can force-feedback increase the illusion of vection?

In this experiment, we started with a minimalist experimental method that was designed to be a proof of concept of our claim. We wanted to test whether a haptic feedback synchronized with a visual stimulation can increase the self-motion sensation. To this aim, we designed an experiment where the haptic feedback can be present or not to observe its specific effect. The stimuli are simple because in this case, the haptic stimulation was in 1 axis and the visual scene was a simple cylindrical tunnel.

### 4.1 Participants

Nine participants took part in this experiment. They were 6 men and 3 women aged between 22 and 56 years. All participants had normal or corrected vision.

### 4.2 Stimuli and Apparatus

Here, the output of the physics engine (figure 2) was a step of acceleration.In this experiment, subjects were submitted to a step of acceleration beginning after 3 seconds and finishing with the trial. The duration of each trials was 25 seconds because we wanted to avoid adaptation to stimulus [4] and possible after effect [13].

The visual scene consisted of a 3D textured cylindric tunnel design in OpenGl. The subject was seated at 1.30 m to the screen, and the dimension of the screen were 1m80 vertically and 2m40 horizontally. The angle of view was 108 degrees vertically and 123 degrees horizontally. For a more realistic immersion, black curtains were tightened between the border of the screen and the chair.

Subjects were strapped on the chair at the level of the shoulder and the belly to avoid vestibular stimulation during the haptic stimulation. Indeed the effect of vestibular stimulation on linear vection is well known and is described in Pavard and Berthoz (1977) [12]. This procedure allows to test the specific impact of haptic cues on vection. They grasp with their two hands an 6DO haptics devices (Virtuose, Haption). The grasping can be seen in the figure 1. We asked subjects to have the thumb of their dominant hand on the button during all the trial. This procedure ensures that the subject pushed (and released) the button exactly at the moment where the illusion of self-motion began (or disappeared). Subjects were also acknowledged to maintain the haptic feedback in the same position (to resist to the force feedback stimulation).

### 4.3 Procedure

Subjects were instructed to press the button when they feel that they have an illusory sensation of motion, not when the image of the screen move, not when the haptic device move, but an illusory sensation of motion comparable to the illusory sensation when a person is in a train and see another train which start. They are also instructed to push the button and to keep pressing it as long as the sensation continues and to stop if the sensation disappears and also restart to push the button if the sensation restarts. After each couple of trials subjects have to judge which one gave him a stronger sensation of self-motion.

### 4.4 Design

Three different conditions were used: haptic-only condition which provides a haptic feedback but with a steady visual field, visual only condition with a moving visual field an a static arm, and the coherent multimodal condition with both haptic and visual field cues. These three different conditions were presented by couple. In one couple the first and second trial was always different. With the order of appearance and three different condition, it means that we had 6 different couples. These 6 couples are randomly presented four time each other. They were 24 couples of trials by experiment, 48 trial in total.

### 4.5 Results

To observe the effect of the haptic feedback in the different conditions, we decided to study usual markers of vection as: the onset, the duration of illusion, the frequency of occurrence of the illusion [11], and we also asked subjects to judge the sensation of motion by couple of trials. In each trial, subjects were in front of the screen, grasping the haptic device.

#### 4.5.1 Frequency of occurrences

The frequency of occurrences of the illusion of self-motion is important to compare the respective power of the different cues to give a sensation of motion. All subjects felt the sensation of self-motion at least one time during the visuo-haptic condition (VH). Eight subjects out of nine felt the sensation of self-motion at least one time during the visual-motion condition, the vection-like condition (V). Three subjects out of nine felt the sensation of self-motion at least one time during the haptic-motion condition (H). We compared the distribution of occurrences between the visuo-haptic condition and the other condition (see Fig.4). To perform this computation we used a Wilcoxson sign rank non-parametric test. We found that occurrences are significantly different when the VH condition is compared with respectively the H ($p=0.0039$) and the V($p=0.0313$).

These results mean that subjects feel an illusion more often when visual and haptic feedback are present in the same time and coherently. Our results in the visual only condition can also be compared with what other works found in linear vection. Three subjects out of nine had the feeling to move in the haptic-only condition. In fact, in this condition a conflict was present between vision and haptic. For us, this condition was considered as a control to show that subjects do not push the button when they feel

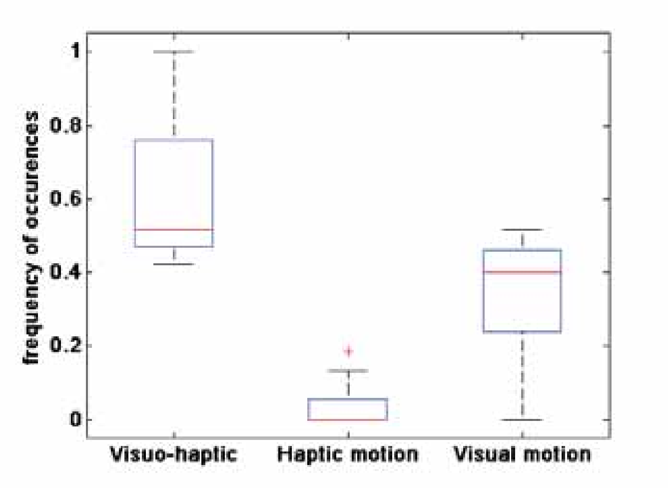


Figure 4: Frequency of occurrences of self-motion illusion in three conditions: Visuo-haptic, Haptic motion, Visual motion. The frequency of occurrences in the Visuo-haptic condition is higher than the frequencies of occurrences in the other conditions.

haptic stimulation. And to control that subject clearly understand the task and not push the button when they feel that something move. Although, in the questioning phase of the experiment we realized that the two exceptional subjects had actually an illusory sensation of motion in the condition and had clearly understood the task. It means that the illusion of motion can be induced with some subjects only with the haptic device.

#### 4.5.2 Duration

The Duration of the illusion is also an important marker used in studies in the area of vection. We showed that the duration illusion is significantly increased in the visuo-haptic condition compared with visual only (Mann-Whitney, $p = 0.013$) and haptic only (Mann-Whitney, $p = 8.4.10^{-7}$) conditions. The distribution is shown in figure 5.

#### 4.5.3 Onset

The onset can be define as the duration between the beginning of a stimulation and the moment where a subject perceived an illusion of self-motion. A representation of the distribution of onsets in each condition is shown in figure 6. It can be seen that the mean of the onset is lower in the haptic motion (HM) condition (2.33) after comes the visuo-haptic (VH) condition (6.24) and the higher onset's mean occurred for the

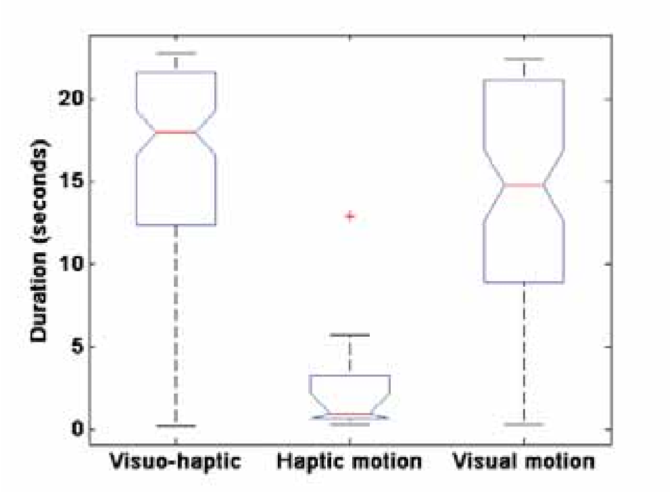


Figure 5: Duration of self-motion Illusion in three conditions: Visuo-haptic, Haptic motion, Visual motion. The duration in the Visuo-haptic condition is significantly longer than the duration in the other conditions.

visual motion (VM) condition (9.16). The distribution of the onset did not follow a normal law. Thus, we computed a non-parametric ANOVA to test the equality of medians in the different conditions. We obtained a p-value of $10^{-8}$ (Chi2(2,36.69)) which implied that the median in the different conditions are not significantly equal. To determine which median are significantly different from the others we computed three different Mann-Whitney tests. For the comparison between VH condition and HM condition we found a p-value of $3.5 * 10^{-5}$, between VH and VM the p-value was $4.4 * 10^{-4}$ and between HM and VM he p-value was $2.3 * 10^{-8}$. This prove that the medians of the three distributions are significantly different. It is possible to state that the onset is significantly different in the three conditions, with a lower onset in the HM condition followed by the onset in VH condition and finally the higher onset is in the VM condition. Thus it was shown that a haptic feedback can decrease the onset needed for a subject to feel an illusion of motion when combined with visual information. It can be also observed that the variability of onsets are ranked in the same order than median.It means that the condition where the onset are lower are also the more concentrated and on the contrary, the condition where the onset was higher is more spread.

#### 4.5.4 Subjective answers

In this experiment we asked the subjects to answer after a couple of trials whether in the second trial of the couple, the sensation of motion was superior or not compared to the first one of the couple. The results

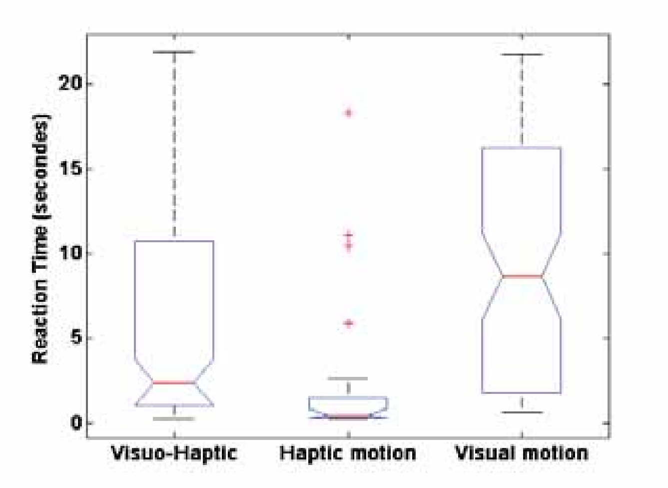


Figure 6: Distribution of the onset in three conditions: Visio-Haptic condition, Haptic only condition and Visual only condition. The haptic motion condition have the lower onset (concentrated around 1 second) after comes the visuo-haptic condition and finally the visual motion condition (more spread with a lot of onsets beginning around 10 seconds).

of this forced choice question is that subjects significantly judge that the visio-haptic condition was the condition where they felt the most important sensation of motion, in second position came the visual only condition and finally the haptic only condition. The results are summarized in figure 7.

The haptic information have a significant impact on frequency of appearance, duration, onset of illusion, and also on the subjective intensity of the sensation of self-motion. Given all these results, we can conclude that a haptic feedback can modify self-motion perception and enhance it. It appears that visio-haptic condition leads to performances issued from the two modalities, i.e. a short onset coming from haptic information and a long duration due to visual information. Moreover, we introduced a new way to analyze data related to illusion of self-motion, the probability of illusion. In the following, and based on the results of experiment 2, we will propose a model of prediction of the probability of illusion.

## 5 Experiment 2: Generalization of the concept

We showed in the previous experiment that a haptic device can improve the sensation of motion of a user. Here, we want to show that our concept can be generalized in three dimensions and in a complex environment. For that reason we choose to used a more curvy tunnel that can give an overview of what it

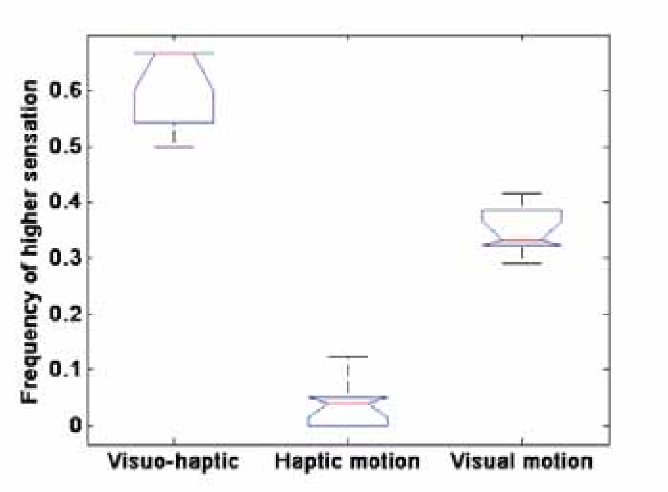


Figure 7: Subjective answer in the forced choice task to evaluate the trial when subjects feel the more important sensation of motion.Significant difference between the three conditions. The condition where the sensation of motion were judged the more important is the visuo-haptic condition after came the visual only condition and then the haptic only condition.

can be done in entertainment applications.

Given that a haptic device can improve greatly the sensation of motion, we wanted to understand more accurately the kind of profile that is important to send to the user to give him a sensation of motion.

To answer to this question we designed 4 realistic haptic patterns and we ask to the different subjects of our experiment to rank those which one gives the most important sensation of self-motion.

### 5.1 Participants

Eight participants took part to this experiment, 4 female and 4 male aged between 21 and 42 years with a mean value of 27.88 years.All participants had normal or corrected vision.

### 5.2 Stimuli and Apparatus

Subjects were strapped on the chair at the level of the shoulder and the belly to avoid vestibular stimulation during the haptic stimulation. Indeed the effect of vestibular stimulation on linear vection is well known and is described in Pavard and Berthoz (1977) [12]. This procedure allows to test the specific impact of haptic cues on vection. They grasp with their two hands an 6DO haptics devices (Virtuose, Haption). The grasping can be seen in the figure 1. Subjects were also acknowledged to maintain the haptic feedback in

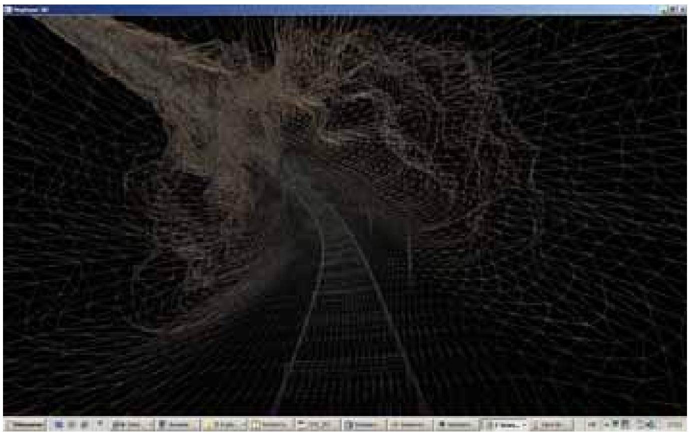

Figure 8: Wire tunnel realized with 3D interpolation spline.

the same position (to resist to the force feedback stimulation).

In this experiment, we simulated an environment and we used a physics engine to deduce the acceleration of a simulated wagon. Subjects were submitted to a continuous acceleration depending of the shape of the tunnel. The motion began after 3 seconds and finished with the trial. For the same reason as those invoked in experiment 1, the duration of each trials was limited to 25 seconds.

The visual scene consisted of a 3D textured twisted tunnel was designed with a graphic engine Neptune3D [3]. This tunnel was generated with control points which determined the cubic splines by interpolation. The screen dimension, the room and the position of the subject was the same as experiment 1.

Then, we placed the rails in the tunnel. We took into account the gravity force, the reaction of the support(rails), friction forces with the rails and the friction forces with the air. And we determine the acceleration vector of the simulated vehicle. After that, we transformed this acceleration in force like described in equation.

### 5.3 Procedure

The task of the subject was to compare two trial based on the ranking of the sensation of self-motion. At the end of the couple of trial, they had to push a button to continue, the button 1 when they have felt a stronger sensation of self-motion in the trial one and 2 otherwise (i.e. forced choice). In the end of the 80 trials, we resubmitted the five different haptic patterns, giving to each of the haptic feedbacks a random

Figure 9: Our 3D tunnel designed with cubic splines, a textured version.

number instead of name. And the subject was supposed to rank these five haptic patterns by giving a note between 1 and 7.

### 5.4 Design

In this experiment, the visual scene was always the same. Five different kinds of haptic feedbacks were submitted to the subjects. In the first condition, the force vector was in the same orientation than the acceleration vector of the simulated wagon and in the same direction. In the second condition, the force vector was in the same orientation than the acceleration vector of the simulated wagon and in the reverse direction. In the third condition, the force vector was in the same orientation than the velocity vector of the simulated wagon and in the same direction. In the fourth condition, the force vector was in the same orientation than the velocity vector of the simulated wagon and with in reverse direction. Finally, in the last condition no force occurred during the trial. This five different haptic feedback was arranged in couple. In one couple the first and second trial was always different. They were ten different couple of trials. If we consider the order of the trial, the number is 20. And each possible couple is repeated two times. Then, the total represents 40 couples of trials (80 trials). These couples are randomly shuffled.

### 5.5 Results

To further understand what kind of haptic information is important to produce the sensation of self-motion, we asked subjects to judge the sensation of motion by couple of trials. They were 4 different haptic conditions, and one condition without haptic feedback. In each trial, subjects were in front of the screen,

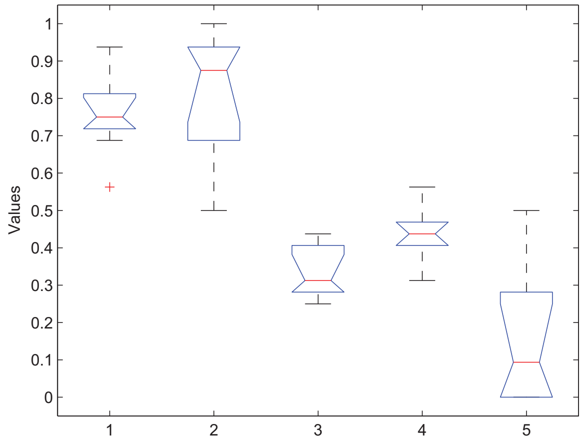


Figure 10: Percentage of time where the trial was considered to give a stronger sensation of self-motion than another one. Condition 1: haptic feedback is related to acceleration and in the same direction, Conditions 2: haptic feedback is related to acceleration and in the opposite direction, Condition 3: haptic feedback is related to velocity and in the same direction, Condition 4: haptic feedback is related to velocity and in the opposite direction.

grasping the haptic device. After the 80 trials subjects had to fill a questionnaire to rank the different haptic feedbacks.

The statistical results showed that when subjects answered to the couple task, they significantly prefer the acceleration profiles (kruskall wallis $p = 10^{-10}$) compare to velocity profile or no haptic condition (see fig. 10). But the preferred direction of stimulation is randomly distributed among subjects for acceleration (Mann-Whitney, p=0.24). The filling of the questionnaire is coherent with the former response in the couple task. Indeed, the acceleration profiles was always ranked first whatever if the criterion is the sensation of self motion, immersion sensation, realism or presence (see tab. 1).

## 6 Discussion

We have presented the haptic motion technique, a new haptic interaction that produces a strong sensation of self-motion by sending a force in the hands of the user. In two experiments, we showed the proof of concept of our new idea and a generalization in a complex 3D environment. We also showed that the manner to provoke a higher sensation of self-motion, is to produce a force related to the inertial

Table 1: Response to the questionnaire: evaluation of the different haptic patterns depending on four criteria (mean values). Acc: acceleration profile; Vel: velocity profile; S: same sens as acceleration; R: reverse sens compared to acceleration.

| | Acc, S | Acc, R | Vel, S | Vel, R | NO |
|---|---|---|---|---|---|
| Self-motion | 5.00 | 5.25 | 2.75 | 2.75 | 1.25 |
| Immersion | 4.25 | 5.00 | 2.75 | 2.75 | 2.25 |
| Realism | 4.38 | 4.75 | 2.50 | 2.38 | 1.88 |
| Presence | 3.75 | 4.38 | 2.25 | 2.38 | 1.88 |

acceleration of a simulated vehicle.

Our specific apparatus warrants some discussion. Firstly, we strapped the shoulder of users to ensure that the effect is not vestibular. Indeed, the motion was not transmitted to the body and the head but localized in the arm. This allows to claim that we do not replicate some older results because the effect of vestibular input in the sensation of self-motion is well-known. On the contrary, this observation has some practical advantages. The most important one is the possibility to give the illusion only by stimulating the hand and the arm. This is important because it means that the illusion is possible with relatively small electrical engine. And it open the possibility to have individuals applications at home. In the same way this also ensures that the technology can be used in a small area and with a relative safety, one is not forced to stand to have the effect.

One of the biggest advantage of our technique is the ability to produce a sensation of acceleration during a long time. An ecological approach can suggest that sensing acceleration is very important for every animals including human being. Indeed, equilibrium have to be ensured in everyday life. To this end, it is very important for the central nervous system to be able to estimate the acceleration, compared to velocity for instance. It is the reason why Humans are very sensitive to acceleration. In the aim to produce more immersive devices, it is critical to be able to send a sensation of acceleration. Some other devices succeed to give this sensation like hexapods or rails but they are limited in the duration of acceleration. In our case we can theoretically give a sensation of acceleration during a long time and with an important perceived amplitude. It is the principal force of our technique.

An important result of our experiment is that subject found more realistic to have an haptic feedback force proportional to acceleration. But the question of the direction of the 3D force vector has to be discussed. Indeed some subjects found more realistic in our experiment when the force was in the direction of acceleration , some others in the opposite direction. If we use arguments based on physics, a passenger that was in a vehicle can sense two kind of force. Based on his interaction with the vehicle, the passenger can sense forces based on inertia or pulling force. The subject can feel that he moves with the vehicle, pulled by it. Or he can feel that he moves relatively to the vehicle with an inertia against it. To illustrate this idea we can give two extreme interactions possible with vehicles. When a subject stands in a train with no possibility to catch something with his hands. When the train accelerate, the standing subject is faced to a virtual force (inertia) that "pushes" him in a direction opposite to the direction of acceleration. In the extreme opposite case, a person that move using waterskiing was pulled by his hand and the force is in the same direction than the vehicle acceleration. In these two cases the sensation of self-motion is important even if the physical manifestation is slightly different.
In the experiment, we did not try to influence the subject by saying what kind of interaction the subject can have in the virtual environment. Thus, the two kind of interactions were possible. It is very interesting that given this equiprobability of interaction, exactly fifty percent of people was more sensitive two one direction and the other fifty percent to the other direction of force stimulation.

Our results suggest that it is possible to generate true sensations of self-motion by sending a force in the hands of the user. This phenomenon, i.e., the illusion of a self-motion, was observed when users were exposed simultaneously to the visual feedback of the corresponding virtual motion. Interestingly, for nearly 30% of the participants it was also observed in absence of visual stimulation but with force feedback alone. In a 3D virtual reality application we could also show that illusion of self-motion was stronger when force feedback was related to the acceleration of the virtual motion as compared to its velocity. Taken together, these results pave the way for novel applications of force-feedback devices such as for augmented navigation sensations in theme parks, video games or virtual reality applications.

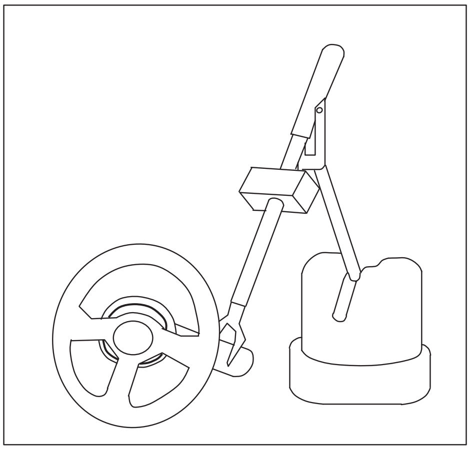

Figure 11: Seven degrees of freedom haptic wheel. New technology based on haptic motion for driving simulator.

## 7 Potential applications

Our technique based on a force-feedback for simulating self-motion could be used in many virtual reality applications such as for training, driving or flight simulators, theme parks, or videogames. Figure 11 displays the concept of a driving simulator in which the driving wheel grasped by the user is mounted at the extremity of a force-feedback arm so to add "haptic motion" when driving a virtual car. Another implementation could concern theme parks' shows and 3D cinemas to enhance the sensations of the participants by using force-feedback joysticks directly embedded in the seats between the legs of the users or, alternatively located on the armchairs.

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