Jean-Claude Leon
Inria,
Grenoble University,
Grenoble 38000, France
e-mail: Jean-Claude.Leon@grenoble-inp.fr

Thomas Dupeux
Inria,
Grenoble 38000, France
e-mail: dupeux.thomas@gmail.com

Jean-Rémy Chardonnet
Arts et Métiers ParisTech,
Chalon-sur-Saône 71100,
France
e-mail: Jean-Remy.Chardonnet@ensam.eu

Jérôme Perret
Haption,
Laval 53000, France
e-mail: jerome.perret@haption.com

Dexterous Grasping Tasks Generated With an Add-on End Effector of a Haptic Feedback System

The simulation of grasping operations in virtual reality (VR) is required for many applications, especially in the domain of industrial product design, but it is very difficult to achieve without any haptic feedback. Force feedback on the fingers can be provided by a hand exoskeleton, but such a device is very complex, invasive, and costly. In this paper, we present a new device, called HaptiHand, which provides position and force input as well as haptic output for four fingers in a noninvasive way, and is mounted on a standard force-feedback arm. The device incorporates four independent modules, one for each finger, inside an ergonomic shape, allowing the user to generate a wide range of virtual hand configurations to grasp naturally an object. It is also possible to reconfigure the virtual finger positions when holding an object. The paper explains how the device is used to control a virtual hand in order to perform dexterous grasping operations. The structure of the HaptiHand is described through the major technical solutions required and tests of key functions serve as validation process for some key requirements. Also, an effective grasping task illustrates some capabilities of the HaptiHand.
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1 Introduction

The evaluation of manual tasks is a common requirement when addressing the usage, manufacturing, maintenance, and decommissioning of a product among other phases of a product development process [1,2]. When no physical mock-up of the product is available, qualitative approaches are still the current ones that can be used in industry to predict/evaluate these manual activities.

Often, the manual tasks addressed contain object grasping or object path finding in a constrained environment. In these cases, it is important to take into account the volume of the virtual hand around the object. Indeed, this volume can influence significantly the solution of these problems. Consequently, the relative position of the hand with respect to the object contributes also to this influence and the ability to easily modify this position can be achieved when the user can rely on an intuitive use of an immersive peripheral. Digital simulations, among which the number of degree-of-freedom (DOFs) of a hand as well as the interaction forces between a hand and the grasped object, involve a large number of parameters that must be acquired and processed [3]. Automatic path planning taking into account the position and volume of the hand is a very complex task that has not been challenged yet to the authors' knowledge.

On a complementary basis, real-time simulations are performed in VR where a human operator can experience the future product in the form of a virtual prototype [4]. Such simulations are strongly relying on the capabilities of the input/output devices available to the user. Haptic devices are well suited because they provide a richer user experience than without any feedback [5], but they either lack channels for the fingers, or are very cumbersome to set up and use. Consequently, a major difficulty is the need to achieve realistic grasping tasks in real time to get closer to the effective operation performed by a human being. Frequently, the grasping task is restricted to a set of predefined grasping configurations that are not close enough to reality. This results in a difficulty for the user to position realistically and naturally his or her hand, respectively, over an object.

Here, we propose a new device called HaptiHand, combined with a haptic arm commercialized by Haption company [6], to help monitor dexterous grasping tasks using haptics at the level of the user's wrist, as generated by the haptic arm, and haptics at the level of the hand fingers to monitor more precisely the hand position with respect to the object position (see Fig. 1). This device is devoted to applications where simulating precise grasping tasks are required, for instance in a virtual product assembly design process or during the simulation of manufacturing processes involving manual tasks, or the simulation of maintenance operations with grasping tasks. Not only grasping is important but the ability for the user to easily configure a virtual hand over an object is also of interest. Using these configurations with a virtual manikin

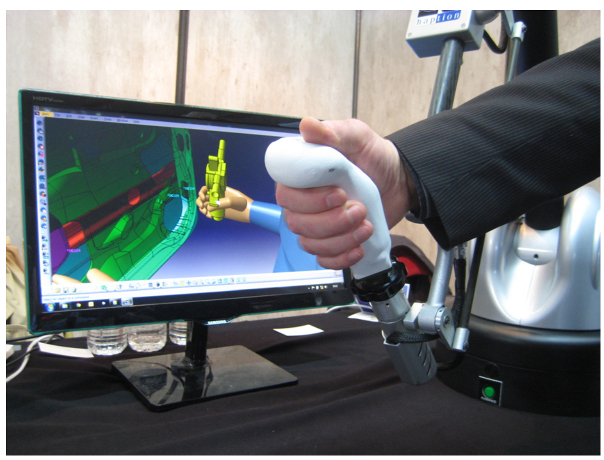

Fig. 1 HaptiHand add-on device as end effector of the Haption haptic arm

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enables more realistic simulations performed in cluttered environments.

The paper is structured as follows. Section 2 reviews prior work to specify more precisely the objectives of the device. Section 3 details the objectives set for the device and Sec. 4 describes the structure and technological solutions used in the device so that a connection can be set between the components, their function, and the signals processed by the overall haptic system. Section 5 briefly describes the content of the models used to process the signals of the device and how they contribute to grasping/releasing tasks. Finally, Sec. 6 addresses the validation issue of the prototype generated, focusing on the impact of rapid prototyping technologies to handle dimensional tolerances of components and measurements performed to evaluate quantitatively some key phenomena.

2 Previous Work

Past research has attempted to allow a user reproducing object manipulation tasks as close to reality as possible [7]. Though manipulation is a common everyday life task, grasp analysis shows that it is actually a highly complex task, resulting in a great amount of possible hand and fingers configurations, as shown for example in the classification of Steinfeld [8]. Therefore, the design of a peripheral device is highly dependent on the simulation objectives and its mechanism should allow the user to configure his/her hand and fingers as naturally as possible.

Haptic interfaces have been proposed for more than twenty years to give the sense of touch, weight, and stiffness. Common haptic devices include haptic arms, such as the PHANToM arm [9] or the Virtuose 6D from Haption, allowing the user to touch and grab virtual objects at a point of the object with either 3 or 6 DOFs force feedback. Despite their ease of use, close-to-real grasping cannot be achieved because only one control point is used to manipulate an object. More complex devices such as the Space Interface Device for Artificial Reality system [10,11] can be used to grasp virtual objects in an intuitive way. Though this interface enables large workspace for complex manipulation tasks, when extending it to a multifinger configuration [12], it becomes unhandy because of the complexity of wires configuration and additionally, only 3DOFs force feedback is returned to the user. Multifinger haptic devices proposed in the literature include exoskeleton-based devices, e.g., Refs. [13] and [14], gloves, e.g., Refs. [15] and [16], or robots, e.g., Ref. [17], providing force feedback on all fingers and hand. With these solutions, a large number of possible configurations can be achieved, thus generating multiple possibilities to move a hand at real scale around a virtual object and subsequently, when grasping it. However, these devices are highly intrusive and complex to handle, leading to cognitive overload, mandatory prior-to-use calibration, and it is not possible to interrupt a current task without losing its current configuration. López et al. [18] designed a modular multifinger haptic device for object manipulation. However, their device is limited to 3 fingers and is used in a desktop workspace configuration. Sone et al. [19] proposed a mechanism on a multifinger haptic device to change the contact location on the user's fingers. This system is invasive, limited to 3 fingers, hence not adapted to our requirements. Hands-on peripheral devices have been developed [20,21], exempting the user to wear intrusive devices. While the former has been mostly developed for advanced haptics rendering for surface exploration, thus without any possibility of grasping and manipulating an object, the latter is devoted to complex manipulation tasks, with the possibility to interrupt the current task anytime but without any haptic feedback.

The use of haptic devices involves strong issues such as collision detection and dynamics computation for force feedback [22]. Indeed, to allow a user better feeling virtual objects, accurate feedback should be returned. These issues have been greatly discussed in past research, especially in the case of a multifinger manipulation task where kinematic close-loops occur in the dynamics computation contributing to possible numerical instabilities. Various algorithms for collision detection exist, such as discrete methods [23], providing fast detection but possibly leading to instability, or continuous [24] ones, providing reliable detection though more complex to implement. Virtual forces can be computed using either penalty-based or constraint-based methods, taking into account complex physical phenomena such as friction [25].

An alternative to haptic feedback consists in passive feedback that can fool the user's proprioceptive senses [26] using very simple and cheap components as proxies [27,28]. This kind of feedback is, however, not compatible with the close-to-real interaction we target.

Prior work analysis shows that we need to define a new plug-and-play device capable of letting the user intuitively locate his/her fingers over the virtual object, grasp it with a large diversity of virtual hand configurations, and in a natural and dexterous way to avoid cognitive overload and achieve close-to-real interaction. The user should be able to reconfigure intuitively his/her virtual hand with respect to the object during a holding task when looking for feasible trajectories. This means, the user may need to reconfigure his/her arm, release his/her hand from the end effector, pause the use of the haptic arm, showing that the device should stay compatible with a noninvasive haptic force feedback system. Detailed specifications of the HaptiHand are given below.

3 Specification of the Objectives of the HaptiHand

Because the HaptiHand device is an add-on to a haptic arm, the overall structure of the haptic system can be synthesized as in Fig. 2.

In order to improve the grasping task of an object with a haptic arm and setup a more realistic behavior of the hand fingers when they are positioned around an object, the following major requirements (Ri) have been setup for the HaptiHand:

R1. Take advantage of the force feedback produced by the haptic arm called Virtuose 6D (6DOFs and 3 force components, 3 moment components) to locate the user's wrist in 3D space and generate the interaction forces between the user's wrist and the virtual environment [6]. These parameters are applied at the reference point of the mechanical model of the wrist of the virtual hand (see Fig. 3 point A);

R2. Be noninvasive so that the user can remove his/her hand easily whenever needed to avoid large forces/moments for safety reasons or just stop his/her ongoing interaction (peak forces can reach 31 N and peak torque 3.1 N m). This is an important feature compared to exoskeleton-based devices because the user may encounter either mechanical stops of the Virtuose 6D (due to its workspace limits) or physiological limits of the user's joints during a path planning. In these configurations, the user needs to reconfigure his/her hand location and configuration while his/her avatar must stand still;

R3. Let the user control in real-time the movement of the virtual hand fingers of his/her avatar so that grasping operations can be achieved with a variable number of fingers, e.g., two, three, four, and the user can monitor the relative position of each finger with respect to the object being grasped;

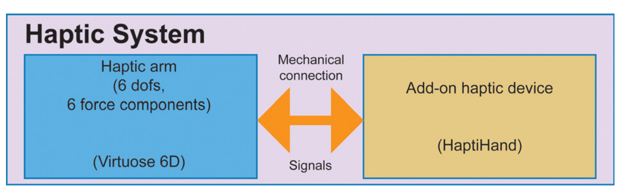


Fig. 2 Global structure of the haptic system including the HaptiHand add-on device

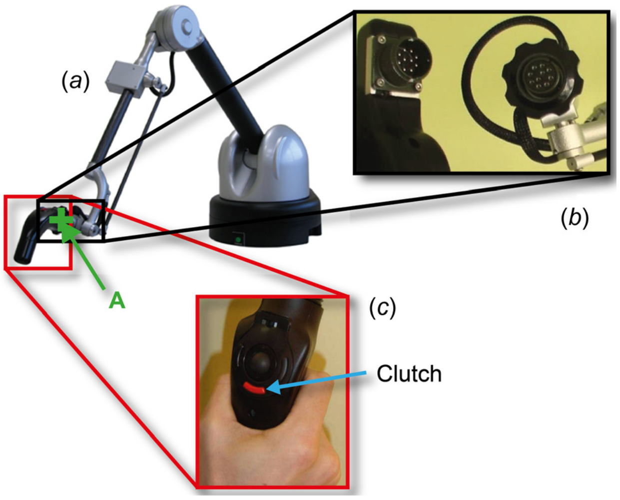


Fig. 3 Physical structure of the haptic system (*a*) showing the location of the end effector (*c*) and the connector between the arm subsystem and the standard end effector (*b*)

R4. Provide user's feedback when the virtual hand and fingers touch any component of the environment so that the user can get a natural sensation of the contact between the virtual hand and its environment to help him/her monitor a grasping task;
R5. Enable the user to grasp an object with a large diversity of hand configurations. The grasping task should somehow incorporate a friction phenomenon to obtain a realistic behavior where the user can either slide the virtual fingers over the object or grip the object without relative movements between the object and the virtual hand. Though this requirement strongly relies on the models used in the physical engine to process the signals emitted by the HaptiHand, it is the consequences of this requirement that are of particular interest for the design of the HaptiHand;
R6. The grasping task should be achieved naturally with a haptic sensory force feedback, i.e., allowing the user to precisely and naturally control the movements of the virtual hand. Though R4 looks close to this one, the current one refers specifically to configurations where the user is pressing the virtual hand onto the object. In this configuration, interaction forces take place between the virtual hand and the object and this must be somehow related to interaction forces between the user's hand and the HaptiHand;
R7. Let the user release the fingers of the virtual hand so that he/she can naturally release an object or modify the hand/finger positions over an object without releasing it. This is a complement to R3 where the HaptiHand should allow virtual fingers to move away from the object when the user physically releases a finger from the HaptiHand and move over the object to a new location to reconfigure the virtual hand over the object while the object is still held by the virtual hand;
R8. Symmetrically to the grasping task, the release operation should involve a haptic phenomenon to obtain a realistic and natural behavior;
R9. The Virtuose 6D is designed to provide the user with a capability to monitor the haptic system using different end effectors, i.e., different add-on devices. Consequently, the HaptiHand should be added/removed easily from the Virtuose 6D to switch rapidly from one end effector to another.

The list of above requirements reflects the content of an action that can be designated as a dexterous grasp and a dexterous path following action with a virtual hand. This characterizes the framework used to design the HaptiHand based on Refs. [2–5] and [21], the authors experience in using haptic devices and a partnership with Haption company.

4 Structure of the HaptiHand

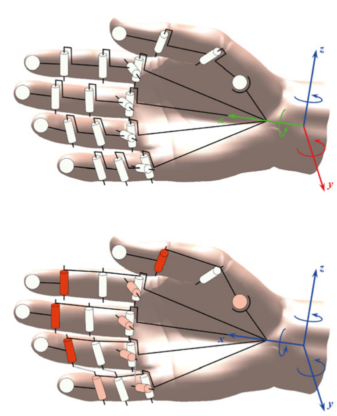
4.1 Overall Structure of the Haptic System. To complement Sec. 3 and Fig. 2 that referred to the schematic architecture of the haptic system, the purpose of this section is to describe the architecture of the overall haptic system to locate the HaptiHand (see Fig. 3) as well as some key features of the hardware that act as design constraints in addition to the requirements listed in Sec. 3.

Figure 3(*a*) shows the physical architecture of the Virtuose 6D with its anthropomorphic structure and the location of its standard end effector. This architecture is modular and Fig. 3(*b*) depicts the standard connector that must be used to connect any effector to the arm structure. Signals transmitted through the connector must be digital but their number does not set any specific restriction since the signals can be multiplexed. Figure 3(*c*) shows a detail of the standard end effector with the location of the clutch. This switch is used to disconnect temporarily the physical movement of the end effector from the movement of the virtual hand. The HaptiHand must incorporate this switch to let the user disconnect/connect it from the virtual hand whenever he/she encounters a physical stop, i.e., a physical boundary of the haptic arm workspace, when performing a grasping action or looking for a path.

Also, the Virtuose 6D features a capability to dynamically compensate inertia of the arm segments and, to some extent, viscous effects: it is the so-called transparent mode where the user can act over the end effector with a feeling as close as possible to a configuration with a null mass and hence, no inertia. The transparent mode is activated/deactivated automatically based on the contact between the user's hand and the end effector and the movement of the end effector initiated by the user. An optical sensor is located inside the end effector to detect the user's hand. This sensor and the corresponding signal processing must be incorporated into the HaptiHand so that the corresponding device can form a module compatible with the modular architecture of Haption's haptic system.

4.2 Structure of the Hand Model. Given the design constraints reviewed in Sec. 4.1 and the requirements listed in Sec. 3, it is now necessary to specify the characteristics of the hand model associated with the HaptiHand device so that it can be designed to meet the control requirements adapted to the hand model setup. Indeed, the HaptiHand is an evolution of a desktop, low cost peripheral for virtual hand simulation [21] and complementary details about the virtual hand model can be found in Ref. [21].

Figure 4(*a*) illustrates the main features of the hand kinematic model used with the HaptiHand. The virtual hand model contains 27DOFs modeled with hinges and spherical links. It is already a simplified version of the DOFs of a real hand [2,3]. Figure 4(*b*)



(a) DOFs 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). The thumb has 5 DOFs (3 for the first phalanx).

(b) DOFs controlled by the HaptiHand. (xyz) frame: DOFs controlled by the Virtuose. In dark color, DOFs controlled by sensors. Light color: internal DOFs. Connections in light gray between the ring and the pinky fingers mean that it is possible to couple these two fingers.

Fig. 4 Kinematics of the virtual hand. (*a*) unconstrained kinematic model, (*b*) kinematic model associated with the HaptiHand.

indicates how these DOFs are related to the virtual hand monitoring. There, simplification hypotheses have been setup to simplify the design of the HaptiHand, in a first place. The strongest simplification holds in reducing the finger movements to flexion/extension only, i.e., the movements of adduction/abduction are not monitored by the user (light orange DOFs in Fig. 4(*b*)). This is especially constraining for the thumb and index movements because it reduces the range of realistic grasping configurations. However, the design of some subassembly of the HaptiHand gets more complex so this has been left, in a first place, for future developments.

Another simplification holds in the relative movements of the ring and pinky fingers. As depicted on Fig. 4(*b*), they behave the same way (flexion/extension) to reduce the amount of DOFs of the HaptiHand. This is justified because the pinky finger contributes to the stability of the grasped object rather than the grasping action itself [2,3], which is observable for a large range of grasping configurations.

Finally, the last simplification is a compromise between the complexity of the control system and the compactness of the device. The HaptiHand being a noninvasive device to meet R2, the whole control system and sensors must lie inside the user's hand so that the user can quickly release the haptic system in case of emergency if high forces and/or torques are generated. In this case, the optical sensor can detect this configuration and switch off all the motors of the haptic system. As a consequence, the user monitors only the position of the last phalanx of each of the four independent fingers (see the dark orange symbols in Fig. 4(*b*)). The other rotational DOFs contributing to the flexion/extension of each independent finger depend on the user-prescribed displacement set at each finger extremity. The corresponding finger movement describes one family of natural finger configurations during a flexion/extension action. Consequently, the number of actuators can be reduced to four, i.e., one per independent finger rather than having each phalanx as an independent segment of a finger with its own actuator. This simplification enables a significant reduction of the volume requirement to insert actuators and sensors inside the user's hand and it is consistent with the overall accuracy of the virtual hand behavior (see Sec. 5.1).

Though it is important to note that the kinematics of the virtual hand simplifies the one of the real hand, the virtual hand monitoring can be achieved with a minimal number of independent DOF as a start. This virtual hand model is local to the HaptiHand device, i.e., under user's control, not through a global kinematic model that is used when the virtual hand is part of a manikin.

As a synthesis of the design constraints mentioned in Sec. 4.1 and the major features of the virtual hand model described previously, it appears that the independent control of each finger to perform dexterous grasping/release requires the same principle/devices for each finger. Therefore, the structure of the HaptiHand should contain four times the same structure of components. This subsystem of the HaptiHand is designated as a "*module*" and its design description is given in Sec. 4.3. The incorporation of the clutch and optical sensor in the HaptiHand is part of its global architecture described at Sec. 4.4.

4.3 Design of a Module. Though it has not been listed as a requirement in Sec. 3, the HaptiHand device must be compatible with the Virtuose 6D and also with the environment of this device. This environment designates other equipment that can contribute to simulations in the context of augmented reality/VR immersions. There, electromagnetic fields can interact with the haptic system and hence, with the HaptiHand. Therefore, the technical solutions described fit into this constraint to rely on technologies that are resistant to perturbations from possible electromagnetic fields emitted by the equipment surrounding the haptic system.

To concentrate on the design of a module, let us review first the main functions to be performed by each module and the corresponding technology selected:

- Kinematic behavior associated with each independent finger to achieve its flexion/extension (R2). The associated behavior can be achieved within a small volume using a microswitch technology (see Fig. 5(*a*)) or mini trackballs (see Fig. 5(*b*)) or scroll pads (see Fig. 5(*c*)). Though mini trackballs could provide two DOFs to be able to monitor the adduction/abduction movement of some finger, their operating conditions did not produce a smooth monitoring of a finger [21] and mini trackballs like those of some cell phones cannot be used because they would be sensitive to electromagnetic perturbations. Also, scroll pads suffer from sensitivity to electromagnetic fields and additionally, they require a finger displacement of nearly 15 mm magnitude [21], which is difficult to achieve for the user when he/she has to oppose to force set by the Virtuose 6D. Consequently, the technology selected for the flexion/extension of a finger is of type microswitch. This technology can generate a finite number of states with the idle state at rest. If a microswitch can be monitored with a small magnitude of displacement, i.e., a couple of mm, it requires a monitoring that relates this displacement to the velocity of the finger rather than its position. This technology results in a velocity-based monitoring of the finger movement rather than a displacement-based control (R3). Therefore, a small displacement of a user's finger may produce a large deflection of a virtual finger, which differs from the behavior of the Virtuose 6D. Having a finger movement based on velocity control rather than a displacement-based control is acceptable since studies on brain activities show that effective musculoskeletal activity can be decoupled from that of the same movements at the brain level [29]. The fact that the HaptiHand is under velocity-based control whereas the Virtuose 6D is under displacement-based control has not brought noticeable usage problems. However, a precise user study on this topic is left for future investigations. As a reminder of Sec. 4.2, to reduce the number of DOFs monitored, one microswitch is used to control a whole finger using an inverse kinematic model for its movement;
- Contact/collision feedback between a virtual finger of the user's avatar and the components of the virtual environment (R4). Because the user has already a contact with the HaptiHand, i.e., this is a necessary condition for the user to feel the haptic feedback as part of his/her immersion, it creates a major difference compared to other immersive devices like data gloves [30]. Consequently, it is necessary to use a complementary immersive phenomenon to haptically inform the user about collisions, i.e., when a virtual finger collide with its environment. To this end, the proposed solution is the use of a vibratory signal to produce a passive haptic signal to each of the user's finger monitoring a microswitch. This vibration forms a haptic texture [31]. In a first place, the purpose is not to generate this passive effect in close relationship with the location of collision over a finger, which means that the vibration source can be located at a constant position on a finger and that the skin area excited by the actuator does

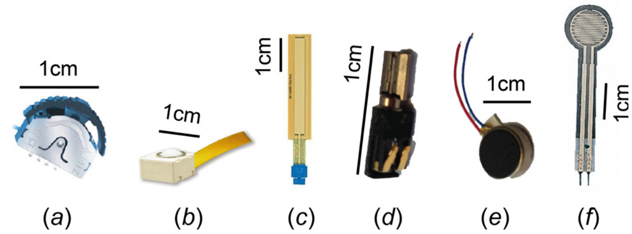


Fig. 5 Different sensors/actuators technologies. From left to right: (*a*) single-axis microswitch, (*b*) trackball, (*c*) scrollpad, (*d*) vibrator with external mobile mass, (*e*) vibrator with internal mobile mass, (*f*) pressure sensor.

not need to be reduced to less than 1 cm^2. Consequently, the use of microvibrators to generate a signal at the user's fingertip is a technology that is well suited for generating the desired passive effect. Among the available technologies of microvibrators, the one based on an unbalanced rotating mass (see Figs. 5(*d*) and 5(*e*)) can provide rather compact devices where this mass can be either external (Fig. 5(*d*)) or internal (Fig. 5(*e*)). The latter is currently used in cell phones and similar devices; its compactness is even smaller than those having an external mass when housing surrounds them. Additionally, the excitation frequency they generate fits well with the skin sensitivity [31] because it has been part of the investigations of their use in cell phones. Their vibration frequency at 12 kHz is considered as fully adequate for our present purpose. Given the rotational movement of the mass, the maximal amplitude of vibration takes place in a plane that is orthogonal to its rotation axis. In the setting defined on Fig. 6, this plane is parallel to the printed circuit board (PCB) plane and the microvibrator is directly in contact with the PCB where the microswitch is mounted to maximize the efficiency of the vibration effects.

Because the purpose of each microvibrator is to generate a haptic effect for each independent finger, i.e., thumb, index, middle, ring, the vibrations must be perceived independently for each finger as each one can interact with virtual objects independently of each other (R3). To this end, each microvibrator must be associated with a corresponding microswitch rather than the shell of the HaptiHand where the vibrations would propagate throughout this structure and could not satisfy the independence condition of each finger. However, this setting is not sufficient to ensure that the vibrations generated at the fingertip of one user's finger do not propagate to other fingers and/or to the user's palm. Indeed, this is a strong issue that requires technical solutions such that the vibrations generated in one module do not propagate to others. Section 4.4 will give more details about this specification and Fig. 6 already shows how some damping systems have been added to each module;

- Haptic behavior when grasping an object (R6, R7). The structure of a haptic feedback arm with the 3 force and 3 moments components is applied to a reference point (see point A on Fig. 3) of the Virtuose 6D that can be regarded as the wrist of the virtual hand as user's avatar. To grasp an object using a haptic sensory feedback, it is necessary to generate some force that takes part to the interaction between the user's fingers and the HaptiHand device so that this force can monitor the interaction between the virtual hand and the object being grasped. This force requires a new device because it is independent of the force feedback produced by the Virtuose 6D. It is a force that is internal to the hand structure, which justifies the fact that the hand model described at Sec. 4.2 is a "local model" that can be processed independently of the physical simulation engine. When a human being grasps an object, this force is naturally generated because he/she needs to compensate the weight of the object and grip it to be able to hold it. In a real grasping action, the corresponding haptic phenomenon is the pressure and its variation at the interface between the surface of the object and the user's palm and interior areas of his/her fingers. When immersed with the haptic system, the user faces a quite similar configuration at the interface between his/her hand and the HaptiHand. Therefore, it is possible to acquire the level of pressure at the interface between each user's finger and the HaptiHand, more precisely at each user's fingertip where lies a microswitch. Then, this pressure level can be processed to monitor in real time the grasping action of the user (R7, R8).

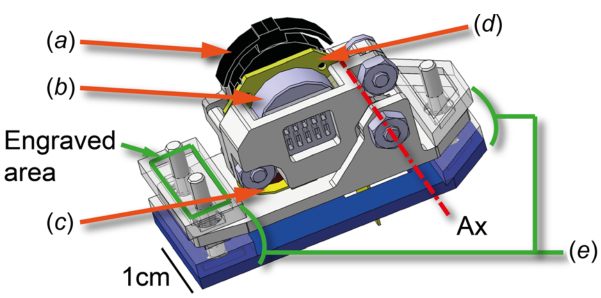


Fig. 6 Computer-aided design (CAD) model of a module of the HaptiHand. (*a*) microswitch used to monitor the finger movement, (*b*) microvibrator generating a passive haptic effect during collisions, (*c*) force sensor used to produce an active haptic effect when grasping/releasing an object, (*d*) PCB, (*e*) damping systems.

The device needed to monitor this haptic phenomenon reduces to a pressure sensor that acquires the pressure under each user's finger. On the contrary to other existing devices like the Virtuose 6D, the force is not initiated by the physical engine and then, transferred to the user as a feedback; rather it is initiated by the user to enhance the level of fidelity of a grasping action. The need for this force generation is also motivated by the fact that the grasping tasks are performed under (pseudo-) physical simulation, i.e., the forces simulated by the physical engine.

The corresponding pressure signal must be continuous to characterize the grasping task, i.e., when the user's virtual hand applies pressure on an object, and the object release, i.e., when the pressure on the object decreases until the user's virtual finger moves away from the object. The sensor technology chosen uses a resistive effect, which is resistant to electromagnetic perturbations, and is rather compact (see Figs. 5(*f*) and 6). To be adequate when monitoring a grasping action, the pressure sensor must be able to produce a signal range large enough so that the user can generate a series of pressure levels he/she can clearly differentiate. This issue will be addressed in Sec. 6.

In addition to Fig. 6, Fig. 7 is an illustration of a prototype module as manufactured using rapid prototyping techniques. Based on the description of a module, the overall architecture of the HaptiHand is described in Sec. 4.4.

4.4 Global Structure of the HaptiHand Device. The external shape of the HaptiHand is subjected to ergonomic constraints to adapt to the user's hand width and length. As a matter of compromise between tightly tuned ergonomic shapes and a general purpose one like the standard end effector of the Virtuose 6D, it has been necessary to consider distinctions between right-handed and left-handed users. This is mandatory because the location of the microswitches over the HaptiHand shell must lie under each user's fingertip that controls an independent finger of the virtual hand. Figure 8 shows a right-handed version of a HaptiHand. Figure 8 does not feature the optical sensor used to comply with R2, which is located opposite to the viewpoint set for this figure. Figure 8 features the clutch that contributes also to R2, the connector to the Virtuose 6D that satisfies R9, the grasping mode selector (GS) devoted to a predefined grasping strategy that can

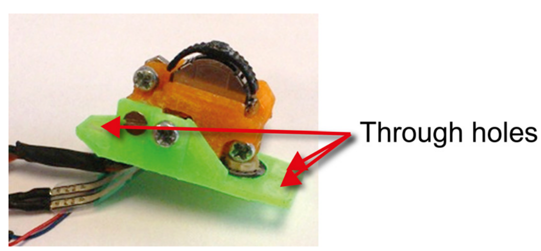


Fig. 7 One of the prototype modules incorporating the various actuators/sensors described and housed in 3D printed components

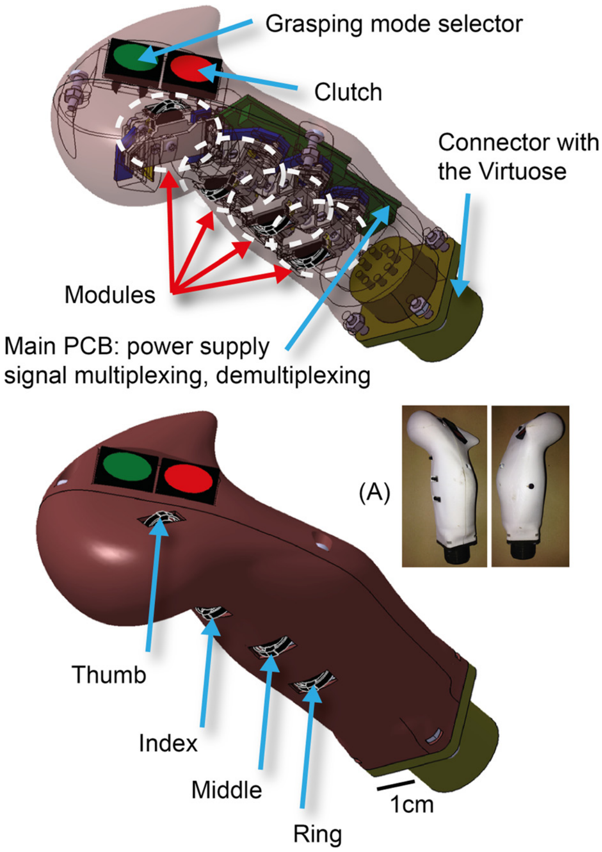


Fig. 8 CAD model of the HaptiHand. The top view shows the location of the major subsystems with the outer shell displayed in transparency mode. The bottom view shows the external view of the HaptiHand prototype. (*A*) Two photos of the physical prototype using opposite viewpoints.

incorporate adduction/abduction movements of the fingers, particularly of the thumb movement, to contribute to R5. GS is a means to extend the current limitations of the modules that cannot provide an adduction/abduction movement. Using GS, the user can select a coupling law that relates the adduction/abduction with respect to the extension/flexion, respectively, of a finger movement. This simple extension with respect to Secs. 4.2 and 4.3 fairly extends the family of possible movements of the virtual hand.

The modules are incorporated into the HaptiHand so that they are isolated from the vibration point of view, i.e., from each other as well as from the housing so that the user can naturally locate the finger that is colliding with its environment and naturally monitor the corresponding finger's movement.

Figure 8 also locates the main PCB inside the HaptiHand shell. All the modules, GS and clutch, are connected to this PCB to exchange signals that are digitized and multiplexed/demultiplexed to be sent/received through the connector to the Virtuose 6D and then, to the controller of the haptic system. Similarly, power supplies for the microvibrators are also available from this PCB. To achieve efficient passive haptic effects described in Sec. 4.3 with microvibrators, each module is equipped with a damping system as shown in Fig. 6. This damping system is achieved with layers of silicon sheets piled up on both sides of the module bracket to adapt its stiffness and adjust its damping effect. The location of each damping system is visible in Fig. 8. Each module contains also additional damping areas around the subsystem (microswitch, PCB, microvibrator (Figs. 6(*a*), 6(*b*), 6(*d*))) to improve the damping effects. To be able to generate a pressure onto the sensor (c) (see Fig. 6) ((a), (b), (d)) is a rotating subsystem whose rotation axis is Ax (see Fig. 6). Damping material is inserted between this subsystem and the module bracket.

Overall, the HaptiHand can be rapidly connected to the Virtuose 6D through the connector and no calibration process is required for the user, i.e., the HaptiHand is plug-and-play.

Based on this global architecture of the HaptiHand, it is now possible to describe its behavior from a signal processing point of view to show how the sensors and actuators contribute to the grasping task. Section. 6 describes how some major functions of the HaptiHand prototype have been evaluated.

5 Grasping Task

5.1 Decomposition of Grasping/Releasing Tasks. The HaptiHand has been designed to achieve dexterous and realistic object manipulations, considering the requirements set in Sec. 3. Then, a typical grasping/releasing task can be decomposed as follows:

(1) The user acts on the microswitches to monitor the flexion/extension of the fingers with a velocity-based control law.
(2) When a virtual finger collides with the virtual object or its environment, the vibrators are then activated for 400 ms. Each finger is processed independently of the others (R3).
(3) When the remaining joints collide, the joints stop moving.
(4) The virtual hand configuration is considered as a valid grasping configuration, i.e., the relative position of the virtual hand with respect to the object is natural from the user point of view. If the user applies a force high enough on the pressure sensor, grasping is then activated and the collision detection between the virtual hand and the virtual object is de-activated. Otherwise, the user can relocate the hand with respect to the object and apply a force on his/her fingers until the threshold (B) is reached.
(5) Once the user wants to release the object, he/she releases the force applied on the force sensor till a threshold (A) is reached. Under this threshold, grasping is deactivated and the collision detection between the hand and the object is activated again.
(6) The user acts on any microswitch to extend the corresponding virtual finger.
(7) When the fingers are released from collision, the vibrators are activated for 400 ms. Indeed, emitting vibrations in this configuration has not appeared as critical. If the adjustment of vibrations duration has been the focus of user studies, its impact when releasing an object needs further investigations. Presently, this is a software option.

Figure 9 describes the chronogram of activation/de-activation of the sensors within one module during a grasping/releasing task according to the different phases described above. It shows the connection between the components contained in one module and how their signals are processed to achieve a realistic simulation of these tasks.

To handle this workflow and process all the signals from the components of the modules, we developed a specific application programming interface linked with interface physics simulation interface, the software library developed by Haption for rigid-body physics simulation with force feedback, that uses extended dynamic engine (XDE) interactive dynamics simulation engine [5]. The overall implementation scheme is depicted in Fig. 10. The HaptiHand and the Virtuose 6D arm are considered as a unique device from the software point of view to simplify the management of the functionalities of the devices.

4.2 Mechanical Simulation of the Grasping/Releasing Tasks. Here, it is not intended to go into the details about the mechanical simulation of a grasping/releasing. Indeed, our aim with the HaptiHand is to offer different possibilities of path planning incorporating different categories of reconfigurations of the virtual hand and fingers onto the virtual object to be grasped,

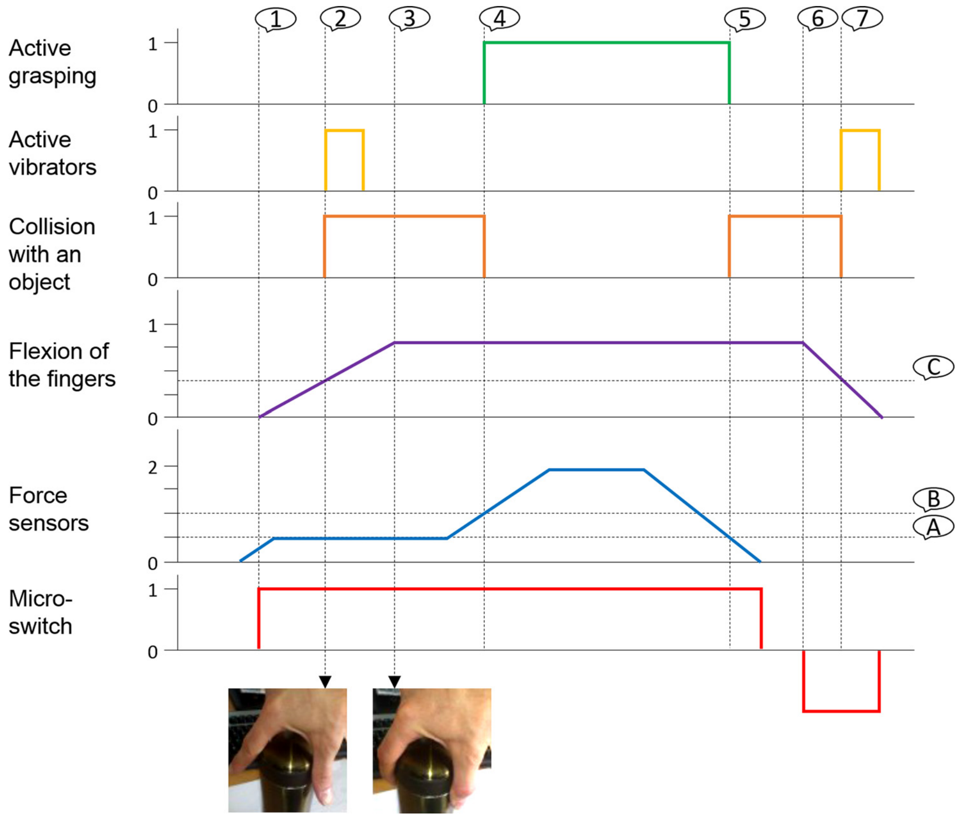


Fig. 9 Chronogram of activation/de-activation of the sensors during a grasping task. (*a*) represents the threshold to de-activate grasping, (*b*) the threshold to activate grasping, and (*c*) the collision detection.

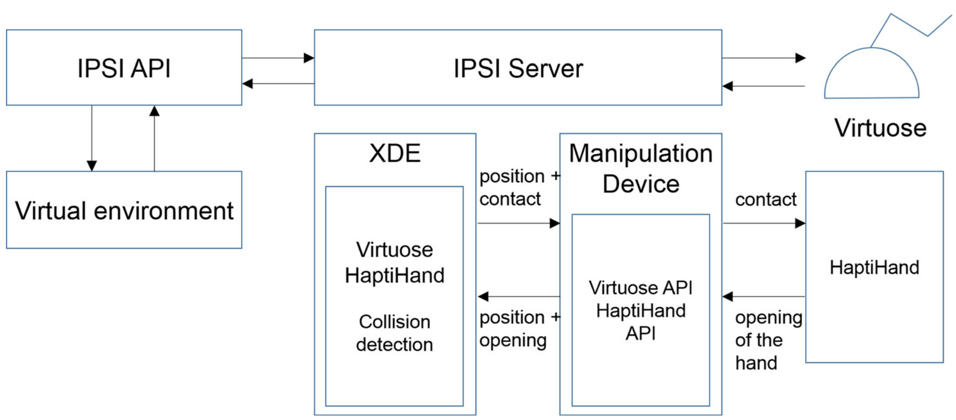


Fig. 10 General architecture of the software application

especially in cluttered situations. When looking for solution paths, the user may need to reconfigure the virtual hand with respect to the grasped object. Because this action may appear at any position along the path generated, it seems important that the object, when released and grasped by the user after the reconfiguration, keeps its 3D location, i.e., the object is *floating* in 3D space and has no contact with any other object of the scene (see for example the car door and its components in Fig. 15). Though this configuration has no physical meaning, it is more convenient for the user. This is one example where we do not require the physical simulation engine to model contacts with friction. In this section, rather, information is given to show how the HaptiHand behaves. The short description hereafter is distinct from the physical simulation engine that processes the whole virtual scene.

As mentioned earlier, the flexion/extension of each finger is managed through a single actuator. Thus, to handle the collision detection between the virtual fingers and the virtual object to be grasped, we considered that the detected contacts are grouped per phalanx and approximated by barycenters of the closest contact points with close normals $\mathbf{n}_i$ (see Fig. 11). The contact points of each phalanx are analyzed by testing the validity of the pairs with the contact points of other phalanxes. A pair of contact points is considered valid if both normal are in the friction cone and correspond to the same object [32] (see Fig. 11). In this case, there exist forces $\mathbf{F}_1$, $\mathbf{F}_2$, opposite to each other that satisfy the static equilibrium equation of the object. Detected pairs are stored and associated to the different phalanxes, and grasping actions are generated for each new phalanx for which the contacts points create a valid pair.

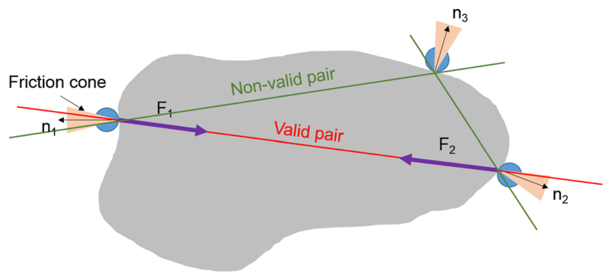


Fig. 11 Mechanical model of the contact virtual hand/object

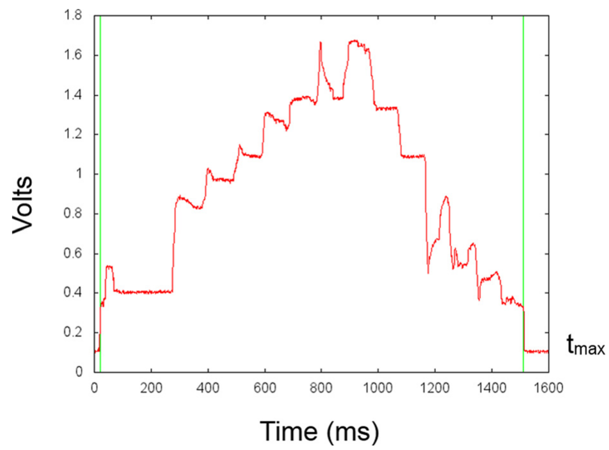


Fig. 12 Typical pressure sensor signal reflecting a stepwise pressure increase and pressure decrease as applied qualitatively by the user

For the management of the grasping itself, as the XDE engine does not include friction in the dynamics computation, object grasping cannot be achieved solely with the numerical calculation of the dynamics engine. Therefore, we chose to generate joint constraints between the hand and the object during the grasping phase (phase 4 in Sec. 5.1). Indeed, we considered the fingers and the object as a chain of rigid bodies with links that are created/removed in accordance with the grasping/releasing tasks, i.e., this is monitored by the pressure obtained through each pressure sensor under each finger.

Though the mechanical simulations used to process the whole scene do not rely on the same range of hypotheses (friction, no friction), our user's tests did not show that the realism of grasping/releasing actions was impaired using this setting.

6 Evaluation of the HaptiHand

This section focuses on the evaluation of the HaptiHand prototype from a functional point of view. The focus is placed on the functional requirements of the device and the description of the corresponding solutions. Consequently, the purpose is to evaluate the efficiency of the functions listed in Secs. 3 and 4.3. It is important to note that apart from the sensors, actuators, and connector with the Virtuose 6D already mentioned, all other components of the HaptiHand prototype have been manufactured using rapid prototyping techniques. As a result, the evaluation of the HaptiHand with respect to some functions has to be performed through an analysis that incorporates some key effects of the rapid prototyping manufacturing techniques. Two major techniques have been used: 3D printing (several categories of 3D printers have been used) and laser cutting.

Prior to focus on HaptiHand functions, it is mandatory to review the incidence of these rapid prototyping manufacturing techniques. One common aspect of these techniques stands in the dimensional tolerances of the manufactured components, i.e., 0.2 mm or more is a common tolerance that had to be incorporated in component dimensions at the design stage to ensure that functional clearances could be obtained when assembling the components. This is a strong issue because clearances could hardly be reduced to less than 0.2 mm whereas the components' dimensions where varying between 2 to 20 mm. This has a significant effect under the action of microvibrators.

Specifically for the laser cutting process used to produce damping components, the constraint is its thermal effect that may not produce clean boundaries depending on the material properties. Good results have been obtained for silicon sheets only among the range of damping material tested. As a result, the adaption of the stiffness parameter of some components (see Fig. 6) leads to the development of an engraving technique to adjust the thickness distribution of each component of the damping system to reduce its stiffness.

Regarding the 3D printing techniques, the most common ones using polyacrylate wire deposit, the surface roughness of the components can get very large (Ra 1.6 to 3.2) compared to the component size. Component shapes and slicing direction of the 3D printer were taken into account to reduce these effects whenever possible and minimize their side effects over the efficiency of the damping system. Because of the complexity of the HaptiHand shell, 3D printers with dissolvable additional stiffeners were mandatory to avoid bad quality surfaces for the damping system of the modules. Also, the large clearances resulting from the inaccuracies of 3D printers lead to the development of new 3D printing processes to be able to insert sheets of damping material during a 3D printing process to improve the damping effect. This technique has been applied to the module bracket in the areas of the through holes for its assembly screw (see Figs. 6 and 7).

Given the constraints of the prototyping processes, the HaptiHand prototype evaluation addresses the quality of the pressure sensor signal and of the damping system. Figure 12 illustrates the ability to deliver a pressure sensor signal with a range of pressure levels that can be identified by the user. A stepwise pressure increase and decrease is applied by the user to the whole module through the microswitch, i.e., operational conditions of a module. The amplitude between successive steps varies because it is user-prescribed based on his/her perception. This protocol has been set up to check that the signal range is adapted enough to a user grading from low to high. Here, 7 intervals were distinguished and it can be observed that there is no hysteretic behavior of the module since the signals at $t = 0$ and $t = t_{max}$ are of same magnitude.

Now considering the damping system, the validation process is based on user's perception to be able to distinguish the vibrator signals: independently of each other, each possible pair, each combination of three, and all vibrators together. If such tests were performed, they do not bring quantitative information to compare various solutions and help specify directions for improvements of the damping solution. Here, the purpose is a quantification of differences between designs of the damping systems. To this end, measurements of accelerations are compared under the following settings: the HaptiHand is rigidly attached to a high inertia object, one vibrator is active at a time, an inertial platform is glued on the HaptiHand shell and used as a reference point. Accelerations are measured in the three reference directions of the accelerometers of the platform. Six different designs (A through F) of the damping system are compared in Fig. 13. The first one, A, is characterized by two plain sheets of silicone of 1 mm thickness and damping components in the mobile part of the module. This design enabled the separation of each finger but combinations of two were not good enough. The last one, F, is characterized by three layers of engraved silicone sheets, damping components in the mobile part of the module, damping inserts in the module brackets and plastic assembly screws rather than metallic ones in A. As quantified in Fig. 13, this produced a significant improvement of the damping system that was deemed satisfactory from the user's point of view as well.

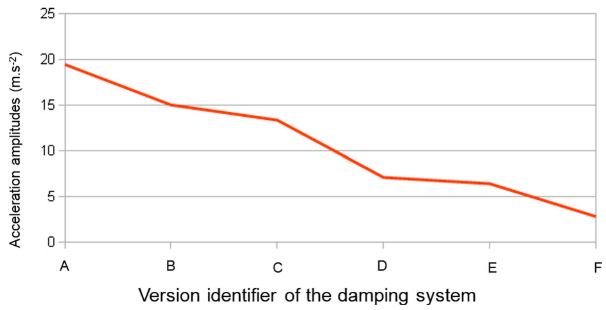


Fig. 13 **Comparison of design variants of the damping system**

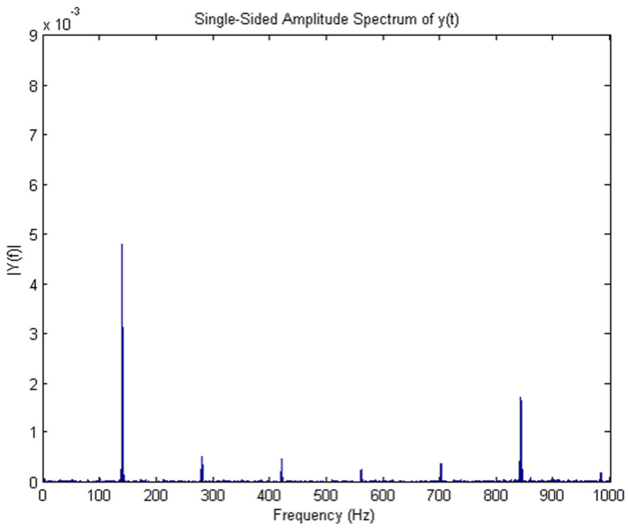


Fig. 14 **Frequency spectrum of the excitation perceived by the user in his/her palm**

As a complement to the previous evaluation, another one has been conducted to characterize the vibration signal with respect to the human physiology. This has been achieved with a spectral measure. When the vibrator of the index is activated, the vibration signal is measured on the shell with a piezo sensor (see Fig. 14). The spectrum obtained is analyzed within the frequency interval of [0, 1000] Hz. The fundamental frequency appears at 150 Hz. Prominently, the frequencies appear below 1000 Hz up to 2000 Hz. It can be observed that the reduction of the stiffness of the best damping systems compared to the previous one is essentially filtering the high frequencies that are not really perceived by a human being, i.e., greater than 1000 Hz [31]. The frequency interval regarded as meaningful for a passive haptic device is [10, 500] Hz in connection with the activation of the Meissner's and Pacinian's corpuscles, part of the human skin. If the reduction of stiffness characterizing the last design improvement of the module is not acting significantly on the frequency spectrum in the interval [10, 500] Hz, it has been observed that some users may feel pins and needles sensations in their fingers after a while. Therefore, a better damping system reduces higher frequencies and contributes to the reduction of the signal power transmitted to the user, which may act on the tingle sensation. This has to be investigated further as future development.

Figure 15 shows an example of a manipulation task performed with the HaptiHand and the Virtuose 6D, here, the insertion of a car window motor drive into a car door in a CAD software environment. The user controls the hand of a virtual manikin to simulate an assembly task. The CAD software provides visual feedback of collision and contact forces.

7 Conclusion

The HaptiHand device targeted to complement a haptic system for performing dexterous grasping tasks has been presented. The HaptiHand lets a user monitor in real time the number of fingers contributing to a grasping configuration and the user can update his/her hand configuration over the grasped object with new finger locations and variation in the number of fingers in contact with the object. These capabilities are achieved in a natural way using haptic sensory feedback when touching, gripping, or releasing an object. Also, it has been shown how the signal sequencing of the sensors/actuators of the HaptiHand contributes to the generation of a natural and intuitive grasping action. The resulting device is noninvasive and the proposed architecture and technical solutions have been evaluated. It has been demonstrated that rapid prototyping manufacture can produce accurate enough prototypes with adaption of these manufacturing techniques. The prototype development is close enough to the industrial product for Haption to proceed with the generation of the industrial counterpart of the HaptiHand.

Future work will investigate the tingle sensation and extend the design of modules to incorporate the real-time monitoring of the movement of adduction/abduction of virtual fingers and the

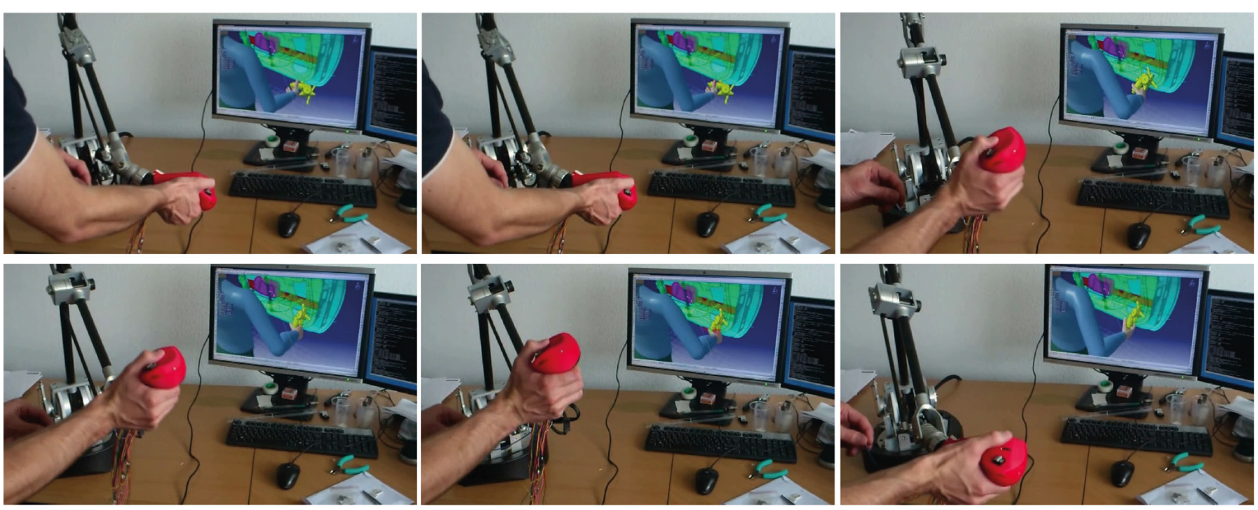


Fig. 15 **Example of manipulation task using the HaptiHand (from left to right: steps 1, 2, 4, 6, 7 in the chronogram of Fig. 8 and free motion of the hand)**

extension of the HaptiHand to the real-time monitoring of the adduction/abduction movements.

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