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AN ADD-ON DEVICE TO PERFORM DEXTEROUS GRASPING TASKS WITH A HAPTIC FEEDBACK SYSTEM

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ABSTRACT

Achieving grasping tasks in real time with haptic feedback may require the control of a large number of degrees of freedom (DOFs) to model hand and finger movements. This is mandatory to grasp objects with dexterity.

Here, a new device called HaptiHand is proposed that can be added to a haptic feedback arm and provide the user with enough DOFs so that he/she can intuitively and dexterously grasp an object, modify the virtual hand configuration and number of fingers with respect to the object while manipulating the object. Furthermore, this device is non-invasive and enables the user to apply forces on the fingers of the virtual hand. The HaptiHand lies inside the user's hand so that the user can apply and release pressure on it in a natural manner that is transferred to the virtual hand using metaphors.

The focus is placed on the description of the technology and structure of the HaptiHand to justify the choices and explain the behavior of the HaptiHand during object grasping and releasing tasks. This is combined with a short description of the models used.

1. INTRODUCTION

The evaluation of manual tasks is a common requirement when addressing the usage, manufacturing, maintenance and decommissioning of a product during its development process [1, 2]. When no physical mock-up of the product is available, qualitative approaches are used in industry to predict/evaluate

these manual activities. Numerical simulations, incorporating the DOFs of a hand as well as the interaction forces between a hand and the grasped object, involve a large number of parameters [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 virtual reality (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 [5], but they either lack channels for the fingers, or are very cumbersome to set up and use. Consequently, the grasping task is usually restricted to a set of pre-defined grasping configurations that are not close enough to reality.

Here, we propose a new device called HaptiHand, that replaces the end-effector of a haptic arm commercialized by Haption company [6] to perform dexterous grasping tasks that takes into account 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). To this end, the paper is structured as follows. Section 2 reviews prior work to specify more precisely the objectives of the device. Then, section 3 details the objectives set for the device and section 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, section 6 addresses the validation of the prototype.

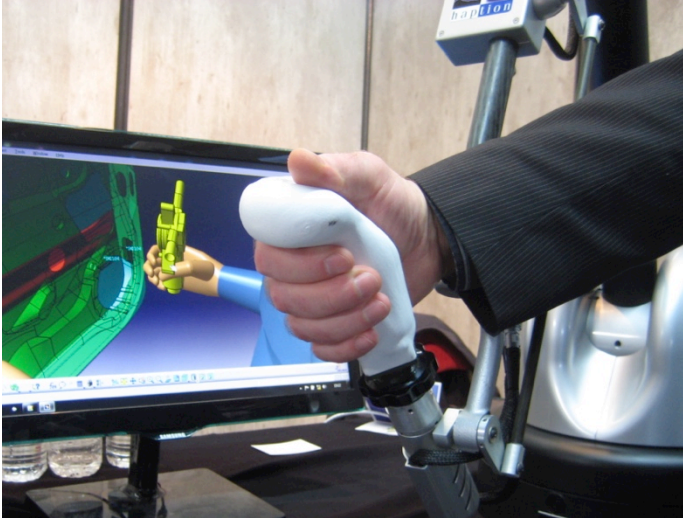


Figure 1: HaptiHand add-on device as end-effector of the Haption haptic arm.

2. PRIOR 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 [8]. Therefore, the design of a peripheral device is highly dependent on the 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 Virtuoso 6D from Haption, allowing the user to touch and grab virtual objects using a virtual attach point 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 SPIDAR system [10, 11] can be used to grasp virtual objects in an intuitive way. Though this interface provides the user with a large workspace for complex manipulation tasks, when extending it to a multi-finger configuration [12], it becomes unhandy because of the complexity of wires configuration and additionally, only 3 DOFs force feedback is returned to the user. Multi-finger haptic devices proposed in the literature include exoskeleton-based devices, e.g., [13, 14], gloves, e.g., [15, 16], or robots, e.g., [17], providing force

feedback on all fingers and wrist. 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, needs 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 multi-finger 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 multi-finger haptic device to change the contact location on the user's fingers. This system is intrusive, 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 to better feel virtual objects, accurate feedback should be returned. These issues have been greatly discussed in past research, especially in the case of a multi-finger 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], providing reliable detection but 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]. However, this kind of feedback is 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 hand configurations in a natural and dexterous way to avoid cognitive overload and achieve close-to-real interaction. The user should be able to reconfigure his/her hand during a holding task in an intuitive way, meaning the device should stay compatible with a non-intrusive haptic force feedback system. Detailed specifications of the HaptiHand are given below.

3. SPECIFICATIONS OF THE HAPTIHAND

In order to improve the grasping task with a haptic arm and set up a more realistic behavior of the hand fingers when they

are positioned around an object, the following major requirements (Ri) have been set up for the HaptiHand:

- R1. The force feedback produced by the haptic arm called Virtuoso 6D (6 DOFs and 3 force components, 3 moment components) to locate the user's wrist in 3D space generates 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;
- R2. The user must be able to bend/extend naturally the virtual hand fingers to configure the hand with respect to the object and 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 31N and peak torque 3.1Nm). This is an important feature compared to exoskeleton-based devices because the user may encounter either mechanical stops of the Virtuoso 6D 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;
- R4. Provide user's feedback when the virtual hand and fingers touch any component of the environment to help the user monitor a grasping task;
- R5. Enable the user to grasp an object with a large diversity of hand configurations, i.e., 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 focus for the design of the HaptiHand;
- R6. The grasping task should be achieved naturally with a haptic phenomenon. In configurations where the user is pressing the virtual hand onto the object, interaction forces must take place between the virtual hand and the object and be somehow related to interaction forces between the user's hand and the HaptiHand. Symmetrically, the release operation should involve a haptic phenomenon;
- 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;
- R8. The HaptiHand should be added/removed easily from the Virtuoso 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 actions with a virtual hand. This characterizes the framework used to design the HaptiHand.

4. STRUCTURE OF THE HAPTIHAND

4.1 Overall structure of the haptic system

The haptic device Virtuoso 6D of Haption has a modular architecture, in that it is equipped with a tool-changer at the basis of the handle, which transports both the mechanical load (forces and torques) and the electrical signals. The signals are digital and can be multiplexed, except for two mandatory functions. The first function is the "clutch", which is used for decoupling the handle from the virtual object, i.e., the same action as lifting a computer mouse but for all directions in 3D space. The second function is the "dead-man", a small optical sensor which shuts down the motor power whenever the user releases the handle. The HaptiHand is designed as a replacement for the standard handle of the Virtuoso 6D and thus, must implement the "clutch" and "dead-man" functions.

4.2 Structure of the hand model

Given the design constraints reviewed in Section 4.1 and the requirements listed in Section 3, it is now necessary to specify the characteristics of the hand model associated with the HaptiHand. Indeed, the HaptiHand is an evolution of a desktop, low cost peripheral for virtual hand simulation (see [21] for complementary details about the virtual hand model).

Figure 2a illustrates the main features of the hand kinematic model used with the HaptiHand. The virtual hand model contains 27 DOFs modeled with hinges and spherical links. It is already a simplified version of the DOFs of a real hand [2, 3]. Figure 2b indicates how these DOFs are related to the virtual hand monitoring. There, simplification hypotheses have been set up 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. 2b). This is especially constraining for the thumb and index movements because it reduces the range of realistic grasping configurations. However, the design of some sub-assembly 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. 2b 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 non-invasive 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. 2b). 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 Section 5.1).

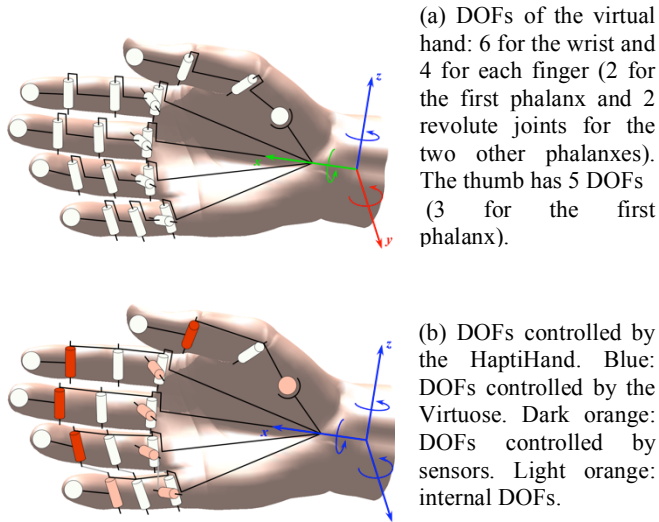


Figure 2: (a) Unconstrained kinematic model of the virtual hand, (b) kinematic model associated with the HaptiHand.

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 DOFs 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 Section 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 sub-system of the HaptiHand is designated

as a module and its design description is given in the following section. The incorporation of the clutch and optical sensor in the HaptiHand is part of its global architecture described at Section 4.4.

4.3 Design of a module

The HaptiHand must be compatible with the Virtuose 6D as well as the environment of this device, i.e., other simulation equipment in the context of AR (Augmented Reality)/VR immersions. There, electro-magnetic fields can interact with the haptic system and hence, with the HaptiHand. Therefore, the technical solutions rely on technologies that are resistant to perturbations from possible electro-magnetic fields.

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.

A- Kinematic behavior to bend/extend each finger (R2). This can be achieved within a small volume using a micro-switch technology (see Fig. 3a) or mini-trackballs (see Fig. 3b) or scrollpads (see Fig. 3c). Though mini-trackballs 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] or could not be used because of their sensitivity to electro-magnetic fields. Also, scrollpads suffer from sensitivity to electro-magnetic fields and additionally, they require a finger displacement of nearly 15mm magnitude [21], which is inconvenient when the user oppose to forces set by the Virtuose 6D. Consequently, the technology selected is of type micro-switch. This technology can generate a finite number of states with the idle state at rest. If a micro-switch 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, which 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]. Thus we will adopt a velocity-based monitoring of the finger movement (R3). 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. 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. To reduce the number of DOFs monitored, one micro-switch is used to control a whole finger using an inverse kinematic model for its movement.

B- Contact/collision feedback between a virtual finger of the user's avatar and 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 is 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 an object. We use of a vibratory signal to produce a passive haptic signal at each user's fingertip

monitoring a micro-switch. This vibration forms a haptic texture [31]. In a first place, the vibration source is located at a constant position on a finger and the skin area excited by the actuator is less than 1cm^2 . Micro-vibrators are used to generate a signal at each user's fingertip to produce the desired passive effect. Among the available technologies of micro-vibrators, the one based on unbalanced rotating mass (see Fig. 3d, e) can provide rather compact devices. The one of Fig. 3e is more compact than those having an external mass when a housing surrounds them. Additionally, the excitation frequency they generate fits well with the skin sensitivity [31]. Their vibration frequency at 12kHz 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. 4, this plane is parallel to the PCB plane and the micro-vibrator is directly in contact with the PCB where the micro-switch is mounted to maximize the efficiency of the vibration effect.

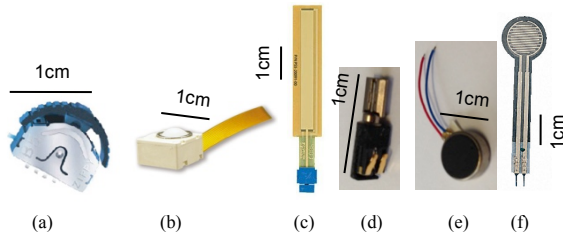


Figure 3: Different sensors/actuators technologies. From left to right: (a) single-axis micro-switch, (b) trackball, (c) scrollpad, (d) vibrator with external mobile mass, (e) vibrator with internal mobile mass, (f) pressure sensor.

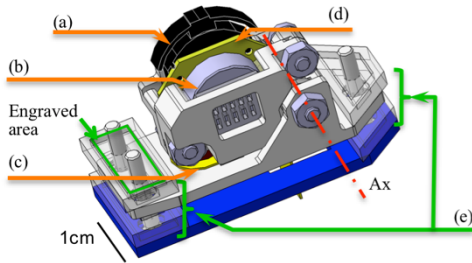


Figure 4: CAD model of a module of the HaptiHand. (a) micro-switch used to monitor the finger movement (black), (b) micro-vibrator generating a passive haptic effect during collisions (gray), (c) pressure sensor used to produce an active haptic effect when grasping/releasing an object (yellow), (d) printed circuit board (PCB) (yellow), (e) damping systems (white transparent).

Each micro-vibrator must generate a haptic effect for each 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 (R3). To this end, each micro-vibrator must be associated with a corresponding micro-switch rather than the shell of the HaptiHand where the vibrations would propagate throughout this structure. However, this setting is not sufficient to ensure that the vibrations

generated at the fingertip of one user's finger does not propagate to other fingers and/or to the user's palm. This is a strong issue that requires solutions to generate vibrations in one module without propagating to others. Section 4.4 gives more details about this specification and Fig. 4 shows how some damping systems have been added to each module.

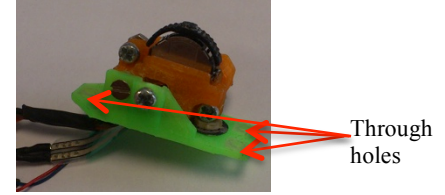


Figure 5: One of the prototype modules incorporating the various actuators/sensors described and housed in 3D printed components.

C- Haptic behavior when grasping an object (R6, R7). The haptic feedback with the 3 force and 3 moments components is applied to a reference point of the Virtuoso 6D defining the wrist of the virtual hand. To grasp an object using a haptic phenomenon, a force must be generated that takes part to the interaction between the user's fingers and the HaptiHand to monitor the interaction between the virtual hand and the object being grasped. This force requires a new device to be independent of the force produced by the Virtuoso 6D. It is a force internal to the hand structure, which justifies that the hand model described at Section 4.2 is a 'local model' processed independently of the physical simulation engine. This force is naturally generated by a human being when grasping an object 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 area 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 fingertip and the HaptiHand, where lies a micro-switch, to monitor the grasping action of the user (R6, R7).

The device used is a pressure sensor to acquire the pressure under each finger. This 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 of 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 to be resistant to electro-magnetic

perturbations (see Fig. 3f and 4). During grasping, 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 Section 6.

In addition to Fig. 4, Fig. 5 illustrates a prototype module. Based on the description of a module, the overall architecture of the HaptiHand is described in the next section.

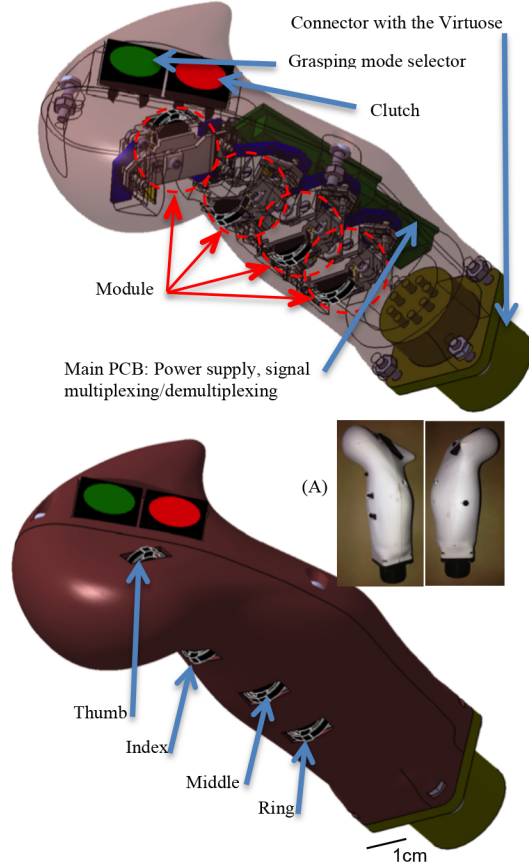


Figure 6: CAD model of the HaptiHand. The top view shows the location of the major sub systems with the outer shell displayed in transparency mode. The bottom view shows the external view of the HaptiHand prototype. (A) Two photos of the physical prototype using opposite viewpoints.

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 size. As a compromise between tightly tuned ergonomic shapes and a general purpose one like the standard end effector of the Virtuose 6D, right-handed and left-handed users have been distinguished. This is mandatory because the location of the micro-switches over the HaptiHand shell must lie under each user's fingertip. Figure 6 shows a right-handed version of a HaptiHand. Figure 6 does not feature the optical sensor used to comply with R2, which is located opposite to the viewpoint set for this figure, but features the clutch that contributes to R2, the

connector to the Virtuose 6D (R8), the grasping mode selector (GS) to select a pre-defined grasping strategy incorporating adduction/abduction movements of the fingers, particularly of the thumb movement (R5). GS removes the current limitations of the modules that cannot provide an adduction/abduction. This simple extension with respect to Sections 4.2, 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 6 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 micro-vibrators are also available from this PCB. To achieve efficient passive haptic effects described in Section 4.3 with micro-vibrators, each module is equipped with a damping system as shown in Fig. 4. 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. 6. Each module contains also additional damping areas around the sub system (micro-switch, PCB, micro-vibrator (Fig. 4a, b, d)) to improve the damping mechanism. To be able to generate a pressure onto the sensor (c) (see Fig. 4), (a, b, d) is a rotating sub system whose rotation axis is A_x (see Fig. 4). Damping material is inserted between this sub system 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. Then, 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 manipulation, considering the requirements set in Section 3. Then, a typical grasping/releasing task can be decomposed as follows (see also Fig. 13):

1. The user acts on the micro-switches 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 400ms. 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 pressure sensor till a threshold (A). Under this threshold, grasping is deactivated and the collision detection between the hand and the object is again activated;
6. The user acts on any micro-switch to extend the corresponding virtual finger;
7. When the fingers release from collision, the vibrators are activated for 400ms. 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.

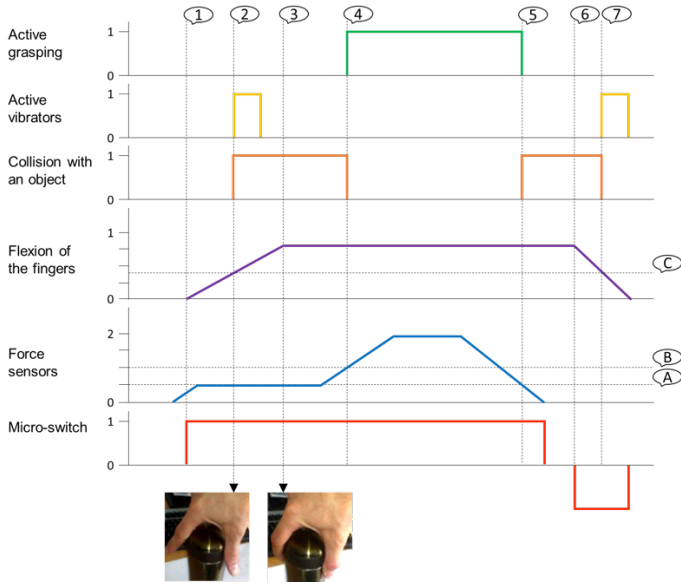


Figure 7: Chronogram of activation/de-activation of the sensors during a grasping task. (A) represents the threshold to de-activate grasping, (B) the threshold to activate grasping and (C) the collision detection.

Figure 7 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 (API) linked with IPSI

(Interface Physics Simulation Interface), the software library developed by Haption for rigid-body physics simulation with force feedback, that uses XDE interactive dynamics simulation engine [6]. The overall implementation scheme is depicted in Fig. 8. The HaptiHand and the Virtuoso 6D arm are considered as a unique device from the software point of view to simplify the management of the functionalities of the devices.

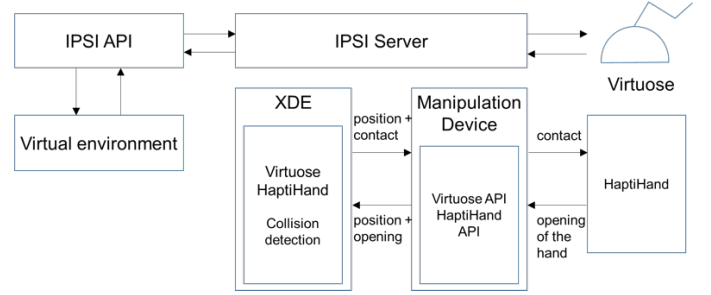


Figure 8: General architecture of the software application.

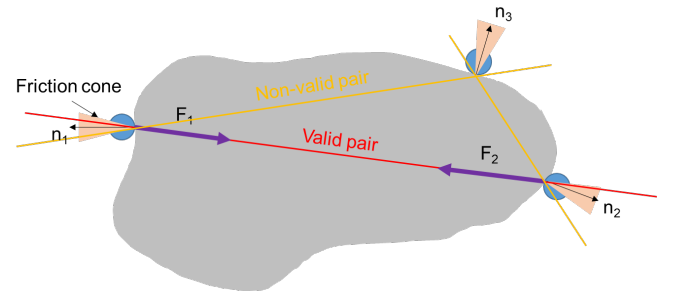


Figure 9: Mechanical model of the contact virtual hand/object.

5.2 Mechanical simulation of the grasping/releasing tasks

Here, it is not intended to give details about the mechanical simulation of a grasping/releasing action because of the lack of space and is left for another publication. Rather, information is given to show how the HaptiHand behaves and it is also important to point out that the simulation approach set up does not require the physical simulation engine to model contacts with friction. 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. 9). 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 normals are in the friction cone and correspond to the same object [32] (see Fig. 9). In this case, there exists 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.

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 in the grasping phase (phase 4 in Section 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.

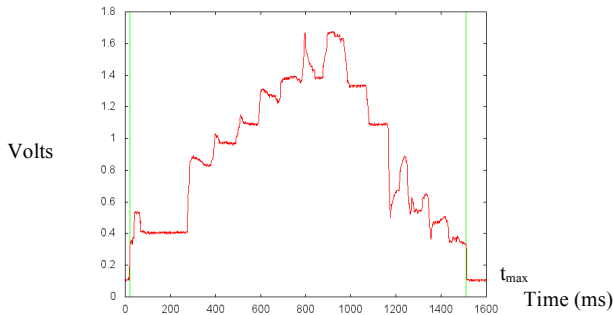


Figure 10: Typical pressure sensor signal reflecting a stepwise pressure increase and pressure decrease as applied qualitatively by the user.

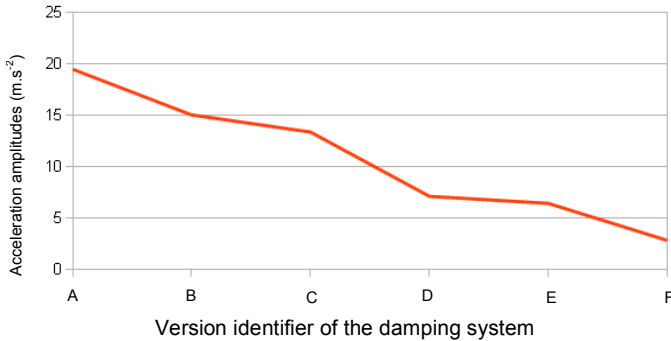


Figure 11: Comparison of design variants of the damping system.

6. FUNCTIONAL EVALUATION OF THE HAPTIHAND

This section focuses on the evaluation of the HaptiHand prototype from a functional point of view. The evaluation of a grasping task using the HaptiHand, i.e., a user study, is left for another publication. Consequently, the purpose is to evaluate the efficiency of functions listed in Sections 3 and 4.3. It is important to note that apart from the sensors, actuators and connector with the Virtuoso 6D already mentioned, all other components of the HaptiHand prototype have been

manufactured using rapid prototyping techniques. Assembly clearances were of 0.2mm magnitude and damping material has been inserted during the 3D printing process of some module components (see Figs. 5, 6).

The HaptiHand prototype evaluation addresses the quality of the pressure sensor signal and damping system. Figure 10 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 micro-switch, 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 enables 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 signal 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 system. 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. 11. The first one, A, is characterized by two plain sheets of silicone of 1mm 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. 11, this produced a significant improvement of the damping system that was deemed satisfactory from the user's point of view.

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. 12). The spectrum obtained is analyzed within the frequency interval of $[0, 1000]$ Hz. The fundamental frequency appears at 150Hz. Prominently, the frequencies appear below 1000Hz up to 2000Hz. 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 1000Hz [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 Paccini'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.

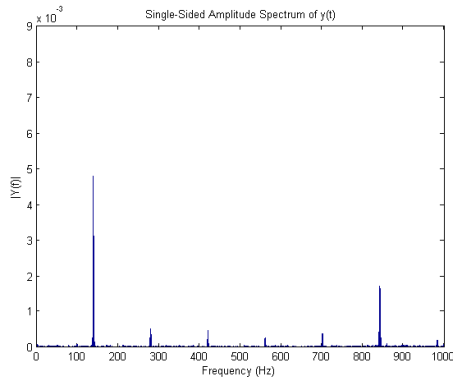


Figure 12: Frequency spectrum of the excitation perceived by the user in his/her palm.

Figure 13 shows an example of a manipulation task performed with the HaptiHand and the Virtuoso 6D. Here, the insertion of a car window motor drive into a car door in a CAD software environment is showed. 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 enriching a haptic system with 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 phenomena when touching, grasping/releasing an object. It has been shown also how the signal sequencing of the sensors/actuators of the HaptiHand contribute to the generation of a natural and intuitive grasping action. The resulting device is non invasive and the proposed architecture and technical solutions have been evaluated. The prototype development is close enough to the industrial product for Haption to proceed with the generation of an 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.

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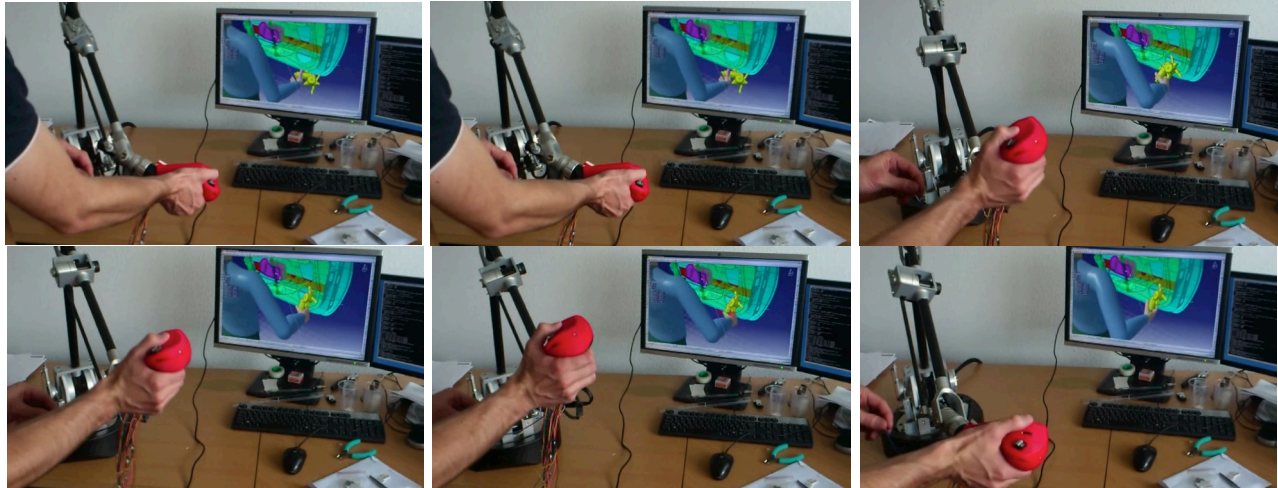


Figure 13: Example of manipulation task using the Haptihand (from left to right: steps 1, 2, 4, 6, 7 in the chronogram of Fig. 7 and free motion of the hand).

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