Full paper

Design and validation of a complete haptic system for manipulative tasks

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Received 12 April 2005; accepted 5 September 2005

Abstract—The present work deals with the design, implementation and assessment of a new haptic system specifically conceived for manipulative tasks in virtual environments. Such a system was designed by taking into account specific issues related to fine manipulation, such as multipoint haptics, coherence, transparency and physical representation. The haptic system described herein is integrated with a virtual environment engine for the simulation of multifinger manipulation. A preliminary evaluation of the system was conducted by comparing human performance in the manipulation of virtual objects with respect to real objects, according to the data available in the literature. The experiments confirm how the most relevant relationships among physiological and physical parameters involved in manipulation are also preserved during virtual manipulation. However, an in-depth analysis of the results shows that simulation parameters affect the level of force control during virtual manipulation and the quality of the perceived force feedback.

Keywords: Haptic interface; virtual grasping; multipoint interaction; friction; human perception.

1. INTRODUCTION

Grasping is one of the basic haptic modes [1], and has key importance in most types of interactions between humans and the world surrounding them. Grasping an object allows us to identify some of its properties (geometry, material, surface textures) [2], change its physical state (position in space, internal structure) and use it for mediated interaction with other objects. The haptic mode is highly dependent on the application [1, 3]. The possibility of interacting with more than one point of contact seems to be fundamental for the manipulation of objects in virtual environments, e.g., tasks such as determining temperature or hardness require only one point of contact, while determining shape and size of an object are usually conducted more efficiently with more than one point of contact.

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Humans unconsciously use suboptimal [4] algorithms for the prehension of objects when performing tasks with their hands. For instance, during a peg-in-hole task, they precisely adjust the relative position and interaction force between the peg and hole. Johansson and Westling conducted a series of experiments relating tactile information to grip force when performing a lifting task [5]. The ability to adjust grip force appears to be independent of the surface friction characteristics, but further studies from the same authors confirmed that this is not true for the case of objects with different curvature and propose an active role of rotational friction for stabilization of the grip [6]. The nature of contact during slip provides important tactile cues regarding features on the surface as well as the nature of movement of the object, and can explain how humans take advantage of slip sensitivity when perceiving objects.

Even if almost all existing haptic interfaces provide a user interaction based on a single contact point, an increased number of contact points not only allows us to display a more natural haptic interaction [7, 8], but also improves the quality of interaction that users can perform in the environment. Multipoint haptics [9, 10] refer to those devices that can simultaneously interact with the user through more than one contact point. These systems allow the representation of force and torque feedback during the simulation of dexterous manipulation and complex maneuvering of virtual objects, and can improve the interaction in several applications, e.g., assembly and disassembly in virtual prototyping [11, 12], medical palpation during simulated physical examination of patients [13] and many other ones. The existing state-of-the-art devices have several limitations for the simulation of grasping with more than one contact point, both in terms of workspace and mechanical interference among fingers. Furthermore, the limited amount of available devices for multifinger manipulation has also slowed down the development of haptic rendering modules for multiple contact points.

Non-direct contact haptic devices [14], such as encountered haptics, that externally track the position of the human fingers, represent a promising technology for the implementation of haptic devices with multiple contact points. Some preliminary prototypes [15] have already been developed; however, the level of technology is still far from reaching suitable quality for a satisfactory multipoint interaction.

From a psychophysical point of view, interactions with virtual objects during multipoint manipulation poses several interesting research questions at the level of sensorimotor coordination of movement in humans. This issue is of great interest in the context of virtual environments, where the simulation can be used also for assessing the performance of humans in the execution of a given task [16].

There is also an increasing request from applications of a better integration of physical stimuli during manipulation in virtual environments. In the CREATE [17] project, children can learn the elements and geometry of a Greek temple by reassembling it from its ruins. In the advanced visualization system the haptic rendering generates the physical perception of the contact and the ability of manipulating objects in a natural fashion, increasing the user’s attention and control.
during the execution of the task and the realism of the interaction. A snapshot of the application is shown on the left-hand side of Fig. 1, while the right-hand side shows the equivalent virtual manipulation analyzed in the present work.

The purpose of the present paper is to assess the capabilities of haptic systems for grasping and manipulation of virtual objects. A new haptic device for manipulative tasks with two contact points is described, designed to overcome most of the existing technological constraints, such as achievement of the colocation of several contact points, increase of force and common workspace capabilities.

The present work also investigates the relationship between the psycho-physical perception of prehension and the features of the physical model used for the force control of the device. Such a model is based on several parameters that represent several physical behaviors such as gravity, friction and dynamics. An assessment phase, designed according to experiments already conducted in real environments, highlighted a good match between the manipulation in virtual environments and reality, providing further indications for the design and the setup of physical manipulative virtual models.

The rest of the paper is organized as follows. Section 2 describes the haptic device used for the analysis, where the most relevant factors influencing the quality of force feedback in manipulation are presented and discussed, and both analytical and experimental measures of performance of the device are provided. Section 3 describes the software architecture and rendering algorithms used to provide a realistic force feedback to the user, with a detailed description of grasping and friction models. Section 4 introduces the assessment phase, reporting how the evaluation was set up and the achieved relevant results. A discussion on the results is finally given in the conclusions. The symbols used in this paper are listed in Table 1.

2. THE TWO-CONTACT POINTS HAPTIC DEVICE

Manipulation by means of standard commercial haptic devices [18], commonly permanently connected to the finger through a thimble, presents some drawbacks
Table 1.  
Symbols used

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Numerical value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q_{m1}$, $q_{m2}$, $q_{m3}$</td>
<td>motor angles</td>
<td></td>
</tr>
<tr>
<td>$x$, $y$, $z$</td>
<td>position of thimble with respect to arm shoulder</td>
<td></td>
</tr>
<tr>
<td>$q_1$</td>
<td>$\pm 25^\circ$</td>
<td>barrel tilt angle</td>
</tr>
<tr>
<td>$q_2$</td>
<td>$\pm 45^\circ$</td>
<td>barrel yaw angle</td>
</tr>
<tr>
<td>$q_3$</td>
<td>0-630 mm</td>
<td>barrel run</td>
</tr>
<tr>
<td>$r_{pm}$</td>
<td>11.25 mm</td>
<td>radius of motor 1 and 2 pulleys</td>
</tr>
<tr>
<td>$r_{c1}$</td>
<td>140.6 mm</td>
<td>radius of tilting capstan</td>
</tr>
<tr>
<td>$r_{c2}$</td>
<td>95.00 mm</td>
<td>radius of yawing capstan</td>
</tr>
<tr>
<td>$r_2$</td>
<td>95.00 mm</td>
<td>radius of differential disk</td>
</tr>
<tr>
<td>$r_b$</td>
<td>10.54 mm</td>
<td>radius of barrel motor pulley (motor 3)</td>
</tr>
<tr>
<td>$L_0$</td>
<td>441 mm</td>
<td>minimal run of the barrel</td>
</tr>
<tr>
<td>$L = L_0 + q_3$</td>
<td>—</td>
<td>distance between the thimble and the arm should center</td>
</tr>
<tr>
<td>$L = \sqrt{x^2 + y^2 + z^2}$</td>
<td>—</td>
<td>distance between the thimble and the arm should center</td>
</tr>
<tr>
<td>$c_{lin}$</td>
<td>—</td>
<td>linear compliance of the arm shoulder transmission</td>
</tr>
<tr>
<td>$c_{tex}$</td>
<td>—</td>
<td>compliance of the barrel beam</td>
</tr>
<tr>
<td>$a_x$</td>
<td>—</td>
<td>compliance coefficients</td>
</tr>
</tbody>
</table>

for the implementation of effective multipoint systems, such as lack of colocation of thimbles due to the mechanical interference during manipulative procedures, restriction of the common workspace and calibration of the relative position of devices when several ones are used for each contact point.

The haptic interface herein presented was designed to specifically enhance manipulation capabilities. The following specifications were addressed in the design:

- **Contact points**: to allow haptic interaction with two or more contact points.
- **Workplace**: to fit within a standard office desktop with minimum encumbrance.
- **Workspace**: to cover a large workspace for two hands/fingers cooperative manipulation. The optimization of device encumbrance often reduces the amount of workspace available at the end effector. Even if specific virtual panning and zooming exploration procedures can be set up to explore large environments [19], these constraints highly reduce the manipulation capabilities of the device.
- **Force range**: to display forces typical of manipulation by hands in unstructured environments.
- **Isotropy**: to achieve a isotropic behavior both under kinematic and dynamic conditions. Isotropy display of forces and inertias is more important for multipoint displays, since differences of transparency between different fingers are easily perceived.
- **Other performances**: to minimize residual friction, reflected inertia and increase mechanical force bandwidth; all these factors influence the transparency of the device.
2.1. System design

The system is composed of two identical robotic arms with equivalent RRPRRR kinematics, shown in Fig. 2, that provide the force-feedback for the two fingers. The user can operate the device by inserting his fingers in two thimbles placed on the end-effectors of both the arms, so that both single-hand (thumb and index) and two-hand (right and left indexes of two hands) interactions are possible. A set of rubber thimbles of different sizes allow any finger size to properly fit in the device.

Each arm has 6 d.o.f., of which the first 3 d.o.f., required to track the position of the fingertip in the space, are actuated, while the last 3 d.o.f., required to track its orientation, are passive. The first 3 d.o.f. are kinematically equivalent to the combination of two orthogonal and incident rotational pairs and one prismatic pair, that drives a barrel along a third incident axis. The combination of these 3 d.o.f. allows us to position the end-effector over a large workspace. The last three rotational pairs form a spherical wrist that allows the rotation of a sizable thimble around a common center. Figure 3 shows the kinematics and the geometric notation adopted for the description of the device.

![Figure 2. Schematic model of the device.](image1)

![Figure 3. Kinematics of the first 3 d.o.f. and kinematic notation.](image2)
The first 2 d.o.f. are actuated by means of a differential transmission composed of two capstans acting on a common driven pulley. The concurrent motion of these capstans produces a barrel rotation (link 3) along the horizontal axis \( z_0 \). The differential (opposite) motion of the capstans produces a barrel rotation along the vertical axis \( y_0 \).

This kind of transmission makes the operation of device symmetric with respect to two possible motions of the barrel (tilting and yawing), achieving high kinematic isotropy along these directions.

2.2. Kinematic analysis

The device kinematics relates the motion of the thimbles to that of the motors. Three angular variables (joint angles) were considered: the barrel tilt angle, the barrel yaw angle and barrel displacement along his main axis, adopting the following nomenclature (as shown in Fig. 3): \( q_1 \) indicates the tilting angle, \( q_2 \) the yaw angle and \( q_3 \) the displacement along the barrel axis.

To evaluate the kinematics, a procedure articulated in two steps was followed: in the first step the motor angles were related to the joint variables and in the second step the resulting thimble motion was computed.

According to the Denavit Hattenberg convention, the relationships among joint and motor angles, due to the differential transmission, are given by the matrix \( K \):

\[
\begin{pmatrix}
q_{m1} \\
q_{m2} \\
q_{m3}
\end{pmatrix}
= \begin{bmatrix}
-\tau_1 & -\tau_1 \tau_2 & 0 \\
\tau_1 & -\tau_1 \tau_2 & 0 \\
0 & 0 & -\tau_3
\end{bmatrix}
\begin{pmatrix}
q_1 \\
q_2 \\
q_3
\end{pmatrix},
\]  

where \( \tau_1 = r_{c1}/r_{pm} \), \( \tau_2 = r_2/r_{c2} = 1 \) and \( \tau_3 = 1/r_b \) represent the reduction ratios, and \( r_b \) is the radius of the motor pulley that actuates the barrel axis.

Once the joint angles are known, the position of the end-effector can be easily computed by the direct kinematic solution:

\[
\begin{align*}
x &= L \cos(q_1) \cos(q_2) \\
y &= L \sin(q_1) \cos(q_2) \\
z &= -L \sin(q_2),
\end{align*}
\]  

(2)

where \( L = L_0 + q_3 \).

The adoption of this particular kinematics with a prismatic joint combined with differential transmission allows us to combine a high kinematic isotropy performance together with a well-shaped workspace. The kinematic Jacobian \( J \) can be easily found as:

\[
\begin{pmatrix}
\dot{x} \\
\dot{y} \\
\dot{z}
\end{pmatrix}
= \begin{bmatrix}
-L \sin q_1 \cos q_2 & -L \cos q_1 \cos q_2 & \cos q_1 \cos q_2 \\
L \cos q_1 \cos q_2 & -L \sin q_1 \sin q_2 & \sin q_1 \cos q_2 \\
0 & -L \cos q_2 & -\sin q_2
\end{bmatrix}
\begin{pmatrix}
\dot{q}_1 \\
\dot{q}_2 \\
\dot{q}_3
\end{pmatrix}.
\]  

(3)

In order to evaluate the performance of the device and to find the optimal values for the design parameters (the radii of pulleys and capstans), the condition number
of $J K^{-1}$ was used as a reference. Since the critical point of the device is reached when the arm is completely extended, we imposed that this point should match with the best value of the conditioning number (i.e., 1). Hence, we used this analysis to verify the properties all over the workspace. Figure 4 shows the variations of the condition number in the $xy$ and $xz$ planes of the device.

According to this design the maximum continuous force in the worst case condition is 4 N, while the maximum peak force in the same position is 10 N. These forces can be applied in any direction. The typical maximum continuous force value (in the center of the workspace) is 7 N in all directions.

2.3. Workspace

The dimensioning procedure is also considered to guarantee a minimal workspace including a box of $300 \times 400 \times 600$ mm. The reachable workspace is given by the intersection of the two manipulator workspaces, as shown in Fig. 5. The geometry of the optimized workspace allows us to integrate the two devices placed one in front
Figure 5. Workspace of the two arms.

of each other. This arrangement does not considerably affect the common reachable workspace, therefore allowing the user to manipulate objects over a large space.

The mechanical interference of the structures is a further limitation occurring during the integration of several devices into the same workspace. In fact, manipulation of virtual objects requires the user to freely move and rotate his/her own hand(s). In this system the degree of interference between the two structures is reduced and does not occur during common manipulative procedures either with one or two hands.

As far as the reflected mass/inertia is concerned, the use of a differential transmission systems has allowed us to make the properties of the mass matrix more regular, consequently reducing the effect of Coriolis and inertia disturbances during fast motions. Specific design solutions for the actuation and the transmission are arranged to fix the transmission cables to the links, reducing the pretensioning of cables and relative friction. No reduction gear was employed in the design, therefore achieving an almost zero backlash system. The actuation was made by low-inertia brushed DC servomotors, with iron-less construction of the rotor. The kinematic solution allowed us to ground the first two motors with larger bulk, thus reducing the amount of moving mass. The third motor, that provides the translational motion of the barrel, also acts as a counterbalance of the barrel weight in the worst kinematic position, i.e., when the barrel is completely extended.

2.4. Static and dynamic performance

The whole structure was made completely of aluminum with some parts of carbon fiber. All links were designed to maximize mechanical stiffness. In order to reduce
the moving mass of the barrel while preserving torsional stiffness, four additional rods were added along each barrel.

Particular attention was given to the mechanical stiffness of the barrel along the $y$ and $z$ directions. Such stiffness depends on the extension of the barrel and may become critical when it is completely extended. In order to evaluate the compliance along these directions, we evaluated the two main contributions:

- A linear contribution $c_{\text{lin}}$ due to the transmission system, concentrated at the level of rotational joints 1 and 2. This compliance is constant at the level of joints, while the equivalent compliance at the end-effector is proportional to the square of the barrel displacement ($L$).

- A flexional contribution $c_{\text{flex}}$ due to the mechanical rigidity of the barrel axis which bends under the action of a tangential force (in the $yz$ planes) applied at its end-effector. The barrel was considered equivalent to a cantilevered rod and, therefore, its compliance may be expressed as a cubic relationship between the applied force and the barrel displacement ($L$).

According to the above consideration, the final compliance at the level of the end-effector can be expressed as

$$c_y = c_{\text{lin}} + c_{\text{flex}} = a_1 L^2 + a_2 L^3. \quad (4)$$

This compliance was experimentally determined by fixing the end-effector of the device to a rigid support and applying command torques to the motors corresponding to increased forces in the direction $F_y$. The displacement error was measured using the information provided by the encoders for different values of the barrel displacement. The interpolating cubic curve was found as the best least-squares fit with experimental data and is shown in Fig. 6. The experimental measured stiffness was in the range from 1.5 to 13.5 N/mm.

![Figure 6. Experimental mechanical compliance along y for different values of barrel displacement.](image-url)
The performance of the device along the barrel axis, since it is almost aligned with the grip direction, can greatly affect the grip control during simulation. The stiffness of the device along the barrel axis was experimentally assessed, by connecting the end-effector to an ATI nano17 force sensor and grounding the sensor to a rigid support. The experimental stiffness estimation was found as the least-squares linear correlation between measured forces and displacements along the barrel axis. A value of $K_x = 23.74 \text{ N/mm (} R_{sq} = 0.994) \text{ was found.}$

Also, the dynamic performance of the device was experimentally assessed by measuring the force response of the device along the barrel direction ($x$-axis) under the same conditions as above. The input torque to the motor was a chirp input command. The force response is shown in Fig. 7 and confirms that the device can reach a large dynamic bandwidth along the $x$ direction (between 70 and 80 Hz).

2.5. Multipoint accuracy

The relative accuracy of the thimbles’ position is of fundamental importance for manipulation. As a matter of fact, these errors may generate a distortion in the perception while grasping and moving an object within the virtual environment. These distortions are reflected both in changes of grasping forces as well as changes in the perception of object size.

The accuracy in determining the thimbles’ positions is both determined by the force applied onto thimbles and the device stiffness, as well as by manufacturing or measurement errors and other factors:

- The kinematic errors related to limited encoder resolution.
- The mechanical accuracy of the manufacturing and tolerance of components.
- The relative errors among manipulators due to the position of the bases’ frames.
Encoder errors were minimized by using high-resolution encoders (1/4000 of revolution) that, in the worst case, correspond to an error of 130 µm (barrel completely extended).

The other errors were compensated for numerically by adopting a specific calibration procedure. In this procedure both arms are tied by their thimbles (as shown in Fig. 8) and automatically move according to a specific trajectory. During this phase, encoder data are collected and statistically employed in order to determine a set of parameters that identify the reciprocal position of the arms.

3. THE HAPTIC RENDERING ARCHITECTURE

The VE engine implements a specific architecture for computing the force feedback during the exploration and manipulation of the objects in the virtual environment. This process should provide a stable force feedback according to the forces arising during explorative and manipulative tasks, such as inertia, weight, contact and friction forces.

3.1. General architecture

The complexity of the interaction in manipulative environments requires a multi-threaded/multirate architecture. Figure 9 describes how components are connected and grouped in different computing threads. Information on two fundamental states is exchanged by the modules:

- The Device State, representing all the information coming from the device, e.g. the position of the contact points.
The Object State, characterized by the position and orientation of each object in the virtual space and their properties.

The stability of the haptic response requires that the rendering process (Haptic Thread) should be updated at high a frequency (1 kHz typically). The Haptic Renderer receives the Device State as input from the Device Controller and computes the corresponding contact forces as output. The haptic rendering is performed on the basis of the collision information of the haptic contact point with the objects, computed by the Collision Thread, running at a much lower rate. The Collision Detection computes the set of primitives that are in a volume around the contact point, which is then used by the Haptic Renderer to compute the force feedback. Collision Detection is actually implemented using an external module based on bounding volume hierarchy and running at about 100 Hz.

The simulation of the dynamics of the objects is achieved through a Dynamic Simulator, that is carried out through a separate thread running at about 200 Hz, because its computation is potentially intensive, depending on the complexity of the environment and the kinematic constraints between the objects.

In the complete architecture, two geometrical representations are associated to each object: the first one is the haptic geometry used for the collision detection with the haptic contact points and the second one is the physics geometry that can be simpler. This approach allows us to achieve a precise haptic interaction, while maintaining a smooth dynamic simulation.

The contact force exerted by the user is applied to the touched object through the Dynamic Simulator, allowing the direct manipulation of the object. It is worthwhile analyzing some stability considerations regarding the manipulation of virtual objects. Whenever an object is grasped in a virtual environment by the user’s fingers, it is virtually tied to the contact points through a couple of springs representing the virtual stiffness of the environment. In this case, the stability limits of manipulation are determined by the typical resonance frequency of this kind of
contact, that can be computed as:

\[ \frac{1}{2\pi} \sqrt{\frac{2K_s}{M_v}}. \]

where \( K_s \) is the object stiffness in the virtual environment and \( M_v \) represents the virtual object mass. For the cases considered in the present work, masses ranging from 0.1 to 0.5 kg and stiffness ranging from 500 to 2000 N/m, the typical resonance frequencies varies between 5 and 45 Hz, well below the frequency of the dynamic simulation.

### 3.2. The linear friction model

The force information for controlling the objects is determined through the position of the contact points. The position of each contact point is measured directly by the haptic interface \((x_h)\) and the relative feedback force \((F)\) is computed through a constraint-based proxy method with friction, based on Refs [20–22]. The haptic rendering algorithm computes the position of an additional point \(x_p\), called the proxy, lying on the object geometry, and on the basis of the current \(x_h\) position of the haptic interface and contact geometry \((C)\) the force is generated through a direct rendering method \(F = G(x_h, x_p, C)\), using the coupling between the proxy \(x_p\) and the interface position \(x_h\). The proxy algorithm should take into account the movement of the object and, in particular, it is necessary to update the last proxy position with the movement of the object—this is easily achieved by representing the proxy in object coordinates.

The standard proxy algorithm is modified with the linear friction algorithm using the friction cone model [21]—the movement of the proxy towards the goal position is prevented by the friction and perceived by the user as a tangential force. The algorithm works by building a friction cone with the top at the haptic contact point, the base centered at the god point and an aperture depending on the friction coefficient. If the last proxy position is inside the cone the proxy is not moved and the user perceives a tangential force opposite to the moving direction, otherwise the proxy is placed at the boundary of the cone. The evaluation of the position of the proxy with respect to the friction cone is equivalent to decomposing the contact force in the normal and tangential components, and evaluating if the tangential is greater than the normal force multiplied by the static friction coefficient. The advantages of this algorithm with respect to others are that this algorithm is only position based and it does not require a velocity estimation for the evaluation of the friction force.

The static friction is extended with the dynamic friction by using a proxy algorithm with two states—slip and not slip. During the not slip state the proxy is not moved if inside the static friction cone, otherwise the state is changed to slip and the proxy moved to the border of the dynamic friction cone; when in slip mode the state is changed to not slip if the proxy is inside the dynamic cone, otherwise the
Figure 10. The linear friction cones.

The algorithm can be implemented numerically through the following steps, performed while the finger is in contact with the object and the contact is not broken. At a generic \(k\)th time sample:

(i) Computation of goal position. The new goal position is computed as \(x_g = x_s\), where \(x_s\) is the surface point which minimizes the distance between the HI point \(x_h\) and the contact surface. \(x_g\) is assumed as the new goal value for \(x_p\). We assume the following definitions:

\[
\begin{align*}
  r &= \|x_g(k) - x_p(k-1)\| \\
  d &= \|x_g(k) - x_h(k)\|.
\end{align*}
\]  

(ii) Analysis of the friction condition. In static conditions the new position of the proxy can be expressed as:

\[
x_p(k) = x_p(k-1) \quad \text{if} \quad \frac{|F_t(k)|}{\mu_s |P(k)|} = \frac{r}{\mu_s d} < 1,
\]

where \(|P| = k_l d\) is the force directed along the contact normal and \(k_l\) is the haptic servo-loop gain, equivalent to the linear stiffness, used for calculating the elastic penetration force. Otherwise, conditions of dynamic friction should be applied and the god-object, sliding over the surface, is moved on the boundary of the dynamic friction cone:

\[
x_p(k) = x_g(k) + r',
\]

with

\[
r' = \frac{x_p(k-1) - x_p(k)}{r} \frac{r}{\mu_s d(d(k)).}
\]

(iii) Computation of friction force. A new force \(F(k) = k_l(x_p(k) - x_g(k))\) is computed using the new value of \(x_p\). Force \(-F(k)\) is applied to the virtual object, while force \(F(k)\) is also applied to the user.
(iv) Computation of the new position of the object. The new velocity $(v, \omega)$ and position $(x, \theta)$ are computed for the virtual object.

(v) Update of the proxy position. The current value of $x_p$ is corrected to take into account the displacement of the virtual object:

$$x_p = x_p + x_c. \quad (9)$$

The algorithm is repeated from step (i).

3.3. The grasping model

The above architecture is easily extendable to multiple contact points: the Device Controller invokes the haptic rendering for each contact point and the Collision Detection component performs a collision test for each contact point. From the point of view of the dynamic simulation, the two contact points are invisible and they affect the simulation by applying forces on the grasped object.

The grasping of objects in this system is based on the friction and on the dynamic simulation of the objects. The grasping force exerted by the user over the object produces a friction tangential force for each of the contact points that allows us to raise and manipulate the object. This model is well integrated in the dynamic simulator because when the object comes in contact with other objects the user receives a force feedback as a change of depth caused by the movement of the object. Figure 11 shows a simple example of object grasping in this system, with the display of the two contact points and the contact forces shown as the yellow vectors.

In the design phase of the grasping there are some parameters that are correlated and should be correctly evaluated for allowing a precise grasp of the object: the static friction coefficient, the mass of the object and the stiffness of the object. The effect of these different parameters is analyzed on a group of subjects in the evaluation part of this paper.

Figure 11. Example of object grasping.
Figure 12 shows the behavior of the system during the grasping of an object, with a diagram for each contact point. Three phases can be identified: the first is the lifting phase when the user starts to grasp the object, the second is the holding phase and, finally, there is the releasing phase when the object starts to slide. In the diagrams the green and red lines represent the position of the contact point and the object along the $y$-axis (aligned along the gravity vector). During the lifting and holding phases the two positions have a constant difference that depends on the grasping point on the object, then in the releasing phase they diverge because the object is falling. The black line shows the status of the friction that is zero when there is no contact, one during the non-slip state and two in the slip state: it is clear that during the lifting and holding phases the proxy is in non-slip state because it is firm between the fingers and, when the object is released, it initially changes to slip mode and then the contact is lost. Finally, the blue line represents the grasping force that has an increasing and varying behavior during the lifting phase, but is almost constant during the holding phase.

![Grasp and slide with the first contact point](image1)

![Grasp and slide with the second contact point](image2)

**Figure 12.** Forces and position during holding and release of a virtual object.
4. EVALUATION OF GRASPING LOAD AND SLIP FORCE IN PICK-AND-PLACE OPERATIONS

In order to assess the efficiency of the device and the rendering for pick-and-place operations, a specific evaluation was performed to compare the available data on human grasping of real objects [4, 23] with the virtual case. The influence of weight on static grip has been experimentally studied in Ref. [4], where safety margins for grasping for prevention of slipping are analyzed. The safety margin is defined as the difference between the grip force and the slip force, i.e., the minimum grip force required for preventing slipping.

4.1. Subjects and general procedures

Three healthy right-handed men, aged between 27 and 35 years, served as subjects for the study. The subjects sat on a height-adjustable chair. In this position the subject might hold the two thimbles connected to the haptic interfaces with his right hand, respectively wearing them on the thumb and right index of his hand. A wide visualization screen was placed in front of the screen and a desktop, where the subject was invited to place his elbow during the experiment. A sequence of 27 objects was presented twice to each subject, for a total of 54 runs performed by each subject. All the objects in the randomized sequence were cubes with the same geometry, with pseudorandom changes in the weight $m$ (0.1, 0.2, 0.4 kg), in the friction coefficient, both static $\mu_s$ (0.4, 0.8, 1.2) and dynamic $\mu_d$ (0.3, 0.6, 1.1), and in the stiffness $k$ (0.5, 1, 2 N/mm). All the possible combinations of weight, friction and stiffness, without repetition, were presented to the subject in each randomized sequence. The values of $\mu_d$ were univocally associated to $\mu_s$. The experiments were conducted with only one grasping condition, with the object held between index and thumb tip of the same hand. Values for friction coefficients were assumed from Ref. [24] where experimental values of linear friction are reported between the index tip and different materials, equal to 0.42, 0.61 and 1.67 for rayon, suede and sandpaper, respectively.

4.2. Methods

The experiment consisted of a series of test runs. At the start of the experiment, one object with the shape of a cube was visualized at the center of the scene.

Each subject was asked to grasp the object by the index and thumb fingers, and to get acquainted with the weight of the object, by lifting it up and letting it falling down by continuously decreasing the gripping force.

After the necessary time to get acquainted with the object, the subject was asked to hold the object stationery in the air for 10 s with the minimum grasp force that he considered necessary, with the elbow leaning on the plane. When the subject was holding the object in the fixed position, both grasp $F_n$ and friction $F_t$ forces (normal and tangential to the object surface, respectively), and positions of finger
tips, object and proxies were recorded for each contact point. Statistical analysis was performed using SPSS 13.0.

4.3. Results

A significant correlation was found between the values of the gripping force $F_n$ and stiffness, weight and friction values, as shown in Table 2. The value of grip force $F_n$ was found to be significantly positively correlated with mass and stiffness, while being negatively correlated with friction value. Table 2 reports the correlation coefficients obtained with a Spearman non-parametric test and significance level $P < 0.001$.

Figure 13 presents several bar plots comparing the grasping force $F_g$ under different conditions according to change in friction (top–bottom) and mass (left–right). Different shades are used for clustered bars representing the effect of stiffness in each test run.

Table 2.
Correlation table

<table>
<thead>
<tr>
<th>Correlation measure</th>
<th>Grip force $F_g$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friction $\mu_s$</td>
<td>$-0.346^a$</td>
</tr>
<tr>
<td>Mass $m$</td>
<td>$0.391^a$</td>
</tr>
<tr>
<td>Stiffness $k$</td>
<td>$0.333^a$</td>
</tr>
</tbody>
</table>

$^a p < 0.001$.

Figure 13. Mean grip force as a function of stiffness, friction and mass values.
Figure 14 shows the change of grip force $F_g$ versus weight, with superimposed error bars with a confidence interval of 95%, for nine different conditions given by different combinations of friction (bottom–top) and stiffness (left–right).

5. CONCLUSIONS

From the analysis of the results it can be seen that greater gripper forces are required for holding heavier weights and stiffer objects, while lower gripper forces are required for higher friction values. This confirms the empirical laws that have been already found in the case of manipulation of real objects with bare fingers. In Ref. [4] it was found that the relative safety margin, defined as the safety margin as percent of the grip force, was about constant during lifting with an increase of weights, was almost constant with change of weight. The calculation of the safety margin in the case of virtual manipulation allows us to make an interesting comparison. As is shown in the logarithmical plot in Fig. 15 in the case of virtual manipulation, the safety margin tends to be reduced with increasing weight of the lifted mass.

This can be explained by the larger dispersion of grip forces observed for lower mass values. In fact, due to the absence of any local sensation of slip, it was more difficult to discriminate the weight of lighter objects. Moreover, lighter objects required a smaller resolution in the control of force ($\Delta F$), that is limited by the position resolution of the device $\Delta X$, according to the law $\Delta F = k\Delta X$, where $k$ is the simulated contact stiffness. This is confirmed by the finding that better safety margins are obtained for lower values of the stiffness, as is evident from the plot of Fig. 16, where grip forces are plotted versus slip forces. While the minimum required grip force is represented by the diagonal line, experimental data can be
clustered in three main groups according to the value of the contact stiffness during the simulation.

The evaluation of the performance during grasping and weight lifting has shown that the simulation produces outcomes that are similar to the experimental findings on real objects. We are currently testing the behavior of the system when the contact friction is also implemented. Future activities will consider including evaluation with respect to angular motions and the comparison of additional feedback stimuli (audio and tactile).
Acknowledgements

The present work was carried out within the framework of the EU Network of Excellence ENACTIVE INTERFACES (www.enactivenetwork.org). The authors are grateful to EU who co-funded the research activities herein reported.

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