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Computing Optimal Forces for Generalised Kinesthetic Feedback on the Human Hand during Virtual Grasping and Manipulation

Costas TZAFESTAS and Philippe COIFFET
Laboratoire de Robotique de Paris
CNRS-UPMC-UVSQ
10-12 Avenue de l'Europe, 78140 Vélizy, France.
E-mail: tzaf@robot.uvsq.fr

Abstract

This paper focuses on the problem of force-feedback for the human-operator hand when manipulating virtual objects. We propose a method for the computation of feedback-forces that have to be applied on each individual phalanx and finger of the human hand in order to display pertinent, kinesthetic information about static or dynamic characteristics of objects present in the virtual scene. External forces and moments of the manipulated virtual objects have to be mapped on the contact-forces space of the virtual grasp. The method is based on the solution of a nonlinear programming problem, formulated by performing a static analysis of a general, multiple contact points virtual grasp. A methodology for modelling interactions within a virtual environment, and performing realistic grasping and manipulation, is also presented.

1 Introduction

In the context of robotic manipulation and interaction within unstructured/unknown environments, the presence of a human operator in the robot control loop is undoubtedly beneficial and may even prove indispensable. This constitutes the domain of teleoperated or human-supervision control systems [16], [13]. Recent developments of such applications using Virtual Reality (VR) techniques [4] demonstrate the requirements for advanced, realistic user interfaces to interact with remote or virtual entities. Creating a sensation of 'presence' in a Virtual Environment (VE) demands the establishment of a human-computer communication using all the available sensory channels of the human operator, i.e. vision, audition, haptic sense etc.

This paper focuses on the problem of force-feedback for the hand of the human-operator that approaches as much as possible to reality. This means that forces on all fingers (and if possible on all phalanges) of the human hand have to be replicated in order for a sufficient sensation of physical interaction with a VE to be rendered. Force-reflecting, glove-like interfaces constitute one solution usually employed for providing feedback on various areas of the human hand [3], [2]. The problem we are dealing with is to determine what forces have to be applied on each region of the human hand, depending on the type of grasp and manipulation performed in the VE. Usually, simple implementation of Hook's law is used to compute hand-feedback forces, thus limiting the information concerning the state of the haptic interaction that can be rendered to the human operator.

In this paper, we propose a method for computing hand-feedback forces based on the solution of a constraint-minimisation problem which is formulated by performing a static analysis of a 'virtual grasp'. The goal is to *project* (map) the *external forces* (and moments) of the virtual object to be grasped, on the contact-forces space of the hand, that is on each intervening phalanx of the human operator hand. What we are intending to do is to establish a natural, haptic, human/computer interaction by providing the operator hand with sufficient kinesthetic feedback, rendering pertinent and precise information about various static and dynamic characteristics of virtual objects being manipulated, not only of their simulated rigidity but also their weight and inertia characteristics, potential collisions and contact configurations with obstacles present in the virtual scene. The final, long-term goal of this research is to exploite the capacity of the human hand in naturally controlling the execution of fine manipulation tasks. It is the big 'challenge' of modern robotics research, to study ways of transferring the human intelligence and skills onto the machine, which means 'teach' the computer how to use strategies employed by the human hand for the control of dexterous tasks. Perception by the human operator hand of external forces and establishment of an intutive and natural, haptic human/machine interaction can certainly lead towards the desired goal.

The following section presents an overview of the VR system configuration developped in our laboratory for experimental purposes. Section 3 describes the method used to model virtual hand - virtual object interactions. Sections 4 and 5 deal with the computation of optimal, hand-feedback forces in the context of virtual grasping. Finally, concluding remarks and future work considerations are given in section 6.

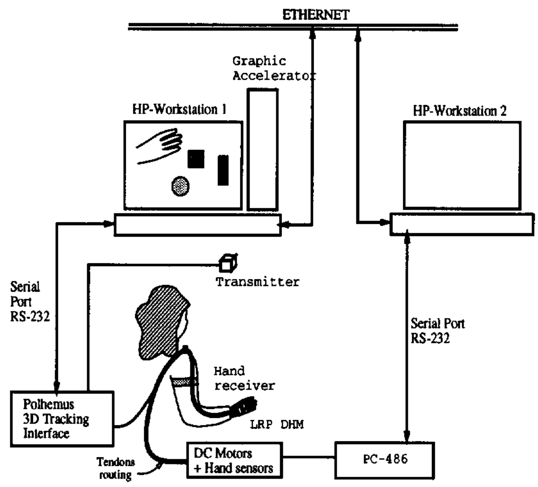

Figure 1: *Experimental System Configuration*

2 VR Experimental System : Hardware Description

Fig.1 shows the configuration of the VR system being developped in our laboratory. It consists of the following components:

(i) Two HP workstations equipped with a graphic accelerator performing :

- graphic rendering and display of the virtual scene
- collision detection and real-time computation of interaction forces and state variables for the dynamic animation of the virtual hand and objects.

These workstations communicate with each other by exchanging data over the Ethernet.

(ii) 3D-tracking device (Polhemus Isotrack™) for the monitoring of the human hand position and orientation. Its precision is measured to be 1mm for a spherical space with a radius of about 1m from the magnetic source.

(iii) A force-reflecting glove, the LRP-Dextrous Hand Master (DHM), which has been developped in our laboratory [2]. The LRP-DHM mechanism consists of an exoskeleton structure and several tendons connected on the top of each finger segment. It can apply forces on each phalanx of the human hand and measure the angle of 14 finger joints. Each joint is actuated through a tendon-sheath transmission by DC, disk motors, placed remotely from the hand. Miniature force sensors are placed on each phalanx in order to measure cable strain and permit the implementation of force/impedance control techniques. Fig.2 shows a photo of the LRP-DHM worn by a human hand.

Figure 2: *The LRP Dexterous Hand Master*

The system described above will be used as a testbed for all future experiments concerning the study of haptic interaction between the human hand and a virtual environment.

3 Modelling interactions in the VE : grasping virtual objects

In a Virtual Reality system, an important issue one must certainly pay attention to is the quality of the displayed 3D image, i.e. its resolution, refresh rate, realism of the graphic model and rendering techniques etc. But what seems to be of ever greater importance, in order to achieve a sense of 'presence' in the virtual scene, is the 'quality' of *interactions* between the human operator and the displayed environment. The human being is rarely satisfied by simply seeing, as a distant observer, a very realistic 3D image, even if it contains spectacular computer animation features. In order to feel 'present' and participate in what he sees, he needs to *act* on objects in a natural way and, most importantly, see the *results* of his actions as he expected them to be. For instance, one could move his own hand to control the motion of a displayed, simulated hand graphic model, in order to 'touch', push or grasp and manipulate objects present in a virtual scene. This however assumes the definition of a *physical model*, besides the graphical one, for each virtual object and for the virtual hand. The graphical model (usually a polyhedral representation) is used for graphics rendering and display purposes. The physical model, on the contrary, consists of:

- defining a solid, geometrical representation and developping algorithms to perform intersection checking (usually refered to as *collision detection*) for arbitrary moving objects.
- computing *interaction forces* and performing dynamic *deformation* for the surface of each virtual object.
- developping algorithms to determine the *behaviour* (state evolution) of each virtual object and the hand under the application of previously computed interaction forces (for instance, for a

virtual object in free phase -no grasp- one could easily use Newton-Euler equations of motion).

As a solution to these problems, we are developping algorithms based on spherical octree representation of objects. Real-time collision detection and dynamic animation of simple polyhedral objects has already been demonstrated [15]. The same methods can be used to construct the physical model of the virtual hand. Each phalanx can be modelled by a tree-structure (not necessarilly an octree) where each node corresponds to a spherical region surrounding a part of the phalanx. On the lower level the phalanx will be represented by a set of spheres completely surrounding it and approximating its geometrical form. We can also take into account the inherent hierarchy of the hand's structure to finally construct a completely hierarchical model for the representation of the whole hand.

Using such a simple hierarchical model for the virtual hand, spherical octrees for the representation of each virtual object and the developped collision detection algorithms (described in [15]) we achieve realistic grasping (including any type of precision or power grasp) of an arbitrary virtual object, in real-time. Fig.3 shows a cube being grasped by the virtual hand. Vectors represent normal directions on each detected contact point between the virtual hand and object models.

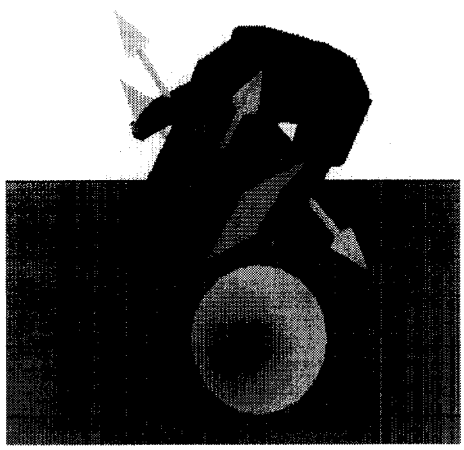

Figure 3: *An example of virtual grasping*

Previous work concerning the control of grasping in a VE uses matrices of control points, distributed on the surface of the virtual hand ([1], [8]). However, the definition of a large density of control points, in order to satisfy precision requirements, may lead to a considerable increase of the computation time needed to perform accurate collision detection between virtual hand and objects models. The main advantage of our method lies on the use of a hierarchical, solid geometry model and a two-stage, recursive, collision detection algorithm, which permits to perform grasping for any type of object present in the virtual scene.

Computation of forces to be fed-back to the human operator hand as well as monitoring of virtual-grasping, stability conditions are issues to be discussed in the following sections.

4 Generalised Force Feedback for the fingers of the human-operator hand - nonlinear programming techniques

The problem we are dealing with is the computation of feedback forces that have to be applied to each finger of the human operator hand. The goal is to provide sufficiently realistic feeling of grasping and manipulating virtual objects and especially adequate haptic cues concerning static or dynamic properties of the objects such as weight, inertia characteristics, contact with virtual obstacles present in the scene, or even the geometric form of the grasped objects etc. For this, external forces and moments, computed by the virtual engine to simulate events (eg. collisions) in the VE, have to be mapped on feedback forces for the fingers of the human hand.

The use of force-feedback gloves till today has been most of the times limited in providing feedback forces concerning the grip of a virtual object with more or less strength. These are 'internal' grasping forces and give only a binary information about grasping or not a virtual object, or at best can provide an idea about its simulated rigidity [3], [9]. However, the use of such techniques, during manipulation of a virtual object, can provide no information about other static or dynamic attributes, like the ones discussed above. Projecting external forces and moments to each individual phalanx of the human operator hand, that is, providing feedback of 'external' grasping forces, can give important supplementary haptic cues and augment the realism of the simulation. The difference between internal and external forces can be found in any book treating the problem of grasping and manipulation (for instance [11]). In two words, one can say that internal grasping forces have zero 'sum', producing no translational or rotational movement to the grasped object, while external grasping forces compensate for externally applied forces and moments (including gravitational and inertial forces).

Feedback of other than simple internal grasping forces during a two(or three)-fingered manipulation, has already been encountered in the work of Howe [7] and Hashimoto [5]. In [7] a 'slight redistribution' of the displayed forces on the thumb and index, during a two-fingered telemanipulation of an object, is used to convey information about object slipping in the slave hand. The device used for fine force display has two fingers, each one consisting of a two-degree-of-freedom, direct-drive mechanism (two pantograph-based links). Hashimoto and Buss are developping a dynamic force simulator system, where external forces applied on the virtual object are projected on the contact space using the pseudo-inverse of the grip matrix. The sensor glove device used has 10 degrees of freedom, 3 d.o.f. for the wrist, 3 for the index finger, 2 for the thumb and 2 for the rest of the fingers, which move as one. A similar haptic device has been also used by Iwata [9]. External forces (for instance the weight of a virtual object) is applied to the palm of the human operator by a 6 d.o.f. parallel manipulator. However, reaction forces to the fingers, displayed through a 3 d.o.f. mechanism, depend only on the solidity of the captured object.

In this paper our goal is to investigate generalised methods for feedback of 'external grasping forces' on the human operator hand during manipulation of virtual objects. The problem can be formulated as follows. Let's consider a virtual object, being grasped by a virtual hand with n_c contact points. For each contact point we use the following notation.

$\vec{f_{ci}}$: the i_{th} contact force vector
$\vec{r_{ci}}$: vector from the object's center to the i_{th} contact point
$\vec{a_{ci}}$: vector normal to the object's surface on the i_{th} contact point

The equilibrium equations for the sum of forces and moments are written as:

$$\sum_{i=1}^{n_c} \vec{f_{ci}} + \vec{F_{ext}} = \vec{0} \qquad (1)$$

$$\sum_{i=1}^{n_c} (\vec{r_{ci}} \times \vec{f_{ci}}) + \vec{N_{ext}} = \vec{0} \qquad (2)$$

where $\vec{F_{ext}}$, $\vec{N_{ext}}$ are vectors computed by the VR simulation as being the total external force and moment being applied to the virtual objetc (including collision forces with virtual obstacles, gravitational and inertia forces due to object acceleration during manipulation).

Equations 1 and 2 can be written in the following, well-known, compact form:

$$G \cdot \vec{f_c} = \vec{w_e} \qquad (3)$$

where

$G = \begin{pmatrix} I_3 & \dots & I_3 \\ R_1 & \dots & R_{nc} \end{pmatrix}$ the $(6 \times 3n_c)$ grasp matrix,

I_3: 3x3 identity matrix,

$$R_i = \begin{pmatrix} 0 & -r_{ciz} & r_{ciy} \\ r_{ciz} & 0 & -r_{cix} \\ -r_{ciy} & r_{cix} & 0 \end{pmatrix}$$

$\vec{f_c} = (f_{1x} f_{1y} f_{1z} \dots f_{ncx} f_{ncy} f_{ncz})^T$:
vector containing the contact forces, and

$\vec{w_e} = \left(-\vec{F_{ext}}, -\vec{N_{ext}}\right)$: external wrench

Equation 3 is usually accompannied by a number of constraints on the solution $\vec{f_{ci}}$, in order to take into account the unilateral nature of the contacts as well as static friction limitations (Coulomb law). These can be written as:

$$\frac{\vec{f_{ci}} \cdot \vec{a_{ci}}}{\left|\vec{f_{ci}}\right|} \geq \frac{1}{\sqrt{1+\mu_i^2}} \qquad i = 1, \dots, n_c \qquad (4)$$

$$\vec{f_{ci}} \cdot \vec{a_{ci}} > 0 \qquad (5)$$

In the general, non-singular case, ($n_c > 2$), the system defined by 3, 4 and 5 presents an infinity of solutions. To solve for the contact forces, an optimality criterion has to be defined. Definition of effective criteria undoubdtetly constitutes the major difficulty of the problem. Particularities related to the special nature of the problem (human-computer interaction in the context of a VR system) have to be taken into account. The effectiveness of each criterion has to be measured with respect to the realism of the feedback and the feeling provided to the human operator (definition of objective quality measures). Issues related to human haptic perception and the distribution of forces usually employed by the human hand, during execution of grasping and manipulation tasks, as measured by biomechanical studies, have to be also considered.

Let's start by defining a simple criterion based on the minimisation of the following quantity:

$$F_1 = (1/2) \sum_{i=1}^{n_c} \left|\vec{f_{ci}}\right|^2 \rightarrow min \qquad (6)$$

F_1 constitutes a measure of the total power (muscular contraction) applied by the human hand. However, this minimisation quantity provides no measure for the stability of the grasping, which is usually related to the internal grasping forces. This can be provided by forces of the form : $(s_i \cdot \vec{a_{ci}})$, which we call 'squeezing forces', because they give a measure of how much the operator hand is squeezing (deforming) the virtual object. The coefficients s_i are proportional to the amount of intersection between virtual hand and object models, at each contact point, and represent the *'intention'* of the human operator to grasp the virtual object with more or less strength. The criterion defined by F_1 can now be rewritten as:

$$F_2 = (1/2) \sum_{i=1}^{n_c} \left|\vec{f_{ci}} - s_i \cdot \vec{a_{ci}}\right|^2 \rightarrow min \qquad (7)$$

The solution of this new constraint minimisation problem consists of finding the contact forces $\vec{f_{ci}}$ which approach as much as possible the 'squeezing forces' while compensating for the externally applied wrench.

An important point we must clarify concerns the computation of the squeezing coefficients s_i, that somehow determine the amplitude of the forces $\vec{f_{ci}}$ at each contact point. To compute s_i, at each sampling instant, it is important to take into account the following data:

• The 'intention' of the human operator to squeeze the virtual object with more or less strength, measured by the intersection between virtual hand and object models. Deformation of the virtual object has been traditionally used to compute feedback forces for the fingers of the human hand (eg. [3]).

• Biomechanical data concerning force/pressure distribution on the human hand for different grasping and manipulation conditions. These data are difficult to extract due to the need of experimental apparatus measuring forces on various areas of the human hand. Simple methods, making use of dynamometers, exist providing measures of isolated finger flexion forces [6] but give insufficient/inaccurate information about simultaneous, force distribution between phalanges and fingers during diffrerent types of grip. Lee and Rim [10] developped an experimental apparatus for measurement of finger -phalangeal forces, based on the use of pressure sensitive sheets. Their experiments provide data concerning the distribution of forces on the human hand and percentage contribution for each individual phalanx and finger, when performing power grip of cylinders with varying diameter. A new hand-grasp measurement system is also being developped in the National Institute of Bioscience and Human Technology of Tsukuba [14]. The device, which has been called Sensor Glove, measures the distribution of grasping pressures at 81 points on the palm and on the inner surfaces of fingers using sensors of pressure-sensitive electroconductive rubber.

Combining the above information, we can compute the coefficients s_i using a simple, linear formula:

$$s_i = d_i \times K_i \times \delta r_i \tag{8}$$

where d_i : constants determining the contribution of each phalanx and finger at the total grip force, different for each grasp type, K_i : rigidity of the contact and δr_i : deformation of the virtual object at the i_{th} contact point. For instance, for a cylindrical power grip, the coefficients d_i can take values as shown in table 1 (see [10] for details).

Phalanx \ Finger	Index	Long	Ring	Little
proximal	0.115	0.126	0.088	0.060
middle	0.021	0.023	0.016	0.011
distal	0.159	0.176	0.122	0.083
Total Contribution	0.295	0.325	0.226	0.154

Table 1: *Finger/Phalangeal contribution for a cylindrical grip.*

We have thus formulated the problem of computing hand feedback forces into that of solving a general optimisation problem defined by the minimisation criterion F_2 (eq. 7) subject to constraints given by relations 3, 4, 5. The solution of such a constraint minimisation problem can be obtained by using several methods [12], like for instance the iterative, Kuhn-Tucker method. This is a generalisation of the Langrangian method for constraint minimisation problems containing inequality constraints. For each such constraint, we assign a coefficient u_i (Langrange multiplier) which becomes nonzero when the corresponding constraint is active. An active inequality then just acts as an equality constraint, which means that it is satisfied on its limit.

The major drawback of such a method, in the context of a VR application, is the computation time required to perform, at each time instant, supplementary iterations in case one or more constraints are not satisfied. Real-time requirements are as we know crucial to achieve satisfactory realism for VR simulations. In the following paragraph we present a simplified version of the problem, that can be sufficient for the purpose of grasping and manipulation in a VE.

5 A Simplified method based on Gaussian Elimination Algorithm

During the manipulation of virtual entities the intentions of the human operator are determined by constantly monitoring the interactions between the virtual hand and object models. Control of these interactions, for instance whether a virtual object will be stably grasped or will slip from the virtual hand, is performed by the operator's hand through actions on the haptic interface (in our case the force feedback glove). It is therefore more reasonable to monitor, instead of imposing as constraints, the stability conditions 4, 5 and subsequently determine the feedback forces and the behaviour of the virtual object in each grasping state. The problem of computing the feedback forces to be applied on each finger of the human hand, in case of a stable grasp (inequalities 4, 5 verified) can be therefore simplified in that of solving the minimisation problem $F_2 \rightarrow$ min subject only to the equilibrium equations 3 as constraints. To solve this problem in the general case, we use the Langrangian theory and transform it to a square system of linear equations:

$$H \cdot \vec{c} = \vec{b} \tag{9}$$

where

$$H = \left(\begin{array}{ccc|cc} I_3 & \cdots & I_3 & \multicolumn{2}{c}{\multirow{2}{*}{O_{(6\times6)}}} \\ R_1 & \cdots & R_{nc} & & \\ \hline & & & -I_3 & R_1 \\ & I_{(3n_c)} & & \vdots & \vdots \\ & & & -I_3 & R_{nc} \end{array} \right)$$

$\vec{c} = \left(\vec{f_c}^T \mid \lambda_1 \ldots \lambda_6\right)^T$ (λ_i: Langrangian multipliers),

$$\vec{b} = \left(-\vec{F_{ext}}^T, -\vec{N_{ext}}^T, s_1 \cdot \vec{a}_1^T, \ldots, s_{nc} \cdot \vec{a}_{nc}^T\right)^T$$

The above system is solved using the Gaussian elimination algorithm. A comprehensive description of this technique and its relation to the theory of LU decomposition of a nonsingular square matrix can be found in [12].

The method described in the previous section has been implemented on our experimental system, using C programming language in one of the HP715, 50 MHz Apollo workstations. Table 2 shows results for the computation time concerning a spherical grip with variable number of contact points (n_c). We observe that: first, the complexity of the algorithm remains approximately linear with respect to n_c and second, even in the worst case of a power grasp with 20 contact points, the computation time does not exceed 20 msecs, which may be sufficient for real time interactions within a VE.

n_c	3	5	10	15	20
dt (ms)	2	3	6	11	18

Table 2: *Computation time (dt) vs. number of grasp contact points (n_c).*

6 Conclusion and Future Work

We proposed a method for the computation of hand-feedback forces when performing general grasping and manipulation tasks in a VE. This method permits the mapping of external wrenches on each phalanx and finger of the human-operator hand. The goal is to achieve realistic interaction within a VR system, by providing pertinent kinesthetic information for various static and dynamic properties of objects present in the scene.

Future work consists of:

• Integration of the force-feedback algorithms on our VR system and experimentations using the LRP-DHM. Other methods, based on the use of neuro-fuzzy techniques will also be considered. The problem being rather complex and difficult to model, the use of more qualitative computational methods could prove to be more efficient, in terms of better satisfying real-time constraints and requirements related to the realism of the haptic sensation rendered by the system.

• Defining objective criteria and experimental procedures for evaluating the 'quality' of force-feedback on the hand of the human operator, i.e. the realism of the rendered sensation of interaction within a VE. This constitutes a rather difficult problem, keeping in mind the fact that haptic perception of characteristics, such as the weight of a manipulated object, is by nature subjective and relative. An evaluation methodology could be based on results provided by biomedical engineering studies concerning the modelling of human-hand, sensori-motor activity, as well as human, internal representation of information supplied by the haptic perception system. This means that we should eventually use existing experimental data analysing the dynamic behaviour of the human hand in presence of external disturbances during precision manipulation tasks.

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