The Hand Force Feedback: Analysis and Control of a Haptic Device for the Human Hand

Carlo Alberto Avizzano, Federico Barbagli, Antonio Frisoli, Massimo Bergamasco

PERCRO

Abstract

The Hand Force Feedback System is an anthropomorphic haptic interface for the replication of the forces arising during grasping and fine manipulation operations. It is composed of four independent finger dorsal exoskeletons which wrap up four fingers of the human hand (the little finger is excluded). Each finger possesses three electrically actuated DOF placed in correspondence with the human finger flexion axes and a passive DOF allowing finger abduction movements. Each exoskeleton finger has three points of attachment to the operator's finger (two for the thumb) at the middle of the phalanges. Mechanical fixtures guarantee that just a force perpendicular to the finger and in its sagittal plane is exchanged at each point of attachment. Such force component is sensed and it is actively controlled in feedback. The present paper illustrates the design and testing of the controller for the thumb exoskeleton. First the mechanical system is analyzed and the features which influence the controller design, such as the presence of unidirectional tendon transmission, are modeled. Then haptic controllers, i.e. feedback controllers aiming at improving the performance of the device when used as haptic interface for Virtual Environments or Telemanipulation, are designed and tested experimentally. Finally the experimental results are discussed.

I. INTRODUCTION

Haptic interfaces for Virtual Environments are robotic systems that aim at reproducing on the operator sensations of contact between his/her body and virtual objects. Such interfaces realize a bi-directional flow of information and energy. On one side the haptic interface sends information about the operator's estimated position and velocity to the virtual environment. On the other side the haptic interface replicates the interaction forces with virtual objects on the operator.

In this paper we focus on the HFF - Hand Force Feedback, an anthropomorphic hand controller for teleoperation and Virtual Environment applications[1]. The design of a haptic interface for the human hand is a very complex matter. This is due to the fact that the possible interactions between a human hand and any object are very different one from the other, according to the purpose of such contact and the type of object involved[2]. Contacts with real objects concern the whole surface of the hand. Ideally an infinite number of actuators positioned all over the user's hand would be required. In practice a limited number of actuators and of contact points with the human finger have to be chosen. A practical solution to this problem is to reduce the number of possible interactions between a phalange and the virtual environment to one single force, perpendicular to the finger and laying in its sagittal plane (see fig.1).

Actuators are a limiting factor for a hand haptic interface that ideally should be at the same time light, easily wearable and capable of creating a realistic feeling of a virtual environment possibly without the user realizing its presence.

One of the possible ways to overcome the limitations of state-of-the-art actuator technologies is to design making use of tendon transmission[4], [5], [8]. Using such a design technique, it is possible to locate the actuators away from the joint axis. This means that constraints on weight and volume of the actuators are partially relaxed and that the moving mass of the link can be reduced. This is obviously of extreme importance when designing a hand haptic interface, being the room between fingers extremely limited.

Among the wide range of possible tendon transmis-
sion designs, tension tendon transmission deserves a special consideration due to its low friction, high efficiency and backdrivability, which is a key issue for haptic interfaces. The key point of such a transmission is that tendons are routed over idle pulleys and are prevented to go slack being a minimum tension always guaranteed. Comparing such a transmission with the ones based upon tendons in shels shows how in the former case force control capabilities are much better even though the whole mechanical system results in being much more complex. The technical choice at PERCRO in designing the HFF is to go for a tension tendon drive.

Tension tendon transmission though introduces new phenomena which have to be analyzed to properly control haptic interfaces. First of all, the presence of elastic tendons connecting the motor inertia to the link inertia determines a resonant mode at a frequency usually lower than the one associated to the structural elasticity of the links. Secondly, tension tendon drive in multi-DOF robots with serial kinematics causes a phenomenon, known as coupling between joint torque and motor torque, not present at all in robots with actuators on the joints. The torque at a joint is not determined exclusively by the actuator directly connected to it, but also by the actuators connected to the tendons passing on that joint to reach a successive link of the robot[6].

A special type of tendon transmission is the unidirectional one, meaning that there is only one tendon from the actuator to the link to be controlled. This implies that the actuator connected to a certain link is only actively moving it in one direction. When the link moves in the other direction, being the actuator passive, return springs have to be used to make sure that the tendon's tension is kept at a minimum level.

The present paper illustrates the design and testing of a haptic controller for the thumb exoskeleton, which is a part of the HFF.

The reminder of this paper is organized as follows. In section III we focus on the HFF mechanical system and the Thumb Exos System - TES. In section IV the features that influence the controller design, such as the presence of unidirectional tension tendon transmission, are modeled. Then the design of haptic controllers, i.e. feedback controllers aiming at improving the performance of the device when used as haptic interface for Virtual Environments or Telemanipulation, is presented in section V. Finally in section VI the experimental results are discussed.

Fig. 2. (a) The HFF. (b) The TES

II. NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tr>
<td>(\tau_i)</td>
<td>Torque at joint (i)</td>
</tr>
<tr>
<td>(T_{\text{load},i})</td>
<td>Load torque applied on rotor (i)</td>
</tr>
<tr>
<td>(T_{d,i})</td>
<td>Angular displacement for driving pulley (i)</td>
</tr>
<tr>
<td>(\theta_i)</td>
<td>Angular displacement for joint (i)</td>
</tr>
<tr>
<td>(N_{i})</td>
<td>Reduction ratio for gearbox applied to motor (i)</td>
</tr>
<tr>
<td>(N_{i})</td>
<td>Transmission ratio for tendon (i)</td>
</tr>
<tr>
<td>(I_{p,i})</td>
<td>Rotor inertia of motor (i)</td>
</tr>
<tr>
<td>(J_{t,i})</td>
<td>Inertias of driving pulley (i)</td>
</tr>
<tr>
<td>(J_{d,i})</td>
<td>Total inertia for driven pulley fixed with link (i) and link (j)</td>
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<tr>
<td>(K_{v,i})</td>
<td>Viscous coefficient for tendon (i)</td>
</tr>
<tr>
<td>(K_{e,i})</td>
<td>Rotor viscous coefficient for motor (i)</td>
</tr>
<tr>
<td>(r_{d,p,i})</td>
<td>Radius of driven pulley fixed to link (i)</td>
</tr>
<tr>
<td>(r_{i})</td>
<td>Radius of idle pulley for tendon (i) fixed with link (j)</td>
</tr>
<tr>
<td>(J_{d,i})</td>
<td>Radius of driving pulley (i)</td>
</tr>
<tr>
<td>(T_{t,i})</td>
<td>Tension of tendon (i)</td>
</tr>
<tr>
<td>(K_{e,i})</td>
<td>Elastic constant for tendon (i)</td>
</tr>
<tr>
<td>(r_{d,i})</td>
<td>Elastic coefficient for return spring (i)</td>
</tr>
<tr>
<td>(q)</td>
<td>Vector ([q_1, q_2, \ldots, q_m])</td>
</tr>
<tr>
<td>(\tau)</td>
<td>Vector ([\tau_1, \tau_2, \ldots, \tau_m])</td>
</tr>
<tr>
<td>(n)</td>
<td>Vector ([n_1, n_2, \ldots, n_m])</td>
</tr>
<tr>
<td>(F)</td>
<td>Decoupling matrix for tendon transmission</td>
</tr>
<tr>
<td>(J(q))</td>
<td>Jacobian matrix for vector (q)</td>
</tr>
<tr>
<td>(f(q))</td>
<td>Control action theoretically computed for the generic motor</td>
</tr>
<tr>
<td>(f(l))</td>
<td>Measured force on the generic link</td>
</tr>
<tr>
<td>(T_{\text{d}})</td>
<td>Desired force on the generic link</td>
</tr>
<tr>
<td>(K)</td>
<td>Matrix \diag[K_1, K_2, K_3]</td>
</tr>
<tr>
<td>(T_{\text{s}})</td>
<td>Derivation time for the PID derivative term</td>
</tr>
<tr>
<td>(T_{\text{c}})</td>
<td>Sampling time for the controller</td>
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<tr>
<td>(K_{\text{p}})</td>
<td>Proportional term's gain for the PID controlling action</td>
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<tr>
<td>(K_{\text{i}})</td>
<td>Derivative term's gain for the PID controlling action</td>
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<td>(K_{\text{d}})</td>
<td>Integral term of the PID controlling action</td>
</tr>
<tr>
<td>(P)</td>
<td>Proportional term of the PID controlling action</td>
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III. SYSTEM DESCRIPTION

The HFF[1] is composed of four exoskeletons (fig.2.a), each of which exerting forces to the phalanges of the hand's fingers (little finger excluded), that all together can be worn as a glove by the user. Each finger exoskeleton consists of four links connected by revolute joints disposed as the joints of each finger. For each joint of the finger exoskeleton, the joint axis has been designed in order to approximate the instantaneous position of the human flexion-extension axis.
during operation. At the metacarpo-phalangeal joint a passive abduction-adduction movement has been also integrated.

More specifically we will focus our attention on the TES (fig. 2b). The TES is slightly different from the other finger exoskeletons. In particular, from a construction point of view, the cantilever supporting the three motors of the thumb assumes a completely different aspect with respect to the ones of the other fingers. Adding to that the TES has only two points of attachment while the other three finger exoskeletons have three. Two force sensors, each of which obtained by 4 strain gauges, are located directly on dorsal surface of each phalange link. Rotation sensors, based on conductive plastic technologies, are integrated at each joint, recording the fingers’ movements.

One of the critical factors encountered during the design of the system has been that of obtaining a system possessing limited weight and volume, in such a way to allow good maneuverability of the hand. A solution has been found with the employment of a tendon drive system (fig. 3). The three motors are located on a cantilever structure fixed with the base frame of each finger exoskeleton. The tendon drives for the distal and medial links (link 2 and 3) are unidirectional, meaning that they actuate only an extension movement. To maintain the tendon’s tension in any operating condition two return springs are used. The proximal link (link 1) has instead a bi-directional tendon drive, while the base link is not actuated and its joint is passive, following the user’s movements.

IV. DYNAMIC MODEL FORMULATION

In the modeling of the TES it is useful to distinguish link 1, which has a bi-directional tendon drive, and links 2 and 3 for which the drive is unidirectional. The same model will be used for all the actuators being them all current controlled DC motors.

A. Actuators

Let us consider the case in which a power amplifier is used to control the current in the motor windings. The input command variable is the electromagnetic torque \( T_{m,i} \) applied to the rotor. The dynamic model for the actuators takes as input also the load torque \( T_{load,i} \) exerted by the driving pulley on the rotor and offers as output the motor angular position \( q_{m,i} \). Note the presence of gearboxes on the motors’ shafts whose reduction ratio is indicated by \( N_i \). Indicating with \( J_{m,i} \) and \( b_{m,i} \), for \( i = 1, 2, 3 \), respectively the motor inertia and the viscous coefficient and with \( T_{dp,i} \) and \( J_{dp,i} \) respectively the torque applied by the transmission on the driving pulleys and the driving pulleys inertia, the actuator equations are:

\[
\begin{align*}
J_{m,i} \ddot{q}_{m,i} + b_{m,i} \dot{q}_{m,i} &= \tau_{m,i} - \frac{T_{load,i}}{N_i} \\
J_{dp,i} \ddot{q}_{dp,i} &= T_{load,i} - \tau_{dp,i} \\
q_{dp,i} &= \frac{q_{m,i}}{N_i}
\end{align*}
\]

from which we obtain the transfer function

\[
\frac{q_{m,i}}{\tau_{m,i} - \frac{T_{load,i}}{N_i}} = \frac{1}{(1/N_i + s + b_{m,i}/N_i)}
\]

where \( J_{tot,i} = J_{m,i} + J_{dp,i}/N_i^2 \).

B. Transmission

The transmission system interconnects the actuators with the links. The cables are modeled as a linear spring and a linear dashpot in parallel. This is an improvement with respect to considering the tendons ideally rigid; it allows to take into account at least the linear elastic effects and predict the frequencies and damping of the elastic resonant modes. The physical behavior of cables, especially those composed of many strands, is much more complex including non-linear and hysteretic behaviors and delays in tension propagation. We will suppose the tension on a same tendon to be constant. This happens if the friction torque on the idle pulleys is negligible and the torque due to the pulleys inertia are small.

Referring to figure 4, indicating with \( J_{t,i} \) the total inertia of link \( i \) and its driven pulley, being \( N_{t,i} := \frac{J_{t,i}}{J_{dp,i}} \), \( k_{t,i} \) and \( b_{t,i} \) the transmission ratio, the elastic and viscous coefficient for tendon \( i \), the following equations describing the dynamics of link 1 hold:

\[
\begin{align*}
\tau_{m,1} &= J_{m,1} \ddot{q}_{m,1} + b_{m,1} \dot{q}_{m,1} + k_{t,1} \left( q_{m,1} - q_{1}' \right) + b_{t,1} \left( \dot{q}_{m,1} - \dot{q}_{1}' \right) \\
J_1 \ddot{q}_{1}' &= k_{t,1} \left( q_{m,1} - q_{1}' \right) + b_{t,1} \left( \dot{q}_{m,1} - \dot{q}_{1}' \right) = \frac{T_{load,1}}{N_1}
\end{align*}
\]
where \( k'_t = \frac{2k_t r_t^2}{N_t^2} \), \( b'_t = \frac{2k_t r_t^2}{N_t^2} \), \( q'_t = q_t \), \( N_t, N_{t,1} \)

and \( J_t = \frac{J_t}{(N_t, N_{t,1})} \).

The equations that hold for links 2 and 3 are slightly different due to the unidirectionality. To describe such dynamics, which are strongly non linear, we will use function \( u \) defined as:

\[
u(t) := \begin{cases} 
0 & t < 0 \\
1 & t \geq 0
\end{cases}
\]

since the tendon's tension cannot be negative. The following equations hold[6]:

\[
\tau_{m, t} = \frac{u(T_{t, i}) T_{t, i} r_{dp, i}}{N_t} = J_{m, i} \dot{q}_{m, i} + b_{m, i} \dot{q}_{m, i}
\]

\[
\tau_{dp, t} = \frac{u(T_{t, i}) T_{t, i} r_{dp, i}}{N_t} = u(T_{t, i}) T_{t, i} r_{dp, i}
\]

where \( T_{t, i} \) is the tension for tendon \( i \).

It is important to express the coupling effect typical of tendon transmissions. Referring to figure 4 it appears clear that in static conditions the following holds:

\[
q = -N^{-1} q_m
\]

where \( N \) is a 3 \times 3 matrix defined as

\[
N = \begin{bmatrix}
N_1 t_{1,1} & 0 & 0 \\
N_1 t_{1,2} & N_2 t_{2,2} & 0 \\
N_1 t_{1,3} & N_2 t_{2,3} & N_3 t_{3,3}
\end{bmatrix}
\]

Supposing that the transmissions don't imply any type of energy loss, matrix \( N \) determines a linear relation between joint torque and motor torque given by

\[
\tau_m = -N^{-T} \tau
\]

C. Links

Referring to figure 4, if all inertial forces are neglected, considering the links to be ideally rigid and the system to be in equilibrium the following vectorial equation holds

\[
\tau_m = N^{-T} (J^T(q) f + (\Phi - K q))
\]

being

\[
K = \begin{bmatrix}
0 & 0 & 0 \\
0 & K_2 & 0 \\
0 & 0 & K_3
\end{bmatrix}, \quad \Phi = \begin{bmatrix}
\Phi_2 \\
\Phi_3
\end{bmatrix}
\]

the terms representing the return springs action on the links \((K_i := \text{elastic constant}, \Phi_i := \text{preload torque for return spring } i)\) and \(J^T(q) f\) the term representing the external forces action on the links. Note that element \((J^T(q) f),_{1,1}\) is null since the user cannot apply any force to link 1 being no mechanical attachment to such part of the TES.

V. CONTROL DESIGN

The controller structure that has been adopted is shown in figure 5. External forces on links 2 and 3 are measured, compared to a reference desired force and processed by two separate control units (one for each link) independently. Considering equation (3) it is then easy to compute the desired motor torque. The compensation of the preload torque for transmissions 2 and 3 is obtained by the use of a proper unit. Finally matrix \(N^{-T}\) is used to get rid of the transmission coupling effect.

It is important to note that, due to the unidirectionality of transmissions 2 and 3, it is basic, for the TES to properly work, to impose torque for motors 2 and 3 to be always positive. Motor 1 on the other side is used only to get rid of the coupling effects proper to the tension tendon transmission. This might be problematic at times since the engines' limited power. Undesired side effects due to saturation appear to the user as unpredictable torque on link 1, which should be still and should follow the user’s finger. In fact, by simply applying equation 3 to compute the motor torque there might be cases in which \(\tau_{m,2}\) or \(\tau_{m,3}\) won’t be physically obtainable, saturating motor 2 or 3. In such case the algorithm commanding the TES should consider the real torque applied to links 2 and 3 to perfectly get rid of the coupling effect on link 1.

Different algorithms have been used to approach this problem.

The purpose of the haptic control unit is to apply a
desired force on the user's fingers. Desired forces are calculated by the virtual environment depending on if the user is interacting with any virtual object or not. The force servo that we implemented does not consider side effects such as gravity, dynamic coupling effects and friction. Two force controllers have been implemented. A proportional controller has been used to estimate the dominant poles of each link while a PID controller has been designed to obtain better performances. The latter controller is based on three digital units, obtained by discretization of equation

\[ \dot{f}(t) = K(f_d(t) - f(t)) + \int \left( f(x) - f(x) \right) dx - K_d \frac{df(t)}{dt} \]

where \( f(t) \) is the measured force, \( f_d(t) \) is the control action applied to the TES and \( f_d(t) \) is the desired action force. Practically, using a low-pass filter for the derivative block, we obtained the following discrete time functions

\[
P(k) = K(f_d(k) - f(k)) \quad (4)\\
I(k) = l(k - 1) + T \left( f_d(k - 1) - F(k - 1) \right) \quad (5)\\
D(k) = \frac{T_d}{T + T_d} D(k - 1) - \frac{K_d}{T + T_d} (f(k) - f(k - 1)) \quad (6)
\]

The Integral part has been realized with an anti wind-up mechanism trying to limit the actuators' saturation.

When the user interacts with virtual objects the desired force is simulated to be elastic, being proportional to the angles at joints 2 and 3.

VI. EXPERIMENTAL RESULTS

Two main types of experiments have been carried out: isometric experiments such as blocking link 2 or link 3 against an infinitely rigid environment, and functional tests such as having a user wear the interface making free movements (isotonic conditions) or interacting with a deformable virtual object.

The isometric experiments have been carried out on the TES blocking link 2 (or link 3) and applying to motor 2 (or 3) a step input force of varying in a range between 100mN and 500mN. The result of such experiments, using a Proportional and a PD and a PID controller, are hereafter presented.

First of all let's focus our attention on the experiments carried out on link 3. Referring to fig.6, function (1) is the step input force to be followed, function (2) is the measured force, function (3) (in fig. c) is the control signal. Experiment (a) has been conducted using a P controller with \( K = 20 \) while experiment (b) using \( K = 30 \). In both cases the step input to be tracked has a 500mN magnitude. Increasing gain \( K \) further we obtain more oscillating signals until the system becomes unstable for gains \( K > 50 \). Experiment (c) is referred to a PID controller with \( K_p = 140, K_i = 10, K_d = 10 \) with a low-pass filter on the measured force signal. Such filter has a pole at 4Hz and a gain equal to 10. The step input to be tracked has an intensity of 100mN. Both the rise time, the overshoot, the settling time are better using the latter controller giving overall better performances. The position-error is null in the latter case due to the integral block of the controller.

Secondly, let's focus on the experiments carried out on link 2. Signals (1)-(4) have the same meanings as the ones indicated above. Considering fig.6, function
(1) is the step input force to be tracked, function (2) is the measured force, function (3) is the control signal while function (4) is the control signal practically obtained on the motors. Experiment (a) is referred to a Proportional controller with $K = 30$, experiment (b) is referred to a PD controller with $K_p = 80$ and $K_d = 10$ and experiment (c) is referred to a PID controller with $K_p = 20$, $K_d = 10$ and $K_i = 65$. All experiments have been conducted tracking a force step input having a 500mN intensity.

In all of these experiments the system always responds with a finite time delay. This is due to a not prefect blocking system for link 2. Experiment (a) has the best performance overall even though the motors saturate. Increasing the proportional gain we obtain a prompter response an a higher overshoot until reaching $K > 70$, which is the threshold when the system becomes unstable. The PD controller (fig.7,b) has better response and overshoot performances but these are not so far from the simpler P controller. Motors tend to saturate even more and the control action is highly non-linear. The PID controller has a better position-error, even though it’s not null due to frictions of the gearbox. The overshoot though is definitely too high probably due to the delays on the motor's action introduced by a friction of the gearboxes.

Let us now consider the functional experiments on link 3. Such a controller has been realized to simulate a soft deformable object with elastic constant $k = 50mN$ per joint angle degree. Experiments conducted on link3 are presented in fig.8 and in fig.9. More specifically fig.8a represents joint angle $q_3$ and fig.8b represents the measured force obtained on link 3 when the deformable object is implemented, while fig.9a represents joint angle $q_3$ and fig.9b represents the measured force obtained on link 3 when the deformable object is not implemented. Figure 8 shows clearly how the measured force is proportional to the angle at joint 3 while figure 9 shows how, being the contact with the deformable elastic object not simulated the measured force is independent from the angle at joint 3 and the force disturbance is not higher than 0.2mN.

VII. CONCLUSIONS

This paper presents some experiments carried on the HFF haptic interface designed at PERCRO lab. The system has been modeled and a haptic servo force controller has been designed and tested for such system. The performances obtained are not yet satisfactory. This is due to the high friction of the motors and to the coupling effects proper of tension tendon drive systems. However a new mechanical project using three bi-directional drives will be soon presented.

REFERENCES