Enabling Multi-finger, Multi-hand Virtualized Grasping

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Abstract

This paper presents a series of kinematic and haptic analyses which lead to the design of a particularly simple, yet useful multi-hand multi-finger haptic interface. We also discuss rendering issues which must be addressed in utilizing it, including and extension of the proxy to more general contact.

1. Introduction

Although the science of haptics gained importance in the last 15 years, and many successful haptic devices have been developed and commercialized, the range of capabilities with current haptic interface technology is still fairly limited. Many different types of haptic devices have been developed through the years. Devices allowing the simulation of single-point contact interaction in 3-D have come into common use in a diverse range of the research communities and, more recently, in commercial applications.

Three-degree-of-freedom devices, such as the PHANTOM [24] and Delta [22] haptic interfaces, have shown that a simple single-point contact interaction metaphor can be surprisingly convincing and useful. This interaction paradigm imposes, however, limits on what a user can do or feel. One of the main features of the haptic sensory modality is its bi-directionality - mechanical energy is exchanged back and forth between human operator and the object being touched - making this the only really interactive sense. However, single point of contact interaction makes it impossible for a user to perform such basic tasks as grasping, manipulation, and multi-point exploration of virtualized objects, thus restricting the overall level of interactivity. Single point interaction severely limits or slows the user's ability to determine object characteristics such as shape, mass, stiffness, size, etc. as noted in a number of perceptual and cognitive studies [10, 7, 16, 14].

The earliest examples of devices allowing users to manipulate virtual or distant objects were typically telemanipulation master-slave systems used in the nuclear and under-sea industry. Such systems typically included strong end-effectors for handling heavy materials, with only a few having even moderate quality force reflecting grip force feedback capability, such as the MA-23 developed by Jean Vertut [20].

The advent of conveniently small and safe "desktop" haptic interfaces has enabled a few researchers to combine two three-degree-of-freedom devices, simulating two point contacts, to allow grasping of virtual objects. Von der Heyde et al. [21, 11] have used two PHANTOM 3.0 devices in order to study one-hand precision grip tasks. Ernst and Banks [6] have used two PHANTOM devices, one for the index finger and one for the thumb, in order to study how humans integrate visual and haptic information while grasping an object. Coutee et al. [1] have used two PHANTOM 1.5 devices in order to simulate assembly and disassembly operations on a computer. Yoshikawa et al. analyzed the stability of the haptic interaction between two fingertips and a virtual object [25] [13] using two 3DOF devices designed at Kyoto University. While the combination of two devices can create highly realistic simulations, problems exist with this configuration. Two devices typically fill significant workspace (limiting the extension to a dual-handed configuration) and their combined workspace (intersection) is typically limited. The cost of two separate devices can also be considerably higher.

A few instances of desktop devices able to provide active force feedback during grasping to exist. In most cases however such devices have been designed to simulate a particular tool, such as various laparoscopic and endoscopic instruments [9, 23, 5]. One device that does allow for a more general purpose[1] simulation of grasping is the Freedom7

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[1] general purpose haptic devices do not implicitly define a particular interaction metaphor but can be adapted, via software, to simulate different scenarios

developed by Hayward [19].

This paper presents a dual-handed general-purpose desktop haptic interface that allows users to grasp and manipulate virtual objects using a thumb and index (or other) finger on each hand. The device has been designed to minimize complexity, which helps keep costs low and enhances transparency [2]. We will present several incrementally more complex designs and, in addition, discuss an extension to present rendering techniques which builds upon the god-object and proxy approaches [26, 17] to enable virtual grasping with soft-finger contacts [18].

The remainder of the paper is organized as follows. Section 2 presents the minimal requirements necessary for a haptic interface to allow grasping of virtual objects. Section 3 presents incrementally more complex designs that allow the simulation of grasping. Section 4 presents haptic rendering algorithms appropriate for use with the class of devices we discuss and introduce the concept of soft finger proxy. Section 5 draws conclusions and indicates future directions for our research.

2. Requirements for simulating grasping

In the following we will determine the minimal requirements to enable a haptic interface to simulate grasping. We will focus our attention on form closure, which can be defined as the capacity of a certain grasp to completely restrain an object against any disturbance wrench[18].

We will assume that users will manipulate virtual objects with their hands using fingertip prehension. We will model the contact between a fingertip and a virtual object as a point contact. While this can seem somewhat limiting it has been proven to be a reasonable approximation and greatly simplifies collision detection and rendering algorithms.

Three types of point contacts will be considered. A *point contact without friction* can only exert a 1-system of wrenches[3] on an object (a force along the contact normal). A *point contact with friction* can exert a 3-system of wrenches on an object (three independent forces through the point of contact). A *soft finger contact* behaves like a point contact with friction, except that that its contact area is large enough that it can support moments (up to a torsional friction limit) about the contact normal.

For our purposes here we will define an *avatar* as a virtual representation of the user through which physical interaction with the virtual environment (VE) occurs (in our case the avatar is a set of virtual fingertips). The user controls the avatar's position inside the VE. When contact arises between the user's avatar and the VE, action and reaction forces occur. Such forces are regulated by the type of contact supported by the avatar and by its geometry. In the case of point-based avatars, such as the proxy and god–object, point contact types are the only ones supported.

Let us suppose that n is the total number of variables needed to describe an avatar position as well as action and reaction forces between avatar and VE. In the case of point-based avatars supporting point contact (with or without friction) $n = 3$, while in the case of soft finger contact $n = 4$. This is the number of sensors and actuators necessary to take full advantage of the motion and force transmitting capabilities of a given avatar. Each sensor allows the user to move its avatar inside the VE along a single degree of freedom twist while each motor maps a single degree of freedom wrench from avatar back to the user. Thus, in order to fully control the position of an avatar and observe its contact forces [3] n sensors and n motors are normally needed.

Finding the minimal requirements, in terms of number of actuators and sensors, in order for a haptic device to perfectly simulate form closure grasping can be seen as a two-step process. The first step is to define a set of avatars that allow form closure[4]. The second step is to design a physical device capable of supporting such avatars.

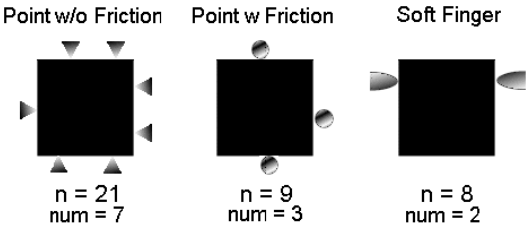

Figure 1. Number of contact points (num) needed to impose form closure and corresponding number of sensors and actuators needed (n).

In the case of point-based avatars the minimal configuration needed for form closure is given by the combination of a soft finger and a point contact with friction[18]. This is an interesting case worth further design study. However, for simplicity in the design phase, we will consider only cases employing avatars of same contact type. Given this constraint, the minimal configurations allowing form closure are given as

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[2] Transparency can be defined as the ability of a device to reproduce the exact contact force computed by the virtual environment (VE) when the operator is colliding with a virtual object, while at the same time not be perceived when the operator moves in free space. Perfect transparency is impossible to obtain since it would mean that a device has no mass or dissipation while being a perfect force and position transducer.

[3] We use the terms wrench and twist to signify generalized forces and motions, respectively, as defined in [18]

[4] the number of contact constraints needed for form closure depends on the dimensionality of VE been considered. In the following we will consider a VE comprised of rigid objects whose position can be uniquely determined by six state variables

- two soft-finger contacts ($n = 8$)
- three friction point contacts ($n = 9$)
- seven frictionless point contacts[5] ($n = 21$)

and are illustrated in Fig. 1. The two-soft-finger design was selected for implementation as it minimizes the number of sensors and actuators needed to enable virtualized grasping. The device that faithfully implements this pair of avatars must be able to exert a 4-system wrenches on two of the user's fingertips, while also time tracking their translation in three dimensions and relative orientation changes about the contact normal. This would require 8 sensors and 8 motors. If we consider grasps between an idealized pair of soft fingers, such that there is no relative finger tip rotation about the axis between the tips (e.g. no internal torsion exerted on an object during grasp), then we need only allocate one sensor to track the rotation of (one of) the fingertips, and one motor to display torques about the grasp axis while objects are held. This brings us to a design requiring 7 sensors and 7 motors.

If fewer motors and/or sensors were used, the device would no longer be able to faithfully reproduce the motion and force/torque interactions afforded by the soft-finger avatars during grasping. As a consequence, while users may still be able to impose form closure on a virtual object they would not be able to arbitrarily position their avatars in space and/or be presented with an incomplete set of contact forces [3].

Figure 2. A device with four motors and four sensors allowing users to grasp and manipulate virtual objects

3. Haptic interface design

We have developed a series of haptic interface device based upon the above principles. Starting with a standard three-degree-of-freedom haptic device such as the PHANTOM or the Delta, additional sensors and/or motors have been added throughout this process. In the following, various prototypes are presented and their performance is discussed. It is important to note that particular attention is placed on limiting the number of motors of the proposed devices, i.e. actuators are considered more "expensive" [6] than sensors. The effect of these design tradeoffs and motor/sensor *asymmetries* haptic interface design is considered more generally in [3].

Note that all of the designs presented in the following are based on a same force reflecting gripper (see Fig. 5) that will be described in section 3.3.

3.1 A 4 motor/4 sensor device

Figure 3. A device with four motors and seven sensors allowing users to grasp and manipulate virtual objects

An example of what is arguably the minimal configuration that allows the simulation of virtual grasping is depicted in Fig. 2. This device has a total of four motors and four sensors. It is based on a PHANTOM Premium 1.5 combined with a force reflecting gripper capable of measuring relative position and exert force between index finger and thumb (see section 3.3). A passive wrist is used to connect the two devices thus not imposing any spurious

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[5] Note that cases exist of objects which cannot be fully restrained using frictionless point contacts, such as the case of a spherical object

[6] in terms of transparency

forces on the user. The user is able to control two soft finger avatars, grasp a virtual object and impose form closure on it. The motion of such avatars is however limited to translations in space. The user cannot impose orientation changes on virtual objects even though he/she is able to restrain a virtual object from rotating around the line connecting the two avatars. Furthermore the user is not able to observe any torque feedback (due to rotational friction or to contact forces not parallel to the line connecting the two avatars). The device is mechanically simple, very transparent, limited in cost and allows for a considerably more complex interaction metaphor than the familiar 3-DOF interface.

3.2 4 motor/5-6-7 sensor device

Sensors (one, two or three) can be added to the wrist of the device presented above. This allows the user to have a higher level of control over the position of grasped virtual object while not increasing the mechanical complexity and transparency of the device presented in section 3.1 in any significant way. While various wrists have been tested we will present the case of one featuring three encoders (see Fig. 3).

The limit of this device is that no torques can be fed back to the user and this may create unrealistic effects. In order to better explain this, consider a 2D virtual environment depicted in Fig. 4, where two avatars can touch opposite faces of a static wall. For simplicity, let us suppose that the center of the line connecting the two points controlled by the user is fixed in the origin of the $x-y$ reference frame. Given the above constraint the position of the two points can be described using two variables: L represents the distance between the two points; α represents the angle between the line connecting the points and the $x-$axis. As a result of contacts with the wall the user will experience a force along the line connecting the two points F_g and a torque τ.

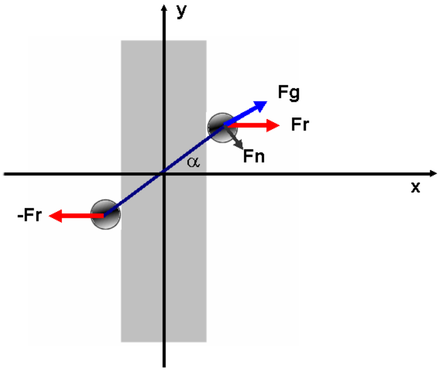

Figure 4. A device with four motors and seven sensors allowing users to grasp and manipulate virtual objects

A device such as the one depicted in Fig.3, (i.e. one with an instrumented wrist, but with no wrist motors) will not be able to display all of the forces of interaction that arise with rotation of α - forces in the frame of the wrist gimbal will be displayed but no reaction torque will be displayed. Further grip force F_g along the line connecting the two avatars will be displayed. This is projection of contact forces occurring in the higher dimension world of the simulation to a lower dimension (due so actuator absence) space of the displayable forces. This is good and bad news. Through active exploration, it does allow the user to gain information about the shape of the wall. However the deficiency in force feedback dimension can, in certain task contexts, and to varying degrees, lead to non-conservative interactions. When this happens, renderings objects will feel active, disrupting the fidelity of interaction by inducing unexpected power flows. In practice, it is not yet clear how significant a problem this will be for simulations of realistic objects (in which dissipations due to friction and viscosity will hide some levels of improper power flow). For a more complete analysis of these issues see [3]. In order to further explore the spectrum of design possibilities between this very simple case and the ideal case presented above we are investigating grasp-capable interfaces with seven sensors and more than four motors.

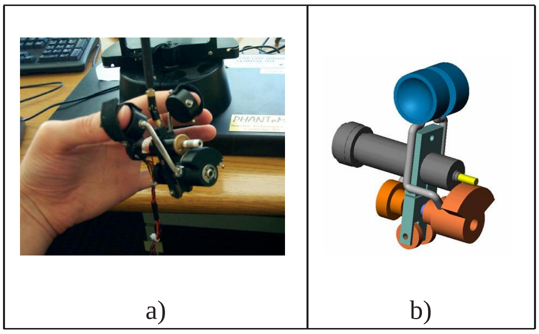
a) b)

Figure 5. The force reflecting gripper

3.3 Force reflecting gripper

One significant challenge in designing a force reflecting gripper is transparency. While this is true in general for haptics it is particularly true in the case of general purpose devices[7], like the ones considered in this paper.

Various characteristics of index finger and thumb make the task of creating a transparent device harder than usual.

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[7] those devices that do not replicate a specific tool but just a transparent source of force

The device should be highly backdrivable and have high position resolution. Index finger and thumb are in fact extremely sensitive to force and position[8]. The device should be small and should exert forces only on the user's finger pads. This strongly limits the possibility of using large cable-based transmissions. The device should be capable of exerting high forces[9].

The classic trade-off between limiting distracting effects, such as friction, backlash and reflected inertia, and being able to simulate large enough forces is thus pushed to a limit. DC motors, typically used in haptic devices, are often very limited in torque capabilities. Higher torques can be obtained by using larger motors (but this increases inertia); using larger gearhead reduction (but this limits backdrivability); using larger cable reduction (but this increases the overall volumetric footprint of the device).

To make things worse in the case of a force reflecting gripper we can only rely on the maximum continuous torque of the DC motor. It is a typical practice to drive haptic devices with transient currents larger than the maximum continuous current while monitoring the thermal state of the device. This works quite well in the case of devices such as the PHANTOM, since contact forces have often very limited duration. The case of a force reflecting gripper is different however, since a user might grasp an object for large durations and forces, thus requiring a design constrained by the motor's maximum continuous current.

One device we developed is depicted in Fig. 5, and its characteristics are summarized in table 3.3. The device is small (it is contained in a $7 \times 8 \times 4$ cm^3 volume) and light and has high position resolution. The particular kinematic solution that has been chosen limits the contact areas between users' hands and device to the index finger and thumb pads. This however creates a force that is variable throughout the device's workspace. The maximum continuous force that can be exerted by the device is quite large given the limited force capabilities of $16mm$ DC motors. This is accomplished using a combination of a small gearhead reduction in series with a cable reduction, which is a good tradeoff between overall device bulk, inertia and backdrivability. Index and thumb are coupled, i.e. both fingers move an equal distance from the devices body and connection point to the PHANTOM.

Parameter	Value
Max Continuous Force (best case)	3.252 [N]
Max Continuous Force (worst case)	1.62 [N]
Peak Force (theoretical) (best case)	20.94 [N]
Peak Force (theoretical) (worst case)	10.47 [N]
Weight	80g
Position Resolution	0.017 mm

Table 1. Parameters that characterize force reflecting gripper

3.4 Overall device

Up to this point we have focused on the design of a single-handed device with two fingers. More generally, we have developed a system allowing two-handed manipulation and exploration of virtual objects, as depicted in Fig. 6. This can be considered an important step in creating more complex and rich VE applications, one that we believe fills a void[10] and capitalizes on lessons about the utility two-handed interfaces learned during the development of the Intuitive Surgical Inc's daVinci(tm) Surgical system.

In our initial experiences using this system to interact with virtual objects, it is clear that two-finger grasping and use of two hands provides a very rich interaction paradigm. Enabling users to instinctively grasp and feel local material properties with their fingers (compliance, friction, shape) and to simultaneously employ two hands to perform large workspace explorations and dominant/non-dominant hand activities, provides a platform for exploring an entirely new class VE applications and research challenges. Successful progress will require further design refinement, development of new rendering techniques, perceptual and skill studies, and ultimately validation in applications.

4. Haptic rendering issues

Current state of the art for single–point contact haptic rendering algorithms [17, 26] is limited to the case of point contact with friction. In the following we propose a proxy–like algorithm that supports soft finger contact. A custom version of the algorithm for the case of two soft fingers is also proposed.

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[8] This is due to the high sensitivity of the sensors in the joints. It has been demonstrated in the past [8] that posture and change of posture of a joint could be perceived with a precision less than one degree

[9] Studies that have focused on forces involved while performing multi-digit couplings [2] have shown that the mean maximum force, in the case of palmar pinch, is 62 **N** in the case of men and 45**N** in the case of women. However, typical everyday activities, such as precision manipulation of tools, don't usually involve such high force levels. For instance several studies (see for instance [12]) have revealed that the forces involved in pick and place tasks are normally the minimal necessary in order for the object not to slip.

[10] In [15] Myron Krueger points out that "The obvious fact that people have found two hands useful, even essential, in daily life has been ignored by the user-interface community, including those working with reality goggles. . . There is almost no scientific literature on how we use two hands".

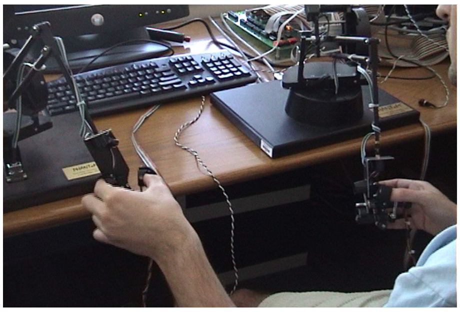

Figure 6. The overall dual-handed system.

A soft finger contact is one that can resist torques about the contact normal. Various models have been proposed in the past for different robotic soft fingers. In the following we will refer to the following equation relating torsional torque to contact force

$$\tau = \mu_m \, {F_n}^{4/3} \tag{1}$$

as proposed by L. Brock in [4].

In order to simulate a soft finger contact a 4 DOF proxy can be used. Three of such degrees of freedom describe the position that the point of contact would ideally have when touching a virtual object (as for the standard proxy algorithm). The fourth variable describes the relative angular motion between the two soft finger avatars and a virtual object. It is important to note that the two parts of the algorithm are disconnected, i.e. they do not influence each other in any way. Thus in the following we will solely consider the evolution of angular variable α and its proxy value α_p.

When a soft finger avatar comes into contact with a virtual object α_p is set to the current value of the angle describing the rotation of the soft finger avatar α_0. The following steps are then performed until contact is not broken[11]. At a generic k-th time sample:

- The new angular position of the users fingers is calculated as $\alpha_g = \alpha_s - \alpha_0$, where α_s is measured by the haptic device. α_g is the new goal value for α.
- α_p new value is computed as

  $$\alpha_p(K) = \alpha_p(K-1) + \beta(K) \tag{2}$$

  where

  $$\beta(K) = 0 \quad \text{if} \quad |F_n(K)|^{4/3} \mu_{TS} > |\tau(K)| \tag{3}$$

  and

  $$\beta(K) = \alpha_g(K) - \alpha_p(K-1) - \frac{|F_n(K)|^{4/3} \mu_{TD}}{k_\tau} \quad \text{otherwise} \tag{4}$$

  where F_n is the force along the contact normal, μ_{TS} and μ_{TD} are the coefficients of static and dynamic torsional friction between virtual object and user, $\tau(K) = k_\tau(\alpha_p(K-1) - \alpha_g(K))$ represents the torque applied to the object due to torsional friction and k_τ is the haptic servo-loop gain.
- A new torque $\tau(K) = k_\tau(\alpha_p(K) - \alpha_g(K))$ is computed using the new value of α_p. Torque $\tau(K)\vec{v}_n$ is applied to the virtual object (where $\vec{v}_n$ represents a unit vector with direction along the contact normal). A torque $\tau(K)$ is also applied to the user (if the device used is capable of actuating such wrench).
- New velocity $(\vec{v}, \vec{\omega})$ and position $(\vec{x}, \vec{\theta})$ is computed for the virtual object. Angle α_c representing how much the object has rotated about axis $\vec{v}_n$ is computed as

  $$\alpha_c = |\vec{\omega} \cdot \vec{v}_n| \, \Delta_T \tag{5}$$

  where Δ_T is the servo-loop sampling time.
- The current value of α_p is corrected to

  $$\alpha_p = \alpha_p + \alpha_c \tag{6}$$

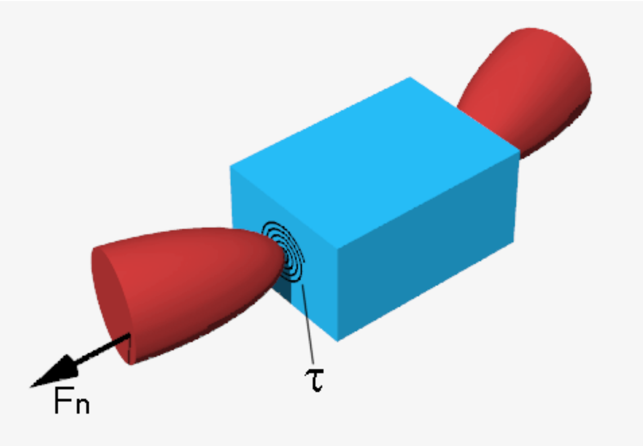

Figure 7. Two soft fingers touching an object: τ is the torque due to torsional friction, F_n is the line connecting the two soft finger contact points.

In the case of two soft fingers (see Fig. 7) we can suppose that torsional friction can only be applied along the line connecting them, and as a consequence in the above algorithm $\vec{v}_n$ is substituted with $\vec{v}_{axis}$.

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[11] the case of the avatar moving over a sharp edge is currently being investigated

5. Conclusions

This paper presents a preliminary view of devices we have developed that enable multi-finger, multi-hand exploration and manipulation of virtual objects. To model physical interactions that occur with this new class of device, and to permit rendering the resulting force interactions, a new soft finger proxy method was developed. Our future work will focus on investigation of the effect of the design offs we have presented on the complexity, fidelity, and utility of this type of interface. Ultimately, we must measure success of our choices by assessment of the interface's ability to enable skilled perception and task performance in computer mediated environments.

6. Acknowledgments

The authors wish to gratefully acknowledge the support that has made this work possible including, in part, contributions from Intuitive Surgical Inc, the Scuola Superiore S.Anna (Pisa, Italy), NIH/NLM Grant LM07295-01, the NCIIA, and the Departments of Computer Science and Surgery at Stanford University (Stanford, CA).

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