Designing and evolving hands-on interaction prototypes for virtual reality

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Abstract— **We analyse and compare several prototypes of the HandNavigator, a peripheral device allowing a user to interact with a virtual environment by controlling a virtual hand with fine dexterity. Our prototypes, as easy to manipulate as a computer mouse, integrate a large panel of small sensors enabling the simultaneous control of a large number of degrees of freedom. Based on this architecture, we address the problems of designing a device where physical phenomena, physiological behavior and device structure are all tightly combined and significantly influence the overall interaction. The issues addressed include the generation of degrees of freedom and decoupling of virtual hand and finger movement, the influence of device shape and sensor type on the decoupling necessary for various tasks, dexterity, and performance. Using these different prototypes, we are able to perform complex tasks, such as virtual sculpture and manipulation of deformable objects in a natural way. The choice of the sensors and of their placement on the device show their influence on the dexterity of the virtual hand and on the range of configurations that can be achieved and addressed by a prototype.**

Keywords- navigation device; sensors; decoupling; interaction; manipulation

I. INTRODUCTION

Manipulating virtual objects using our real hands is a great challenge for the virtual reality community. Multiple solutions exist to interact with virtual worlds, that could be used to control a virtual hand. Controlling hand tasks with these devices faces the critical question of user's dexterity and user's comfort. This paper extends and generalizes the HandNavigator, a device specifically introduced for hands-on interaction in virtual environments [1]. To overcome the weaknesses of the original device, we set up a comparative study of several novel prototypes, where the physical phenomena used in sensors, the kinematic structure of the device and its shape are adapted in order to improve ergonomics, usability, dexterity and user's performance.
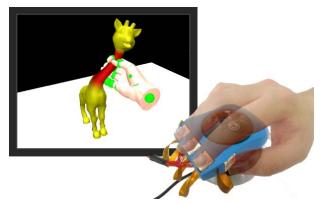

Figure 1. HandNavigator: hands-on interaction peripheral device for virtual reality and applied to the manipulation of deformable objects.

A. Previous work

Many solutions were proposed to achieve manipulation tasks in virtual environments through the use of a peripheral device to transform real hand movements to virtual ones [2]. The corresponding solutions are often based on optical motion capture systems (for example through cameras) [3,4], or on mechanical motion capture systems (for example data gloves where sensors are associated to an exoskeleton touching the hand) [5]. These solutions, either optical or mechanical, have several important drawbacks. Calibration must be performed at the beginning of each use, requiring a good knowledge of the device and a non-negligible setup time. Thus, these systems are not ready-to-use at a moment's notice. Vision-based systems face occlusion problems. Indeed, there is often a point that is not visible by a camera, for example if the user's fingers or hand are hiding other fingers, or if the fingers are hidden because the hand is closed. To solve these problems, several cameras can be added. However, the cost and space required for the setup greatly increase, while there are still configurations for which occlusion problems remain. From an ergonomic point of view, an important issue is that long tasks with a "raised hand"

necessary for motion capture lead quickly to a muscular tiredness.

Some solutions additionally integrate haptic feedback [6,7]. This feedback can also be found in larger devices including force feedback, such as haptic devices that permit interaction with physical simulations (see, for example, [8,9]). These solutions enhance the level of information returned to the user and thus better take advantage of the brain sensorial capabilities. Haptic feedback is perceived only when a user is colliding with a virtual object but lacks entirely or so when moving in the air without any contact [10,11]. Active haptic systems get more complex if the number of returned force components increases (many devices provide just two, three, or six returned force components). These systems allow a user to better perceive objects in virtual worlds, but are rarely used by ordinary people. The main reasons are the high cost of such systems, and as such they are only found in companies or academic labs. One explanation is that these systems have a technological complexity that requires a good knowledge of the device and its limitations since tuning of parameters is necessary to implement a reasonable sensation of physical models, and such a tuning is generally subjective.

A last solution is to offer some kind of passive feedback. This feedback can be perceived as an improvement compared to systems without feedback [12], and can fool the proprioceptive senses of the user [13] when using a proxy such as a sponge, a small ball [11,14]. The benefit of such solutions is their low cost and ability to be integrated in classical computer devices.

B. Overview

In contrast with previous works, our solutions rely on passive feedback and are devoted to hands-on interaction. We extend the HandNavigator device presented in [1]. Our focus is on the design of improved solutions, and the dependencies between the model of interaction, the device structure, sensors, ergonomics, and dexterity, which is absent in [1]. More specifically, our studies about the technologies of sensors lead to a more dexterous control of the virtual hand, while ensuring user comfort and enabling intensive use without fatigue. Validation tests involving users are a subsequent problem which we leave for future work.

The paper is structured as follows. In the next section, we will expose in detail the main objectives of our device. The problematics appearing for such a device associated with its kinematic structure will be explained in Section III, and one of them, namely connection between user's interactions and virtual hand kinematics will be analyzed in Section IV. Then, detailed analyses of ergonomics and sensors for the design of several prototypes will be proposed in Section V. We will show some results and applications in Section VI before concluding.

II. OBJECTIVES

Our goal is to develop a peripheral device allowing a user to control a virtual hand in a virtual environment with his real hand, using a high number of virtual degrees of freedom to achieve high dexterity, while getting passive feedback. Dexterity can be defined here as the coordination of the hands and fingers with the eyes, implying the ability of using the hands and fingers to perform rather precise activities. Therefore, tactile and visual feedbacks are two modalities to achieve dexterity [15]. More precisely, the concept of dexterity is reduced here to a set of tasks we want to be able to perform with our device. They can be summarized as:

- the independent or group movements of each virtual finger in the air, as naturally as possible;

- grasping rigid objects as easily as possible.

We want to address kinematic issues to control independently the position and orientation of the hand, and the motion of the fingers, which will be needed to achieve a large panel of tasks when the user interacts, i.e. applies forces, on the device.

We also want to consider ergonomic issues to allow a user to perform complex motions without generating any muscular pain or tiredness that dramatically reduces motion dexterity and does not enable the desired intensive use (typically ranging from several minutes to hours). Well chosen sensors must be integrated into the device to achieve a good control of the virtual fingers.

Our device must be cheap, easy and ready to use, and calibration free to ease integration with standard computer devices.

Finally, a modular software interface must be implemented to integrate our peripheral device in several applications. Especially, this interface must have a detailed model of a hand, including a high number of degrees of freedom to achieve realistic and dexterous hand motions, as well as intuitive interaction models to get high quality visual feedback.
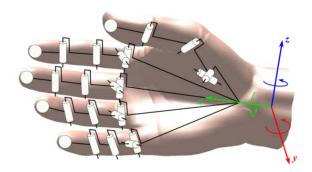
III. KINEMATIC STRUCTURE

To design a peripheral device that takes into account all these objectives, two important problems must be addressed:
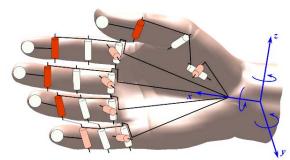
- on the one hand, the way degrees of freedom are generated to control the virtual hand and its fingers;

- on the other hand, the analysis of the user's interaction with the device and its consequences on the motion control of both the hand and the virtual fingers to avoid interferences between each other. This is needed to increase the range of tasks performed by the virtual hand while preserving a precise kinematic control.

Furthermore, the type of peripheral devices must be considered as their choice is critical and closely linked to the objectives. A peripheral device can be classified into the following categories [16]:

- isotonic: the motion of the effector is free and can be achieved with a null or nearly null resistance;

(a) Degrees of freedom of the virtual hand: 6 for the wrist and 4 for each finger (2 for the first phalanx and 2 revolute joints for the two other phalanxes). Note that the kinematics of the virtual hand does not exactly correspond to the one of the real hand.

(b) Degrees of freedom controlled by the device. In blue, the degrees controlled by a navigation device. In dark orange, the degrees controlled by the sensors. In light orange, the degrees that can be controlled. The strokes in light gray between the ring and the pinky fingers mean that it is possible to couple these two fingers.

Figure 2.   Kinematics of the virtual hand.

- isometric: the motion of the effector is constrained and the force applied on the effector is measured;

- elastic: the effector is not fixed and the resistance on the effector increases with the displacement.

This classification must however be used with care, as it depends on the point of view from which the device is considered. Indeed, a classification linked with the user's perception could be interpreted as purely subjective, whereas a classification linked with physical (or mechanical) properties or physiological concepts is more objective. Here, we will always seek which category of peripheral device best fits the objectives, in terms of performance and desired tasks.

A.   Generating the degrees of freedom

The virtual hand set up has 26 degrees of freedom (DOF) (see Figure 2(a)). This implies the treatment of a large quantity of data. In our case, we will constrain some degrees of freedom to simplify the device in terms of data flow acquisition. More precisely, some phalanxes can be constrained by the kinematics of the virtual hand, so that only the end part of the fingers will be controlled (see Figure 2(b)). Note that in our case, we ensure the uniqueness of finger configurations to avoid unexpected virtual motions of the fingers using an inverse kinematics algorithm with joint limit constraints, which is not necessarily the case for other approaches like finger motion of data gloves.

The position and orientation control of the virtual hand corresponding to the motion of the wrist can be achieved through a navigation device. In a first place, we test for this purpose the SpaceNavigator from 3dConnexion[1] as it is a cheap and widely commercialized device, compared to other devices such as accelerometers, and meets some of our needs in terms of calibration and integration in desktop environments. This device will be described and analyzed in the next section.

Most of the fingers joints are modeled by revolute

joints, i.e., by a 1-DOF joint. Consequently, to control these degrees of freedom, we can use elementary sensors that give only one physical value. These sensors will be described in Section V.D.

The interest of having such a number of degrees of freedom is not trivial. Let us consider the action depicted in Figure 1. If the user wants to grasp the neck of the giraffe, at least one grasping point is enough to deform the neck at this point and, in this case, a simple computer mouse can be sufficient to achieve this task. Conversely, if the user wants to generate more complex deformations, as a human does with his real hand, e.g., twisting an object grabbed with two fingers needs at least two or three contact points and cannot be achieved easily with classical interfaces because the user cannot control precisely these points, whereas with our device we ensure the user to achieve such dexterous manipulation tasks, as if it was for real. In other words, increasing the number of degrees of freedom effectively increases the range of possibilities in manipulating and interacting with objects.

B.   Features of the navigation device

The SpaceNavigator is a velocity-controlled device consisting in two main parts (see Figure 3[2]):

- a heavy base avoiding the user to move the device while using it;

- a moving part mounted on the base with which the user interacts to generate movements in accordance to the degrees of freedom.

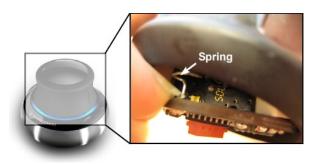Figure 3.   The SpaceNavigator and its degrees of freedom.
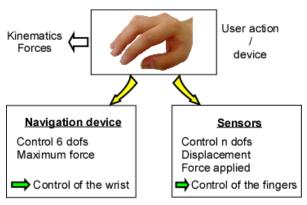
Figure 4.   Inside the SpaceNavigator.

Figure 5.   Control of the hand.

This device allows the user to control the six degrees of freedom of an object position in 3D space. Springs located inside the device are deformed when a user acts on its moving part (see Figure 4), the corresponding strains are measured and then converted into a velocity along the 6 DOFS. If we consider again the classification of [16], the SpaceNavigator has an elastic behaviour because of its mechanical properties.

IV.   INTERACTION ANALYSIS AND KINEMATIC MONITORING

Combining such a device (the SpaceNavigator) with sensors can create interferences between each other. Indeed, we want to control the position and orientation of the hand and the motion of the fingers without side effects between of each other, i.e., the hand moves while the user wants only a movement of some fingers. The necessity of separating all degrees of freedom comes from the fact that we have to consider two independent elements: the navigation part and the sensors for the fingers (see Figure 5). Furthermore, several studies mention that usability of a device increases when separating controls, see for example [17]. The difficulty in using the SpaceNavigator holds in its sensitivity to any perturbation because of its elastic behavior. In other words, the way the user will interact with the sensors as well as their technology can influence the behavior of the navigation device. The capability to decouple these two motions depends on:

- the shape of the peripheral device we want to develop, which will also improve the user's comfort of use;
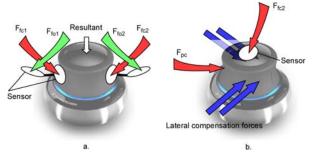

Figure 6. Force compensation (here with two fingers). In red: closing pressure (F_{fc} for the fingers and F_{pc} for the palm), in green: opening pressure (F_{fo} for the fingers), in blue: compensation forces. a.: homogeneous distribution of forces when opening/closing simultaneously two fingers. b.: if the sensor is on the top of the device, it is necessary to apply strong lateral forces to maintain the desired wrist configuration.

- and on the types of sensors, especially their mechanical properties.

To obtain such a property, the navigation device and the sensors could be completely independent, e.g., one hand manipulating the navigation device and the other hand acting on the sensors. However this configuration is not natural to control a virtual hand, especially for novices, and we aim at an all-in-one device to simplify manipulation.

Decoupling is linked to the way forces acting on the SpaceNavigator stay independent of the forces generated to monitor the position of the fingers and hence, the way tasks should be performed to achieve an intuitive behavior. In other words, one of the modality to achieve good decoupling is the level of forces the user has to apply on the device. Indeed, if a user has to apply on the sensors a force larger than the one of the threshold on the navigation device, it will result in an undesired motion of the hand. The consequences in terms of physiology are a contraction at the user's muscles, i.e., to avoid this motion bias the user has to compensate the unbalanced force with phalanxes or palm contacts. Hence, difficulties appear to move easily the real hand as well as a substantial fatigue for long tasks. In Figure 6, we show several cases of force compensation with one or two fingers supposed to act over pressure sensors. If sensors are uniformly distributed around the SpaceNavigator and all fingers are moving in the same manner (all fingers closing or opening), it results in a good force compensation of F_{fc} and thus no perturbation will be generated on the moving part of the SpaceNavigator (see Figure 6a.). As a result, the position of the virtual hand can stand still while moving the fingers, which conforms to the desired behavior. However, if sensors are located on top of the SpaceNavigator, if a user wants to close the fingers while moving the hand frontward, he will have to compensate the vertical forces on the sensors, e.g., with lateral forces that are high enough, to keep the virtual hand moving frontward without going downward, which requires muscular strength either from the palm or other phalanxes to achieve the compensation. This compensation issue must be taken into account in the device design process so that we produce prototypes that meet the objectives of dexterity stated in Section II.

Figure 7. Versions V1 (left) and V2 (right) of the prototypes.

The smaller the compensation forces, the higher the dexterity of the motion. We can distinguish two types of dexterity: dexterity in reaching desired virtual hand configurations and dexterity in grasping an object. The first dexterity derives from the previous paragraph. The second one has a stronger link to visual and tactile feedbacks because the user will use his proprioceptive senses to perform manipulation tasks, as mentioned earlier. Therefore, the application software should include helpers such as shadows and markers. Studies on this issue can be found in [15].

The dexterity we are looking for should allow a user to perform tasks that are rather simple, such as grasping and manipulating rigid objects, but also more complex tasks, such as virtual sculpture or shape deformations, in configurations of the virtual hand that are as close as possible to those of a real hand. Traditional devices such as a mouse or simple buttons cannot cope with these tasks.

Note that this compensation mechanism can be achieved through software, however it needs parameter tuning and more sophisticated algorithms whereas the current work is a first level of prototype design.

V. ANALYSIS OF THE PROTOTYPES AND EVOLUTION

A. Initial prototypes

An initial prototype, called V1, was presented in [1]. It consists in two parts: the SpaceNavigator presented earlier, which allows the control of the position and orientation of the virtual hand, enhanced with sensors (see Figure 7). The HandNavigator allows the user controlling the virtual fingers and consists in a lightweight metallic structure mounted on the moving part of the SpaceNavigator where metallic petals with a low stiffness (a few N.mm^{-1}) are fixed for each finger. Note that this stiffness allows a passive feedback. However, if we consider that the proprioceptive effects are not important, this stiffness is not of any interest for the device in terms of sensing. Therefore, another interest of this stiffness is to help the user in compensating the forces applied on the SpaceNavigator (see above). Each petal has two pressure sensors, one for opening and the other one for closing the fingers. Each finger is controlled separately in velocity: the velocity of the fingers open-close motion is a function of the pressure applied on the sensors. Thus, when the user does not press any sensor, the virtual fingers do not move. We can see one major benefit of this device compared to other solutions such as data gloves: the user can interrupt a task anytime to start another task such as modifying scene parameters of an application or even

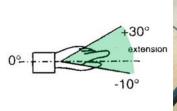Figure 8. Ergonomics analysis setup.

making a call or answering an e-mail, and resume the virtual task without losing any information.
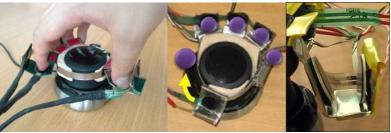
A second prototype called V2 was made on the same basis as the V1 prototype (see Figure 7). This prototype more effectively takes into account the shape of the users' hand. One difference between both prototypes is the way the petals are laid out around the SpaceNavigator. For the V1 prototype, petals are spread uniformly around the moving part, allowing a homogeneous force distribution on the SpaceNavigator, meaning a configuration of applied forces that is mostly centripetal which produces a low resulting force and thus, generates low interaction with the forces applied to the SpaceNavigator to control the position of the hand in 3D space. The main drawback of such a force distribution is that it produces pain and tiredness for the user. This problem was partially fixed in version V2. We will develop in details ergonomic issues later. Furthermore, the prototypes allow the user to control only four fingers, which is a reasonable choice since many studies show that the motion of the pinky and ring fingers are generally linked and since most real grasping tasks are performed using three or four fingers.

B. Ergonomic analysis

Using methods from ergonomics we set up an ergonomic study of both versions V1 and V2 (see Figure 8). This analysis allowed us to highlight the drawbacks of these versions of the HandNavigator. Then, work on the shape of future prototypes that take into account the remarks on dexterity and force compensation previously mentioned has been carried out. To make this study, three persons with different hand sizes were taken. These persons were between 25 and 40 years old. The scenario for evaluating these prototypes was to move first the virtual hand to a virtual object without moving the fingers along a pre-defined path, then move the fingers without moving the hand and finally go back to the initial position along the same path. The main observations are as follows (see Figure 9):

1. the posture of the wrist: to use the HandNavigator, the user must bend his wrist with a high angle, leading to an uncomfortable posture of the arm and the hand, and hence to a motion of the hand and the fingers that is difficult to perform because of a substantial contraction of the wrist;

(a) Recommended angular area for the posture of the wrist.

(b) Hand taking the Hand Navigator.

(c) The distribution of the petals does not correspond to the natural distribution.

(d) Bad interaction between the sensors and the nail.

Figure 9. Ergonomics analysis.

2. for a user sitting at a desk, the HandNavigator is difficult to hold as it is too high, requiring a raised position of the arm, thus generating tiredness, or to bend further his wrist, which constrains further the motion of the hand and the fingers;

3. the distribution of the petals on the V2 prototype does not correspond to the natural distribution of real fingers and adds tiredness to the user and difficulty to move the fingers. Furthermore, on the V2 prototype, there are no color markers helping the user place his fingers correctly;

4. interaction between the fingers and the sensors: to open the virtual fingers, with the current distribution of the pressure sensors on the petals, the user must press the corresponding sensors with his nails, which is quite difficult and does not allow fine dexterity;

5. force feedback: the user cannot know whether the virtual fingers are colliding with an object or not because the pressure sensors do not return any haptic (or pseudo-haptic) feedback;

6. visual feedback: the software that was developed with the two prototypes V1 and V2 does not integrate any orientation limits on the virtual hand (i.e. the hand can become in an unnatural configuration) and the virtual camera is moving in the virtual hand's frame. Thus, the user can quickly loose the reference of position and orientation between the virtual hand and his real hand.

Items 1 through 4 above show that it is critical to generate user's hand postures where wrist, hand and fingers contraction is kept low so that the user can monitor the device more accurately.

C. Shape design

Following this study, several possible shapes were considered to take into account these remarks, especially considering the problems of tiredness caused by a bad posture of the hand and a bad distribution of the fingers. In a first place, we keep the same sensors and will consider other technologies later on.

The first shape is based on the one of version V2: it has still metallic petals, but follows the natural distribution of the fingers (see Figure 10(a)). Thus, it is no longer necessary to bend the wrist as it can be hold easily, avoiding any muscular contraction. However, when the user presses the sensors, it generates a momentum that is high enough to create a non-negligible perturbation on the SpaceNavigator that must be canceled, hence generating an undesired motion of the SpaceNavigator hardly avoidable. Indeed, because of the sensors' low sensitivity, as discussed above, the user has to apply forces that are much higher than that needed to generate a motion of the navigation device. It is typically a case where separating the degrees of freedom of the hand and those of the fingers, as discussed earlier, is difficult. Consequently, we did not stick to this shape anymore.

The second shape is based on the one of the SpaceNavigator: the structure on which sensors are placed wraps around the navigation device to allow the user to place naturally his fingers without generating any tiredness (see Figure 10(b)). A small rod was fixed to help

(a) The first shape based on the one of the V2 prototype.

(b) The second shape based on the one of the SpaceNavigator.

(c) The third shape based on the one of a computer mouse.

Figure 10. Shape analysis.

force compensation when pressing the sensors. We however did not keep this shape as there was not enough space to put the sensors.

The third shape is based on the one of a computer mouse: this shape solves the problems of the wrist postures and those of interaction between the fingers and the nails (see Figure 10(c)). This shape is also well known by most people and thus can be easily approached. Moreover, it is possible to easily compensate the forces generated when pressing the sensors. We kept this shape for the future prototypes.

Through this analysis, we clearly see that the position of the sensor is important in the design of the HandNavigator. Especially, with the two first prototypes, motion control difficulties can be faced when performing the transition between opening and closing motions of a finger as it is linked to two different sensors whereas a natural finger motion is achieved through a change of motion orientation.

D. Technological analysis of the sensors

We also made a detailed analysis of different sensor technologies. This analysis is important since the technology used depends on the shape chosen, on the task we want to perform with the HandNavigator and hence, on the control law to be implemented, as mentioned earlier. Along with a new ergonomic shape for our device, we tested several technologies of existing sensors that can meet our requirements:

- the user must not feel any pain or tiredness to move the virtual fingers;

- decoupling with the navigation device must be as high as possible;

- the sensor must be small enough, lightweight and sensitive to avoid generating undesired motions;

- passive feedback can be integrated to help the user achieve more dexterous motions.

Considering these constraints, we tested the sensors depicted in Figure 11[3].

As mentioned in Section IV, dexterity can be achieved if the user can get desired configurations of the virtual hand, which implies to apply forces on sensors that are smaller than those on the navigation device. It is obvious
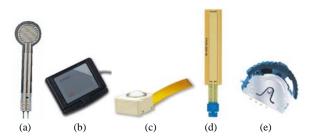
that whatever technology we use for controlling the virtual fingers, forces have to be applied. The aim here is to find one or several technologies of sensors that minimize the level of efforts to apply.

For the two first prototypes, pressure sensors were used. Because of their mechanical design, they are adapted to velocity-based control, enabling to interrupt and resume anytime a task without losing the virtual hand's configuration, which is, as mentioned earlier, one of our objectives. However, to activate these sensors, a force of more than 1N is necessary, which is high compared to the force applied to the SpaceNavigator, implying the user to make undesired motions of the virtual hand and causing substantial fatigue at the user's wrist.

Compared to pressure sensors, touch-pads and scroll-pads (see Figure 11(b) and (d)) offer good characteristics in terms of forces to apply. Indeed a light touch (0.6N for scroll-pads) generates a signal, allowing better decoupling as stated in Section IV and avoiding meanwhile tiredness. Note that the touch-pads can take two degrees of freedom, whereas scroll-pads are designed for one degree of freedom. These sensors however do not integrate any passive feedback, unlike trackballs and single-axis switches (see Figure 11(c) and (e)).

Trackballs are interesting as only 0.35N is necessary to activate them, meaning that motion of the virtual fingers can be done without disturbing the one of the hand.

Through this analysis, we see that the dexterity the user will be able to achieve in the virtual environment depends on the sensor technology. Especially, the sensor sensitivity and its capability to return relevant information

(a) The V4 prototype integrates a touchpad for the fingers except the thumb and a trackball on each side for the thumb.

Figure 11. Different sensors' technologies. From left to right: pressure sensors, tactile pad, trackball, scroll-pad, single-axis switch.

(b) The V5 prototype integrates only trackballs.

Figure 12. Versions V4 and V5 of the prototypes.

to the user are important. Among all the technologies, tactile pad, trackball, scroll-pad, single-axis switch can achieve opening and closing motions through reverse motion on sensor, which is a metaphor similar to the finger movement and hence more natural for the user.

E. Prototyping new peripherial devices

Based on these ergonomic and technological considerations, we designed several prototypes using various types of sensors and called V3 (see Figure 10(c)), V4, and V5 (see Figure 12), respectively. We chose a mouse-like shape for each prototype to get modularity with different sensor technologies as well as an easy integration into several applications.

Similarly to the initial prototypes, the V3 prototype integrates pressure sensors. Interaction with the sensors is much easier than with the initial prototypes. A rod helps the user compensate the forces applied to pressure sensors together with the user's palm, meaning better kinematic decoupling with the SpaceNavigator. However, latency problems of transition between the finger's open/close motions still hold because of two different sensors per finger. This version operates with a velocity-based control of the fingers, which meets the initial requirements of the HandNavigator.

The V4 prototype integrates a tactile pad, currently acquiring only one finger motion, aiming at monitoring the motion of all fingers except the thumb and a trackball for the thumb.

The V5 prototype integrates trackballs only. The small size of these devices lead to an overall small size of the prototype and, as for the initial prototypes, the pinky and the ring fingers are kinematically linked.

For the last two prototypes, we tried to produce very simple and easy-to-use devices, requiring low forces to move the virtual fingers because the sensors are sensitive. Thus, the SpaceNavigator is better decoupled from the HandNavigator, which improves the dexterity of the virtual hand and fingers. Moreover, their shape is symmetric, allowing left-handed persons to use them. Finally, it is possible to incorporate either a position-based or a velocity-based control, even if the first control mode is more suited to the technology of sensors used here. Indeed, the tactile pad with a raw velocity-based control gets harder to monitor from a user's point of view because when lifting up his hand from the pad does not leave the fingers in their current position. With a position-based control, it is still possible to interrupt a task because the position returned by the sensor and the finger position stands still right away when idle. Using only one sensor for both opening and closing motions enables a smooth transition producing a better dexterity in object manipulation tasks and finger movements in the air, as desired in the objectives.

Each of these three prototypes have an isometric behavior getting close to an isotonic one because the user tend to apply very low forces and can perform large movements with his real fingers, i.e., around 15mm, in order to generate large virtual movements. This property of the device to be at the boundary between isometric and
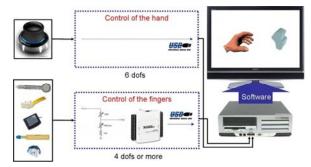

Figure 13. General outline of the Hand Navigator.

isotonic categories seems to best meet the objectives stated in Section II because it produces a good kinematic decoupling of the SpaceNavigator, which enables fine dexterity movements.

Finally, these prototypes were manufactured with rapid prototyping processes of type 'stratoconception'. This technology allows us to get rigid components to test the real use of the device but sets constraints on the thickness of shell areas because of cutter forces applied during the material removal process.

The general outline of the HandNavigator is depicted in Figure 13.

VI. RESULTS

Thanks to a deep analysis of the ergonomics as well as different sensors' technologies, we were able to propose a large range of prototypes integrating small sensors. The analysis of such a range of prototypes shows that we can reach the user's needs without any difficulty and at low cost. Our device is cheaper and easier to integrate in office environments than other proposed solutions, calibration free compared to data gloves.

Moreover, a C++ library was developed to allow a user to interface the HandNavigator with various applications quickly and without any extra effort, using pre-defined functions returning the desired data. More precisely, the proposed device is integrated in virtual sculpture applications (see Figure 14) or applications where a user can directly interact with virtual deformable objects and play with them (see Figure 15). For the last application, we use the software of Rohmer *et al.* that computes constant volume deformation [18] to get an object deformation that is visually realistic. When the virtual hand gets close to the object and the user bends the
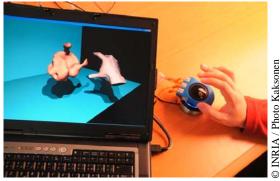

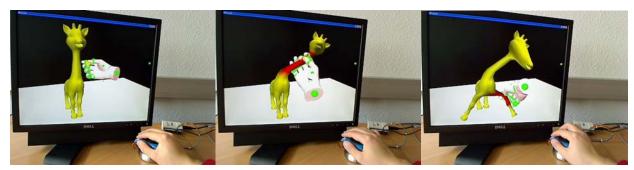Figure 14. Virtual sculpture with the V5 prototype.

Figure 15. Playing with a deformable giraffe.

first three fingers (the thumb, the index and the middle), the area of the object close to the virtual hand changes color, meaning the object is grasped in this area. Here, we use a very simple distance algorithm to detect whether the virtual hand is close to a part of the object or not. The integration of the HandNavigator in this application is a first level toward a more global evaluation of the device efficiency covering entirely the range of an interaction. Note that in our library the virtual camera can be either attached to the scene or attached to the hand, depending on the user's requirements. For our examples here, the camera is attached to the scene to show a global view of the scene.

More complex scenarios can be considered such as the placement of virtual avatars (including the position and orientation of each body) in virtual scenes or manipulation of elements for assembly processes, that are nowadays highly difficult to perform with traditional devices. This difficulty comes from the fact that with traditional devices we are limited in the number of degrees of freedom and so in the motions we can make.

All prototypes were tested with the same scenario of manipulating deformable bodies and we clearly experienced difficulties with the first prototypes (V1, V2) because we could not easily open and close the fingers as naturally as needed. As mentioned in the previous section, the fact that prototypes V4 and V5 are using only one sensor per finger to move the fingers highly helps the user in performing the desired tasks whereas with prototypes using two different sensors per finger, we observed that the user often needs to look at his real hand to verify that his fingers are placed correctly on the device. With the V4 and V5 prototypes, the user has only to concentrate on what he sees on the screen to perform the desired tasks since his interaction with the sensor follows the natural

scheme of the finger movements.

The passive feedback observed on the initial prototypes originated from the low stiffness of the metallic petals, as mentioned earlier. Because of the mechanical design of the sensors, the V5 prototype integrates a passive feedback, which does not hold for the V4 prototype because a touchpad does not have such a functionality.

These prototypes were tested by several users (about 20 participants both male and female) in a public fair on the demonstration of Figure 15, where the users were common people, mostly unfamiliar with such devices and specifically with the SpaceNavigator (see Figure 16). Most of these users had some difficulties to get used to the SpaceNavigator but after 5 minutes, people could manipulate the virtual hand and play with the giraffe. As for the sensors, users could easily act on them and perform desired motions. We plan to perform more precise tests with several users to get feedbacks on our device in terms of controllability, usability, and performance and assess other issues about hand and finger sizes, left-handed or right-handed effects as well as human perception factors.

VII. CONCLUSION AND PERSPECTIVES

We presented several versions of a peripheral device allowing a user to control a virtual hand in position, orientation, and gesture. Successive studies and comparisons led to the design of new prototypes that more closely meet the objectives of accurate control of hand postures and fine dexterity for tasks such as moving the fingers in the air to generate a hand posture and grabbing objects. Our specific focus is the selection of device shape and sensor technology to best enable kinematic decoupling with the underlying SpaceNavigator. The comparative study among sensor technologies has led to scientific issues where physical phenomena, physiological behaviors and device structure significantly influence an overall interaction between real and virtual worlds.

These prototypes will be tested by several users so that we can improve them in terms of shapes, ergonomics, sensors, and propose a device suited for a range of users and a set of tasks.

Figure 16. User testing one prototype of the HandNavigator in a public demonstration fair.

Until now, we use the SpaceNavigator to control the position and orientation of the hand but it would be interesting to reconsider the way to generate the six degrees of freedom of the hand. In the future, we will study other devices based on wireless mouses or

accelerometers to evaluate the influence of this technology over the device behavior.

Our devices already provide some passive feedback but it would be interesting to be able to adapt it according to the context: vibrators could be used to generate some tactile feedback on a finger when the associated virtual finger is in contact with an object of the virtual environment. To start with, the mapping between the captured sensor input and the virtual fingers motion could also be automatically tuned from such contact criteria, so that the virtual hand moves and deforms more easily in free space.

The HandNavigator has been designed to be integrated in several applications fields, such as physical simulation, interactive shape manipulations or teleoperations. Future work will address these fields to produce new interaction capabilities. During physical simulations, our device could increase the sensation of immersion in virtual worlds. Shape manipulation could be performed in a very natural way through a hands-on interaction. Finally, disabled persons could use the HandNavigator to control a robotic arm helping them grasp objects.

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