Force Replication to the Human Operator: the Development of Arm and Hand Exoskeletons as Haptic Interfaces

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Abstract

This paper deals with a particular aspect of the research on teleoperation and on the interaction with Virtual Environments (VE), i.e. the design and the development of man-machine interfaces. These systems must be adequate to both record the movements of the human operator's hand and arms and replicate on them forces detected by the end-effector of the remote robot, or modelled in the VE, at the interaction with the external, or virtual environment. In particular issues related to force replication to the human operator are considered.

At first the set of requirements needed for the Force Display Device (FDD) to allow the human operator to perform a good control of manipulative and exploratory tasks are presented. Such issues as manoeuvrability, fidelity, transparency or passivity of the FDD will be addressed. Two basic topologies of FDDs are analyzed in terms of workspaces and force replication.

The work carried out at Scuola Superiore S.Anna for the development of FDDs is then presented. In particular two prototypes of Arm and Hand Exoskeletons are described in detail together with the experiments carried out up to now by exploiting a virtual environment testing scenario.

The approach to the design of a second prototype of Arm Exoskeleton, devised for application in the rehabilitation field, is presented.

1 Introduction

Tasks related to teleoperation or to the interaction with Virtual Environments (VE) require the capability for the human operator to acquire knowledge about features of the touched objects. Common object's features refer to shape, hardness, surface temperature, surface texture, presence of holes on occluded sides, etc. The acquisition of such information in a real environment is performed by haptic exploration procedures exploiting cutaneous and kinesthetic inputs [1]. The rendering to the human operator of the sensation of a physical interaction with a remote or virtual environment can be achieved by utilizing appropriate interface systems capable of generating adequate sensory cutaneous *stimuli* to the operator. However, since a strict correlation exists between the typical hand movement pattern related to a specific exploratory procedure and the associated object knowledge, the interface system should allow the human operator to execute such a procedure by exploiting correct, natural, movements.

The possibility for the human operator to execute realistic movements and, at the same time, to perceive adequate sensory *stimuli* is then a fundamental requisite for achieving satisfactory control of the operation. *Realism of interaction*, especially for haptic perception tasks, is then strictly related to the capabilities of the interface system to allow natural movements to the human operator's hands as well as to the fidelity in reproducing adequate cutaneous stimuli on them.

Such a *transparency* of the interface system can be achieved through appropriate design integrating the above functionalities.

The basis for haptic perception is represented by *cutaneous* and *kinesthetic* inputs. During the execution of an exploratory procedure of an object belonging to a virtual environment, the *kinesthetic inputs* that are presented to the operator's perceptual systems are *real* kinesthetic information he/she achieves from the movements and postures of his/her hands. Adequate kinesthetic inputs should then derive from correct exploratory movements executed by the human operator. This need directly affects the design approach of the interface system.

The other essential issue to be considered for haptic perception is represented by *cutaneous inputs*. Under this type of sensory information we include *force* and *tactile inputs*. Since now, interface systems devoted to the rendering of force and tactile information during the interaction with the VE, have been separately developed as force and tactile feedback systems. In this paper we discuss the development of force display devices (FDD) capable of replicating forces at the level of the human upper limb and, at the same time, maintaining its correct natural movement pattern. However, we believe that a correct approach should address the design of force and tactile feedback systems as an integrated Haptic Interface system embedding the replication of both functionalities. Recently, an important trend in the design of interface systems has considered the development of "Haptic interfaces" (or manipulandum, or hand controllers) [2][3][4][5]: in these cases the human operator usually interacts with an actuated external device by means of an handle or a stylus. In this way the force stimuli perceived is generated by the device, while the tactile input is completely real (and not realistic) since the user grasp the end-point of the real device. Hand controllers allow only a limited control of manipulative or exploratory procedures that do not require the presence of a tool in the hand; natural movements of the human hand working in free conditions cannot be easily performed.

We are interested in the ultimate concept of haptic interfaces allowing a large spectrum of natural pattern of movements of the human upper limb (hand included) and capable of replicating adequate cutaneous inputs. The design of the FDD developed in our laboratory followed this last approach.

2 Force Feedback Systems

The importance of force replication, or force feedback, on the human operator is well recognized since the first telemanipulation experiments carried out in US in late 1950s [6]. From the development of electrical master systems, characterizing the second generation of telemanipulation systems [7], the present technology level of force feedback interfaces greatly exploits the achievements of the last two decades in the areas of sensor technologies and control architectures. More recently, the possibility of integrating complex end-effectors at the slave level, such as sensorized dexterous robotic hands, brought new emphasis on the design of adequate hand controllers [8][9]. At present a great boosting action for the design of new man-machine interfaces has been induced by the innovative research in the field of the interaction with the Virtual Environments (VE).

The problem of the design of the interface system, especially in terms of afferent sensory information replicated to the human operator's hand, can be considered in VE as very closed to the one to be tackled for the control of teleoperators for telemenipulation task [10]. In the course of the paper we assume that the Force Feedback system is composed by:

- one or more Force Display Devices (FDD);
- their control systems;
- a modelling module devoted to generate the force to be replicated.

The set of general features that force feedback systems must possess for allowing a good control of the task by the human operator comprehends issues such as:

- **maneuverability**: the interface system must allow a natural mobility to the human hand and arm. This requirement can be seen in terms of the natural workspace of the human hand-arm complex which must not be restricted from the presence of the FDD mechanical structure. This condition is difficult to be achieved from the design point of view because the FDD possesses its own workspace which intersection with the human-hand workspace must be optimized;
- **fidelity**: the interface system must be able to reproduce in a faithful way to the human hand-arm the forces modelled in the VE. In

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Figure 1: Different Topologies of Force Display Devices

previous papers we have analyzed how the forces (wrenches) which can be replicated depend on the kinematics of the FDD [11][12];

- **impedance**: the impedance offered to the human hand-arm complex by the force feedback system must match the same condition of impedance seen by the human hand-arm complex during the performance of a real grasping or manipulative operation. This requirement implies a condition of transparency of the interface system during operation. This condition of passivity of the force feedback system subtends also the need of rendering, for whatever kinematic configuration of the structure, a complete inertial and weight compensation;

- **wearability**: wearability and also portability of the FDD represent two important features for the synthesis of the final mechanism.

From the topological point of view it is possible to devise two main categories of FDDs [13]:

1. FDD with several DOF which structure is external with respect to the human limb (finger, hand, arm, leg, etc). Only the FDD endpoint is connected to the human limb and through this point the forces are transmitted. Since the human limb is constrained to be connected with the FDD end-point (which base frame is fixed to the ground), the resulting maneuverability is limited to the intersection of the FDD's and limb workspaces. In terms of force replication, however, the force exerted by the FDD is perceived by the human operator as an external force, without "side effects"; in the case that multiple contact points should be considered, an equivalent number of FDDs must be utilized;

2. FDD possessing several DOF which structure wraps up the human limb (finger, arm, leg, trunk, etc). In this case the FDD kinematics reflects the one of the limb since the joint axes are the same (Exoskeletons).

   Exoskeletons can be designed with one or more points of attachment with the human limb as well as with their base frame fixed to the ground (external to the body) or to the human limb (see Fig.1). In the last condition side effects phenomena due to the presence of reaction forces at the level of the base frame attachment point are present.

When the interaction between the human operator and the virtual environment comprehends grasping, manipulative as well as exploratory procedures, the set of virtual forces that can be modelled in the virtual environment can belong to a large spectrum, in terms of magnitude, direction and also point of application. This topic as been analyzed in [14].

The main assumption we have introduced in our work in order to design a force feedback system capable of replicating the above complete range of forces is the following: "since the proprioceptive information (sensation on force exerted) perceived by humans is based on signals generated by sensors located at the joints, muscles and tendons, we base the concept of force replication by considering forces that can stimulate tracts of the limb comprehensive of the same muscles and joint which will be interested during the performance of the same task in a real condition". These forces will be replicated to the human limbs by different FDDs, possessing different performances in terms of magnitude, orientation and direction of forces to be replicated.

3 Force Display Devices

At PERCRO of the Scuola Superiore S.Anna, a complete Force Feedback System consisting of a) two serially connected FDD components, b) their control systems, c) a modelling module for generating the forces and d) a graphical module for the representation of the VE scenario, has been designed and realized.

The FDD components, represented in Fig.2, consist of two exoskeleton systems devoted to replicate forces at the level of the arm and of the operator's fingers. In particular the components are:

- a FDD component, called Arm Exoskeleton or External Force Feedback (EFF) system, with 7 DOF which are coincident with the principal joint axes of the human arm. The Arm Exoskeleton has been designed to be completely supported by the operator's body by means of a purposely designed trunk

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Figure 2: Arm and Hand Exoskeletons

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Figure 3: Kinematic Representation of the Arm Exoskeleton

Link	a	d	α	θ	*Mass*	
#1	0	0	$-\pi/2$	0	1.5	
#2	0	0	$-\pi/2$	$-\pi/2$	0.53	
#3	0	$-L_{arm}$	$-\pi/2$	0	2.775	
#4	0	0	$-\pi/2$	$-\pi/2$	0.644	
#5	0	L_{farm}	$\pi/2$	$\pi/2$	1.423	0.75
#6	L_w	0	$-\pi/2$	$\pi/2$	0.199	0
#7	H_h	L_h	0	0	0.052	0

Table 1: Denavit-Hartenberg parameters and link masses for the Arm Exoskeleton

structure or by a fixed frame structure which allows easier wearing conditions in case of repeated experimental tests;

- a FDD component, called Hand Exoskeleton or Hand Force Feedback (HFF) system, consisting of 4 parallel FDDs wrapping up four fingers of the human hand (little finger excluded) and each one possessing 3 DOF in correspondence of the finger joint axes (the total number of DOF is then 12). The 4 FDD are connected to a base plate located at the metacarpus and corresponding to the end-point of the Arm Exoskeleton.

Both FDD components have ben designed in order to maximize the resulting workspaces of the human arm and hand during operation. In case the EFF system is supported by the trunk structure, the complete FDD system becomes portable and allows a large physical mobility to the human operator inside the control space. This fact extends its use also for augmented reality applications.

Consequences of the described solution can be summarized as:

- the serial links kinematics of the EFF and HFF exoskeletons is given and cannot be changed to improve its inertial and elastic properties;
- the mechanical design presents a certain degree of complexity: limitations to the human arm movements must be reduced and for this reason the links should be slender and their surfaces have to be free of protrusions which could hurt the operator limbs;
- the portability of the FDD system on the operator trunk imposes tight constraints in terms of weight of structural parts and actuators and it requires a careful mass distribution to mitigate the operator effort needed to balance the system.

3.1 Arm Exoskeleton

Fig.3 depicts the scheme of the kinematic chain of the complete 7 DOF Arm Exoskeleton [15]. In this configuration (called *Exos7*), the end-point of the mechanical structure consists of a plate where the Hand Exoskeleton can be connected. The Arm Exoskeleton can be also utilized according to a configuration with 5 DOF (called *Exos5*) in which the last 2 DOF, corresponding to the wrist flexion-extension and abduction-adduction movements, have been removed and substituted by a fixed handle.

The Denavit-Hartenberg parameters describing the Arm Exoskeleton kinematics are given in Table 1.

The length of the arm L_{arm} is adjustable ($\pm 0.015\ m$) around the nominal value of $0.33\ m$. The values of the other parameters are $L_{farm} = 0.255\ m$, $L_w = 0.01\ m$, $L_h = 0.063\ m$, $H_h = 0.023\ m$ for the *Exos7* configuration and $L_{farm} = 0.33\ m$, $L_w = L_h = H_h = 0.0\ m$ for the *Exos5*.

The actuation and transmission system of each joint of the Arm Exoskeleton is composed of a DC electric motor, a gear box mounted on the motor axis, a cable transmission system transmitting the movement of the gear box output stage

The basic consideration for the choice of the actuation and transmission system has been that of using gear boxes that would increase the maximum output torque of small and light motors while still keeping the joints backdrivable. At the same time, the cable circuits which are routed with idle pulleys allow a further reduction ratio with very high efficiency and, as far as possible, to place the actuators on the more proximal links instead on each joint. The actuators for joints #3, #4, #5 are placed on link #3, while on link #5 the actuators for joint #6 and #7; the great influence of the motor location on the mass distribution of the Arm Exoskeleton can be seen by analyzing Table 1.

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Figure 4: The Arm Exoskeleton in the 5 DOF configuration (*Exos5*)

Although all the Arm Exoskeleton joints are backdrivable, their actual friction is still far to be negligible. The solution devised to overcome friction problems consists in the integration in the cable transmission system of differential tendon tension sensors. Such devices give an indirect measure of joint torques so that a local joint torque feedback loop can be implemented to reduce the influence of motor, gear box and cable circuit friction on joint behaviour. In the first prototype of Arm Exoskeleton, differential tendon tension sensors are present only on the two wrist joints and on the forearm prono-supination joint; the next version of the Arm Exoskeleton will mount them on all joints. Table 2 gives the joint excursion limits which have been measured with the operator actually wearing the Arm Exoskeleton to obtain values corresponding to the intersection between the human arm workspace and that of the FDD component.

Joint	θ_{min}	θ_{max}
#1	$-25.0°$	$-73.26°$
#2	$-40.38°$	$49.4°$
#3	$-80°$	$72.9°$
#4	$-21.17°$	$74.56°$
#5	$-85.0°$	$90.0°$
#6	$-80.0°$	$80.0°$
#7	$-35.0°$	$25.0°$

Table 2: Joint rotation limits (in degrees) of the operator wearing the EFF

Kinesthetic sensors of the Arm Exoskeleton consists of optical encoders located on the motor shafts; encoders #1 to #5 give out 500 impulses per revolution; encoders #6 and #7 give out 15 impulses per revolution.

3.2 Force Modelling and FDD Control Strategy

Experiments have been carried out with the aim of studying the behaviour of the human operator during the execution of interaction procedures in the VE.

The implementation of force feedback from the VE is based on evaluating the operator hand position from the Arm Exoskeleton kinesthetic sensors data, performing collision detection procedures, calculating the forces due to collisions with virtual surfaces, and finally controlling the force between the FDD and the operator's hand to the computed value [12][17].

Models of the interaction between the human hand and virtual objects can be very complex and computationally heavy if the detailed geometry of contact is taken into account [16]. The operator hand is modelled with only one control point c so that its inter-penetration into virtual bodies is summarized by a single interpenetration vector d which represents its distance from the surface.

A contact between the operator hand and a virtual body generates a force $\boldsymbol{F}_{react}$ according to a dynamic model of contact which represents the elastic and viscous properties of the virtual body:

$$\boldsymbol{F}_{react} = \begin{cases} -K\,d + B\,v_{op} \cdot \dfrac{\boldsymbol{d}}{|\boldsymbol{d}|} & \text{at contact} \\ 0 & \text{otherwise} \end{cases}$$

The elastic component of the surface reaction force models a rigid surface of stiffness K. The viscosity coefficient B is introduced to take into account the dissipative phenomena occurring during a real collision in the same way a restitution coefficient of the collision would do [18]. The force-based interaction between the operator and the VE is affected by system sampling time, simulation and communication delays, errors in force replications due to the FDD.

The implementation of the proposed interaction is realized by using as control variables the Arm Exoskeleton join torques [15]. The joint torques to be utilized for the control of the Arm Exoskeleton joints in order to exert on the operator hand a desired wrench $\boldsymbol{F}_{react}$ should compensate the inertia, the Coriolis and centrifugal effects, the friction and the weight. A complete mapping of external wrenches at the hand level into joint torques will thus be dependent on exoskeleton configuration, joint velocities and accelerations:

$$\tau = M(\boldsymbol{q})\ddot{\boldsymbol{q}} + C(\boldsymbol{q}, \dot{\boldsymbol{q}}) + D(\boldsymbol{q}, \dot{\boldsymbol{q}}) + G(\boldsymbol{q}) + J^T(\boldsymbol{q})\boldsymbol{F}_{react}$$

where M is the inertia matrix of the Arm Exoskeleton, C is the vector of Coriolis and centrifugal terms, D is the vector of friction terms, and G is the vector of gravity effects.

In our case we have decided to use only the gravity compensation term; this choice greatly

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Figure 5: Kinematics scheme of the Hand Exoskeleton

simplifies the control law but it introduces a force error especially when joint velocities and accelerations are high. Since no force/torque sensors are present on joint #1-#4, an open loop control law has been implemented as follows:

$$\tau_{control} = \hat{G} + J^T(\boldsymbol{q})\boldsymbol{F}_{react}$$

where $\hat{G}$ indicates an estimate of G. Such an open loop scheme can be used since all joints are backdrivable. Friction and modelling errors in the estimation of G introduce further force errors. An improvement in the force replication accuracy can be obtained by using a closed loop control law when joint torque sensors are available.

The Arm Exoskeleton controller and the Force Feedback subsystem of the VE have been digitally implemented on a 6 transputer network and run at a sampling frequency $\frac{1}{t_c}$, with t_c the cycle period of sampling, varying in the range $1 - 0.001s$ [12].

Experiments have been carried out by using the Arm Exoskeleton with the aim of reproducing two basic interactions of the human hand with a rigid surface: the collision with a virtual surface and the following of the virtual surface. Experiments have been carried out by varying the parameters of the VE such as the system sampling time t_c, the virtual surface elastic coefficient K and the virtual surface viscosity coefficient B. Results have been extensively reported in [12] and summarized in [17] and [18].

3.3 Hand Exoskeleton

The second component of the complete FDD system is called Hand Exoskeleton and consists of 4 FDD exerting forces to the phalanges of the hand's fingers (little finger excluded). Each finger exoskeleton, which kinematic scheme is represented in Fig.5, consists of four links connected by revolute joints. For each joint of the finger exoskeleton, the joint axis has been designed in order to approximate the instantaneous position of the flexion-extension axis during operation. At the metacarpo-phalangeal joint a passive abduction-adduction movement has been also integrated.

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Figure 6: The Hand Exoskeleton

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Figure 7: Another view of the Hand Exoskeleton

The actuation system for one finger exoskeleton is based on three DC servomotor and associated tendon tension transmission systems. Each tendon is pulling on the middle point of each phalanx of the finger in order to execute the extension movement; at each joint, the flexion movement is obtained by a passive torsion spring integrated on the joint axis. The three motors are located on a cantilever structure fixed with the base frame of each finger exoskeleton. Rotation sensors, based on conductive plastics technologies, are integrated at each joint while force sensors, capable of recording the interaction force between the exoskeleton structure and each phalanx, are located directly on the dorsal surface of each phalanx link.

A picture of the resulting Hand Exoskeleton is given in Fig.6 and in Fig.7.

The kinematic structure of the thumb exoskeleton is slightly different to the one of the other fingers. In particular, from the construction point of view, the cantilever supporting the three motors of the thumb assumes a completely different aspect with respect to the one of the other fingers.

The Hand Exoskeleton system is controlled by a transputer-based control architecture. One of the critical factors encountered during the design of the system has been that of obtaining a system possessing limited weight and volumes, in such a way to allow good manoeuvrability of the hand. During wearing conditions, the ranges of motion of the fingers can be considered very close to those of the free human hand. In terms of the mechanical performances of the Hand Exoskeleton system, we obtained a maximum extension force of $0.3N$, being the force sensor range of $-0.5N$—$3.0N$. Force resolution is $0.0025N$, while the force feedback bandwidth is $0.5Hz$ with an angular displacement of $90°$ for all the 3 DOF.

In order to test the performances of each finger exoskeleton, a purposely designed test-bed actuated structure has been realized. Fig.8 shows the operating condition of the test-bed system: one finger exoskeleton is fixed to the base plate of the test-bed and connected, by means of appropriate connection particulars, to the links of the test-bed system. The test-bed is controlled in parallel to the finger exoskeleton in order to

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Figure 8: The Hand Exoskeleton Test-bed

execute both isometric and isotonic tests. During isotonic tests, the finger exoskeleton is commanded to exert constant forces on its phalanges, while the test-bed is controlled in order to impose appropriate movement patterns to the finger exoskeleton links. The objective of the test is that of monitoring the force error as a function of the frequency of the displacement at each joint. In the framework of isometric tests, sinusoidal force inputs to the Hand Exoskeleton will be provided, while the test-bed will impose on it constant displacements (fixed configurations). In terms of positioning bandwidth, the test-bed system has been designed for $8Hz$ on 90° for all the 3 DOF. The maximum transmittable force to the Hand Exoskeleton is $110N$, and the position resolution has been estimated to $3.5arcmin$.

4 The Design of a New Arm Exoskeleton

In the framework of a project dealing with rehabilitative applications, the design of a new Arm Exoskeleton has been addressed. The objectives of the new FDD system can be summarized as:

1. capability to exert forces not only at the level of the hand but also on the forearm or/and arm (multiple contact point);
2. capability to wear the structure from the lateral side and without inserting the human arm only through the shoulder hollow;
3. general reduction of the masses and inertia by exploiting a remote arrangement of the motors. The objective is the reduction of mobile masses in order to diminish unbalancing moments on the human body;
4. to analyze the influence of a set of design parameters on the accuracy of force replication.

The design of the new Arm Exoskeleton exploits a kinematics similar to the one presented in Section 3 for the prototypical solution. However, several attachment points have been foreseen along the human arm; at present, it has been assumed that the replication of forces at the level of the arm-hand complex will be performed only at one of the possible locations, but, with the purchasing of low-cost force sensors, the control could be contemporarily extended to several points.

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Figure 9: Prototype of structural parts of the new Arm Exoskeleton (By courtesy of Ferrari S.p.A.)

In order to allow a lateral wearing of the FDD (for disable people this condition is fundamental) the joints of the arm rotation and forearm prono-supination have been designed by utilizing open circular guides with an angular encumbrance of 210° instead of 360° of common ball bearings. The open circular guides leave the necessary clearance for lateral insertion of the arm.

Structural parts will be analyzed with finite elements methods and built by exploiting composite material technologies: Fig.9 shows the first prototype of the motor case located on the back of the human operator; this prototype has been designed and realized by Ferrari S.p.A., Modena, Italy.

The actuation system has been carefully studied in order to reduce the total weight. Torque motors have been selected to obtain high torque/weight ratios. For the first 4 DOF the actuation system consists of the DC torque motor, the gear box with a transmission ratio of 5 and one resolver as rotation sensor. These 4 motors have been remotely located on the back of the operator, while the 3 motors corresponding to the last 3 distal joints have been integrated on the forearm structure close to the elbow joint.

The yardstick on which verify the performances in terms of force feedback has been devised as the accuracy of force replication. Our objective is to obtain an accuracy of 4% on the whole operative range (force, displacement, temperature). All the design parameters influencing accuracy will be analyzed (stiffness of the arm exoskeleton, backlash, transmission friction, resolution and accuracy of position and torque sensors at the joints, controller design). At present, since the arm exoskeleton structure presents several DOF, the analysis has been approached by assuming simplified hypotheses.

5 Conclusions

The work described in this paper has addressed the description of Force Display Devices developed at PERCRO of Scuola Superiore S.Anna, Pisa, Italy. The design of FDD has been approached by considering the requirements of natural manoeuvrability and fidelity in replicating forces that the interface system should possess in order to satisfy conditions of realism during the interaction with the virtual environment. A complete FDD system has been presented consisting of two serially connected FDD components: an Arm Exoskeleton system and a Hand Exoskeleton system. Results of preliminary tests related to the control of the interaction with virtual surfaces and to contour following procedures of virtual surfaces have been introduced. The design of a new Arm Exoskeleton has been preliminary presented by focusing on the innovative included features. Until now the approach to the design of FDD systems has been characterized by a great effort in terms of pragmatical work and pure drawings of mechanical solutions. However, on such a basis, PERCRO is now starting a new approach for the design of FDD which exploits analysis and methodological estimations of the foreseen solutions. We believe that a great amount of theoretical work can still be opened inside this research field.

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