Multimodal Interfaces: an Introduction to ENACTIVE systems

Massimo Bergamasco[†]

PERCRO, Scuola Superiore S.Anna, Pisa, ITALY

Abstract

Enactive Interfaces are related to a fundamental "interaction" concept which is not exploited by most of the existing human-computer interface technologies. The traditional interaction with the information mediated by a computer is mostly based on symbolic or iconic knowledge, and not on enactive knowledge. While in the symbolic way of learning knowledge is stored as words, mathematical symbols or other symbol systems, in the iconic stage knowledge is stored in the form of visual images, such as diagrams and illustrations that can accompany verbal information. On the other hand, enactive knowledge is a form of knowledge based on the active use of the hand for apprehension tasks.

Enactive knowledge is not simply multisensory mediated knowledge, but knowledge stored in the form of motor responses and acquired by the act of "doing". A typical example of enactive knowledge is constituted by the competence required by tasks such as typing, driving a car, dancing, playing a musical instrument, modelling objects from clay, which would be difficult to describe in an iconic or symbolic form. This type of knowledge transmission can be considered the most direct, in the sense that it is natural and intuitive, since it is based on the experience and on the perceptual responses to motor acts.

1. Introduction

Enactive Interfaces are related to a fundamental “interaction” concept which is not exploited by most of the existing human-computer interface technologies. As stated by the famous cognitive psychologist Jerome Bruner, the traditional interaction with the information mediated by a computer is mostly based on symbolic or iconic knowledge, and not on enactive knowledge. While in the symbolic way of learning knowledge is stored as words, mathematical symbols or other symbol systems, in the iconic stage knowledge is stored in the form of visual images, such as diagrams and illustrations that can accompany verbal information. On the other hand, enactive knowledge is a form of knowledge based on the active use of the hand for apprehension tasks.

Enactive knowledge is not simply multisensory mediated knowledge, but knowledge stored in the form of motor responses and acquired by the act of “doing”. A typical example of enactive knowledge is constituted by the competence required by tasks such as typing, driving a car, dancing, playing a musical instrument, modelling objects from clay, which would be difficult to describe in an iconic or symbolic form. This type of knowledge transmission can be considered the most direct, in the sense that it is natural and intuitive, since it is based on the experience and on the perceptual responses to motor acts.

Notwithstanding the wide literature available in exploring human computer interaction, enactive interaction is a rather unexplored mean of communication within the interaction capabilities between users and computers. The control processes based on the computer related to this kind of interaction would require not only faster computers and systems able to cope with more complex information, but also new kinds of interfaces, computing architectures and software modules able to work with the users at a more complex degree of information representation. A thorough understanding of the systems, mechanisms, algorithms and the representation forms related to this kind of interaction is funda-

---

[†] Coordinator of the EU ENACTIVE Network of Excellence

mental to develop the future generation of Şhuman mediated computer interactionŤ.

The proposed paradigm shift is probably of the same importance that the introduction of standard in graphical inputs during the 70s. At that time, the change in the role and the architecture of what was called, at that time "graphical inputs", transformed fundamentally the standard in Computer Graphics. Following this stage, the graphical inputs have been nested inside the graphic kernel systems and so doing, they became the foundations of contemporary interactivity concepts linking graphical icons and gestural inputs.

The recent introduction in the field of Virtual Environments and Robotics of haptic devices that strongly link actions and perceptions, as well as the enthusiasm that this caused in most of the IST-related research domains, indicates that the ENACTIVE community is trying to participate in a major change in the design of human-computer interfaces and, beyond, of human-computer and human-to-human communications. In the contemporary context of high degree of development that "action-iconic" interfaces drives, the concept of Enaction, is able to push further the first revolution of interactivity.

The driving concept of Enactive Interfaces is then the fundamental role of motor action for storing and acquiring knowledge (action driven interfaces). Enactive Interfaces are then capable of conveying and understanding gestures of the user, in order to provide an adequate response in perceptual terms. Enactive Interfaces can be considered a new step in the development of the human-computer interaction because they are characterised by a closed loop between the natural gestures of the user (efferent component of the system) and the perceptual modalities activated (afferent component). Enactive Interfaces can be conceived to exploit this direct loop and the capability of recognising complex gestures. Intelligent interfaces recognise the gesture of the user at the beginning of the action and are able to interpret the gestures (in terms of intentions, skills and competence) and to adapt to them in order to improve the users performance.

A prototypical existing example of what can be considered a preliminary Intelligent Enactive system is constituted by Reactive Interfaces, i.e. robots working always in contact with the human hand and capable of interpreting hand's movements and correct/guide them with the aim of skillfully performing manipulative tasks.

Enactive Interfaces are a rather unexplored field of research with a high degree of future potential impact. In order to co-ordinate the development activities have addressed the following three main sets of objectives: integration, research and dissemination.

2. Course Scheduling

The proposed tutorial will introduce the present developments in the fields of ENACTIVE systems, including: systems able to cope with more complex information, but also new kinds of interfaces, computing architectures and software modules able to work with the users at a more complex degree of information representation.

1. ENACTIVE Systems:
    - Introduction;
    - Components;
    - Architecture;
2. Haptic interfaces:
    - Introduction to haptic interfaces;
    - Chronological developments;
    - Principles of design and control;
    - Future trends of research.
3. Enactive interfaces: integration of haptics with vision and sound:
    - Technological and scientific aspects of multisensory integration between vision, action and sound.
4. Model of the user: kinematic and behavioural model of the user when interacting with Enactive interfaces.
5. Haptic rendering: control strategies for rendering the force on Enactive interfaces.
6. Physical base modelling: integration of physical models within VEs and their control by means of Enactive devices. Analysis of interaction techniques and numerical integration methods.
7. Trends, future and Applications of Enactive interfaces:
    - Art and cultural heritage;
    - Medicine and rehabilitation;
    - Education;
    - Engineering.
8. Final considerations

Haptic Interfaces

Massimo Bergamasco, Carlo Alberto Avizzano

PERCRO
Scuola Superiore S.Anna
Pisa, Italy

Abstract

The analysis of the behaviour of the human operator during the interaction with Virtual Environments requires the availability of adequate interface systems. In particular, when the control of manipulative and explorative procedures is required, all the movements of the hand should be recorded and tactile as well as contact force stimuli should be replicated at the level of the hand. In this paper we address the aspects related to the development of force feedback systems devoted to generate such stimuli with the aim to allow the human operator to obtain a realistic control of the operation. The peculiar roles of force feedback systems will be presented with direct reference to the grasping and explorative tasks. The general functionalities of force feedback systems are highlighted together with the description of the Haptic interfaces systems developed at the Scuola Superiore S.Anna. Tactile feedback is presented by considering the modelling of both thermal and indentation stimuli.

1. Introduction

In a paper of 1990, S. Lederman and R. Klatzky [1] considered procedures of haptic exploration of objects performed by the human "observer" with the aim of apprehension and recognition of object features. In the same paper *Haptics* was defined as "a perceptual system that uses both cutaneous (including thermal) and kinesthetic inputs to derive information about objects, their properties, and their spatial layout" [1] [2]. Lederman and Klatzky, by referring to the work made by J.J. Gibson in 1962 [3], clarify the importance of "the purposive aspect of haptics" in terms of the acquisition of information related to object's features with respect to the sensation resulting from passive stimulation of the skin performed by external means or devices. The same paper highlighted the correlation between the typical hand movement pattern related to a specific exploratory procedure and the particular object knowledge associated during the execution of the procedure [1]. Our interest in that paper was referred to the implications on the control of manipulative procedures during teleoperation where a human operator is asked to control movements and forces exerted on objects by a remote robotic system. The introduction of the concepts of *telepresence* and *virtual presence* stresses once more the importance of the capability for the human operator to extract realistic information about the features of the object remotely or virtually manipulated [4]. Conceptually, 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 stimuli to the operator. However the stimulation should be performed by leaving the human operator to execute the task according to a natural, realistic procedure. In this way the movement patterns, in particular of the arms and hands, should be maintained as close as possible to those associated to a real exploratory procedure. Coherency between the purposive aspect of the task, performed by the human operator with the intent to acquire information about a specific object's feature, and the operator's hand movements should be the key for haptic perception also in the case the object is remotely located or virtually represented. The possibility for the human operator to execute realistic movements and, at the same time, to achieve adequate sensory stimuli is then a fundamental requisite for achieving a 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 stimuli on them. As it comes out from the definition of Haptics given above, the basis for haptic perception is represented by *cutaneous* and *kinesthetic* inputs; when the human operator tries to execute an exploratory procedure of an object belonging to a virtual environment, the kinesthetic inputs that are presented to his/her perceptual systems are *real* kinesthetic information he/she achieves from the movements and postures of his/her hands. Kinesthetic inputs cannot be artificially generated: those utilized during exploratory procedures are those coming from the real proprioceptive system of the human operator. Adequate kinesthetic inputs should then derive from correct exploratory movements executed by the human operator. From this consideration it derives that when interacting with the virtual environment, the human operator, in order to have the correct kinesthetic inputs for haptic perception, should perform the correct movement patterns related to the specific features he/she wants to extract from the object during the exploratory procedure.

It derives that in order to achieve a realistic behaviour of the operator during the interaction with Virtual Environments, the design of haptic interface must consider both aspects of limb movement of tracking and faithful stimuli replication. If we consider manipulative procedures performed by the human operator without grasped tools in his/her hand, the design solution for haptic interface must refer to anthropomorphic systems. The present paper deals with design and control considerations on *anthropomorphic haptic interfaces*. Anthropomorphic haptic interfaces can be considered as a specific class of haptic devices. The main feature refers to their kinematics which is similar (sometimes identical) to the humen limb where forces have to be applied. Differences with desktop haptic interfaces will be described in terms of technical functionalities and performances in the following.

2. Technical and Functional Issues for Haptic Interfaces

2.1. Technical Specifications

The term **Degree of Freedom** of an haptic device should be carefully treated with reference to the number of contact points between the operator and the haptic interface. In the case of device which can be grasped or which present just one attach point, Millmann suggested a minimum of six degree of freedom which are suitable for almost all kind of tasks.

With reference to existing haptic devices, the real number of DOF largely varies depending on the nature of the interface and on the kind of task. Force feedback joysticks and mouses generally presents 2 or 3 degrees of freedom, while exoskeleton like interfaces which are a specific class of anthropomorphic haptic interfaces present up to 27 degrees of freedom.

The**Workspace** of an haptic interface greatly influences the number of tasks a user can perform with it. Small operation volumes usually reduce the operator fatigue while wide workspaces improve mobility into the environment. Large workspaces allow the user to easily reach a wider set of objects distributed into the environment. The workspace is generally calibrated with respect to the specific class of tasks the interface is designed for. A sheet like volume is indicative for mouse or pen like interfaces, while a larger workspace can be requested for full arm operations.

Technical	**Functional**	**Fit-to-Use**
Degree of Freedom	Dexterity	Design Complexity
Workspace	Single Hand	Cost
Maximum Force	Workload	Safety
Max Velocity	Fine Motion	Sizeability
Maximum Friction	Control Modes	Easy to use
Coupling Effects	Encumbrance	
Stiffness	Robustness	
Inertia		
Gravitational Balance		
Gain Ratios (Force/Position) and backriveability		
Positional Bandwidth		
Force Bandwidth		
Backlash		

Table 1: *Issues for haptic interface design*

The **Maximum Force** is influencing the range of contacts which could be displayed by means of an interface. Larger peak values will require bigger motorization and usually compromise other system performances such as bandwidth, backdriveability, cost. The Maximum force design is a classical minimax problem. The engineer should carefully evaluate the maximum force the VE is required to replicate and then satisfy this constraint with the minimal motorization. The human operator, the task and the user movements should be kept into consideration during this phase. The output force of the system should always be matched on the capabilities of the human operator.

The **Maximum Velocity** should ensure that the system could be capable of moving at a speed that will not frustrate the operator. An essential environment issue, for achieving a good sense of presence, is that the user can move in the same manner he usually moves in the real environment. Typical velocities are estimated in about 1m/s for the maximum velocity, 1g for the maximum acceleration.

All devices should be designed in order to show the lowest friction it is possible. The **Maximum Friction** parameter can be considered as indicative of the design quality. High friction values decrease the interface admittance resulting in a general degradation of the displayable-force resolution and in the increase of the force thresholds (force required to the contact for a movement).

Small motors, direct-drive based design, low transmission ratios and simple design help to keep the global friction small.

Coupling Effects generally arises when unwanted motions, principally due to static reaction forces and the kinematic arrangement of the haptic interface, alter the movement the user is trying to perform. This is particularly evident when the user is attempting to execute some kind of fine adjustment motions. Coupling may be static or dynamic, compensation techniques and feed-forward compensation of the manipulator dynamics help to keep down this parameter.

All mechanical structures are subjected to deflections. The deflection, under static external disturbances is a function of the haptic interface compliance, the drive compliance, the servo system compliance and the transmission compliance. This sort of interface **stiffness** can degrade sensations when trying to simulate the contact/interaction with some “hard” (low admittance) virtual object. Haptic interface stiffness, cannot be measured or corrected by means of control software and consequently should be kept as low as the task and the interface scope require.

When developing a system for a human operator, some maximum values for the minimum interface stiffness can be given. In fact, operator senses cannot distinguish between contacts with very “hard” objects (such as wood or steel) in terms of stiffness since the operator’s skeleton/tendons structure is much less stiffer than the objects. Consequently, depending on the kind of haptic interface, some maximum reference value can be established. These values can be furthermore reduced if in the virtual environment no such stiff object has to be reproduced.

A rule of thumb for the minimum stiffness of the HI equals to the minimum between the human stiffness and the VE-objects maximum stiffness.

The **Inertia** should be kept as low as possible for the interface design. Inertia lowers the admittance of the interface. Devices capable of high endpoint admittance provide the operator with more sensitivity at low force levels. During an experimental session two different kinds of inertia can be felt from the operator: the virtual-object inertia (which is programmed by the control law) and the interface inertia. In most common control schemes, the inertia loads are not canceled by the system. The suppression of the inertia factor by means of feedback control is truly hard. This operation required the information about the interface acceleration available into the environment. Since the interfaces generally provide data about position, acceleration can be only derived by means of double derivation which introduces noise and consequently errors in the computation. The detailed analysis on the influence of derivation errors on the inertia’s compensation was carried out by Adelstein in 1989. He concluded that a good compensation is not always feasible with the available control hardware for haptic interfaces.

The inertia factor, the **Gravitational Effects** of the manipulator should be counterbalanced whenever it is possible. Even if it is feasible to provide control signal to cancel these effects with motors, this operation will require that motors operate with unbalanced load and therefore a powerful set of motors which should be able not only to reproduce the desired force at contact but also to cancel the additional gravity forces caused by mass umbalancing. Whenever a detailed design could improve the system balance, the overall performances improves since proper motors and transmission can be chosen for the system.

A particular care should be given to the effective **gain ratio** to be adopted during the interface design. Higher ratios imply that the interface movements are largely reduced in comparison to the motor movements that caused them. Increasing such transmission ratio will help to improve the manipulator precision and to diminish the mass effect due to manipulator dynamic as seen on the motor shafts.

As Townsend and Salisbury explained [12,13] increasing the overall gain ratio of the manipulator transmission does not produce positive effects on haptic interfaces. This can be seen if we imagine the haptic mechanics as a two-ports units which maps forces and positions the motor produces onto positions and forces the operator displays. In fact, in the case of an ideal manipulator (Zero mass, no friction, perfectly rigid links and joints with no compliance due to structure or transmission), the functional rules of this block can be expressed as:

$$M\delta\omega = F\delta P$$

where we imagined a simplified structure where all rotational motors produced a vector M of torques to which corresponds a vector $\delta\omega$ of movements. The expression above represents the principle of “Virtual Work” for a non dissipative mechanism. When we apply a gain ratio between $\delta\omega$ and δP such as $\delta\omega = K\delta P$ we obtain that $F = KM$. Recalling that the mechanism is just a two ports device, the above relation states that improving accuracy in positioning of the motors and their maximum forces reduced at the haptic contact will cause a degeneration in the force and position sensitivity of the control.

If we reconsider the effects due to friction, compliance and inertia masses belonging to the system, it is easy to understand that an interface which has higher gain ratios can be hardly moved from the operator. This property is known as **backdriveability**.

Even if the use of feedback control can help in making a non backdrivable system a backdrivable one, the haptic interface should be designed in order to make the interface backdriveable since only a marginal correction (non satisfactory for haptic interactions) can be achieved in this way [14].

The **Positional Bandwidth** indicates the maximum bandwidth of the position which can be imposed to the interface without compromising the haptic mechanism. It is quite important to specify the amplitude of the input signal at which the bandwidth is estimated. The minimal required bandwidth is depending on the particular task the haptic interface is used for. A very large analysis in this sense was made by Brooks [15].

Many results, coming from teleoperation research, evidenced that in case of closed loop (i.e. with the force feedback activated in the control loop) the required bandwidth may be largely dependent on the operator posture and the working load.

The suggested bandwidth when no payload is considered ranges between 10-30Hz depending on the author and it can be considered as equivalent to the positional bandwidth required to an haptic interface.

The **Force Bandwidth** that a person can feel is higher than the frequency range he can exert with his motor system. Just for example the tactile system sensors of the human hand can feel surface vibrations far beyond 100Hz while it is proved that his motor bandwidth is far below 40Hz. Just like for the positional bandwidth it is important to point out the amplitude at which a certain force bandwidth is required.

As shown by Brooks and others, the human control loop is asymmetric. His force/positional sensitivity is higher than his capability of movements and, even if the bandwidth of the exerted forces and position is quite narrow, the design of an haptic interface should require much more powerful capabilities otherwise instability may arise in the control loops.

2.2. Functional Issues

Dexterity is defined as the capability of the interface of satisfying all the movements required by the user for the specified task and giving out feedback forces as expected by the user. Joint clashes, limits, singularities, non-uniform manipulation ellipsoids are all sources for a reduced dexterity system. The system dexterity maps differently on several design factors such as transmission routing, motor types, collocation and so on. Dexterity may be quantified in terms of available workspace and manipulability but rarely maps into a unique design factor.

An important issue for an haptic interface is its capability of achieving and generating as more feedback information as possible from and to the user. It is desirable to reach the situation where a **single hand** could control an avatar in the virtual environment without requiring the introduction of auxiliary or complex procedures.

The complexity of the haptic design allows more user friendly interfaces which can exchange more information with the operator.

Accuracy in virtual environments is both related to the control strategy which maps real movements in differently scaled virtual positions and to the mechanical design. Since haptic interfaces are almost different each other, no general types of tests do exist for measuring accuracy and comparing devices.

The operator **Workload** measures the interface performances both in term of physical than mental and visual loading. All interfaces require in fact some efforts to be exerted by the operator for adapting himself to the virtual context. When a high workload is present, operators show to be fatigued by interface driving. The more intuitive the motions of the interface are, the lower is the workload for the operator.

Haptic interfaces can be used for several kinds of operation: as exploring tool they should be able to display forces to the user, in teaching systems they should be able both to learn movements and to replicate them…the functionality of an haptic interface can be measured from the **number of control** types the interface can support. This issue can be translated in term of technical specification in a mix of sensors/actuators which allow all the necessary actions of the mechanical device.

Finally **Encumbrance** and **Robustness** are the key factors which can determine the effective usability for the system. Encumbrance should be evaluated in respect to the environment the interface operates and should be reduced such that the interface does not interfere with operator movements and with the real objects. Robustness should guarantee that the interface works without any malfunction even in presence of an unproper operating input exerted by the user. Haptic interfaces are in direct contact with the human being so that no assumption on the correct operating can be made “a-priori”.

2.3. Operation Issues

In terms or **design complexity** it is very difficult to produce simple and efficient interfaces. This is primarily due to the design decisions kept in order to render the interface backdriveable. In complex designs too many chains, links or pulleys are present. This makes the design less attractive for the task and let the interface to look as fragile.

Costs influence the effective exploitation of the interface on a commercial basis. This is a very crucial factor in the

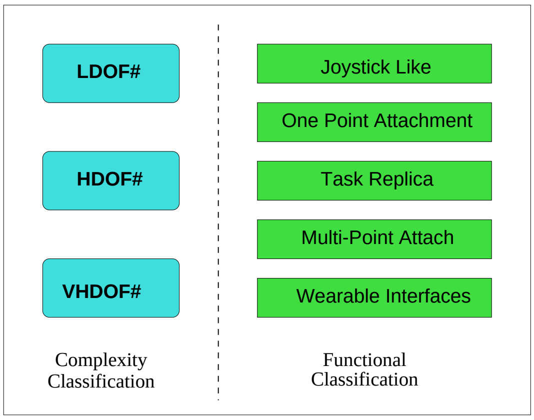


Figure 1: *HI Classifications*

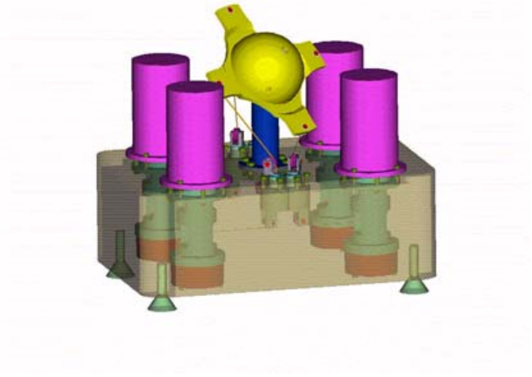


Figure 2: *A 3DOF (LDOF# Joystick) designed at PERCRO*

field of haptic interfaces. Only recently some simple force feedback joysticks have been introduced in the game and entertainment market due to the reduction of costs of the technology.

Safety is the primary rule to follow when producing a robot which interacts with human. Even if the user drives the interface not properly, the haptic interface shall always be safe for the operator. This should be done by providing a careful design which is not only robust, but also capable of detecting that the interface is properly working and to provide emergency buttons for making the system unoffensive.

Most of the existing haptic interface have been designed for a standard user, but, just like dresses, they should be designed on the size of the user they are dedicated for. In wearable haptic interfaces such as arm exoskeleton and gloves mechanism should be present for sizing correctly on the user. **Sizeability** should be pursued whenever it does not complicate too much the mechanical design.

Easiness is the interface property of being driven by commands which are intuitive or easy to be learned by the operator. Easy interface requires load learning times and offer a better presence sense since they does not compel the operator to work in an unnatural manner.

3. Classification of the haptics

A first classification for the haptic interfaces was presented by Vincent Hayward in. The Hayward classification distinguishes haptics interfaces on the basis of the design complexity in terms of Degree of Freedom of the interface. He defined three big classes:

- Low DOF Devices (LDOF#);
- High DOF Devices (HDOF#);
- Very High DOF Devices (VHDOF#);

A **Low DOF Devices** is an interface which presents few degree of freedom. The LDOF# does not attempt to address the literal emulation of a task or of a sensation which would occur during some kind of virtual experience.

It has been found that for example 2 or 3 controlled mechanical freedoms could provide the operator with a sufficient impressive information capable or realizing a "metaphor" sufficiently suggestive for leading to an high level of usefulness. The combined use of several LDOF# tools can lead to a richer set of metaphors.

The figure 2 represents the case of a simple three DOFs joystick interface realized at PERCRO laboratory. The interface possesses X, Y, Z rotational DOF and can exert force feedback along these axes. It has been conceived for desktop operation such as "Virtual Prototyping", testing and access for disabled patient.

High DOF Devices attempt to recreate the task force information as they were produced inside the environments. Under this category we find all devices which have been designed around an hand-held manipulandum and applying arbitrary forces and torques. In fact, in this case the interface should be designed with at least 6 DOFs for allowing to the user a complete freedom of operation. The HDOF# have at least 6 DOFs.

Figure 3 is a 6DOF Joystick. Using such a Joystick, which has been designed for a 400mm-edge cubic workspace, the user has the possibility of feeling forces inside the workspace with an high degree of fidelity. The adoption of the parallel kinematics structure helps to improve forces and backdriveability while preserving all required degrees of motion.

Very High DOF devices are those interfaces whose number of DOFs is greater than six. VHDOF# interfaces are generally used for realizing extremely complex interactions. The motivation for such a type of interfaces can be found in the application which presents a complex kinematical structure or in contextes which require the presence of many haptic feedbacks. The PERCRO Hand EXOS and the Arm EXOSkeletons represented in figure 4 are an example of

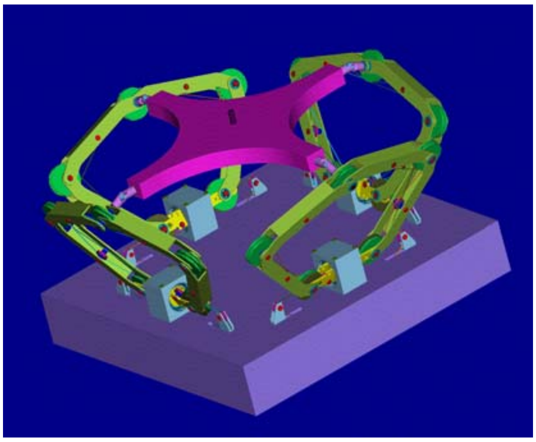


Figure 3: *A 6DOF (HDOF# Joystick) realized at PERCRO*

VHDOF# devices. These interface present up to 26 DOFs with an active force feedback on 15 (or 21 depending on the configuration) DOFs.

Other types of haptic interfaces may have a large number of DOF which are not concentrated on an unique part of the body but distributed along it. Some cases of vehicle simulators, (for example the MORIS a motorbike simulator) may have a large number of DOF (not all intended to reproduce haptic stimuli) distributed all over the system for reproducing force information on several body parts (actuated brakes, steer, gear,. . .). In this case the system cannot be split into several HDOF# or LDOF# interfaces since all feedbacks are correlated each other.

As shown before haptic applications and rendering techniques may largely vary depending on the number of DOFs the interfaces have. Here it is presented another classification for the HIs which is based on the nature of the contact and, consequently, to the rendering techniques which are allowed with the relative class.

- Joystick like devices (LDOF#);
- One point attached devices (LDOF# or HDOF#);
- Task replica devices (LDOF# or HDOF#);
- Multi point attached devices (HDOF# or VHDOF#);
- Wearable interfaces (VHDOF#).

Joystick like interfaces have easy kinematics and can behave excellent mechanical properties in terms of impedance, force peak display, bandwidth encumbrance. . . their design is relatively simple and they can be produced at low costs.

Force feedback joysticks represent the simplest class of HIs but their use is greatly reduced due to the relative limitation of movement, workspace and kinematics which are generally poor. Joysticks usually exploit 2 or 3 degrees of mechanical freedoms. Consequently the force information which can be transmitted by means of these interfaces is limited to a couple (or a triad) of torques.

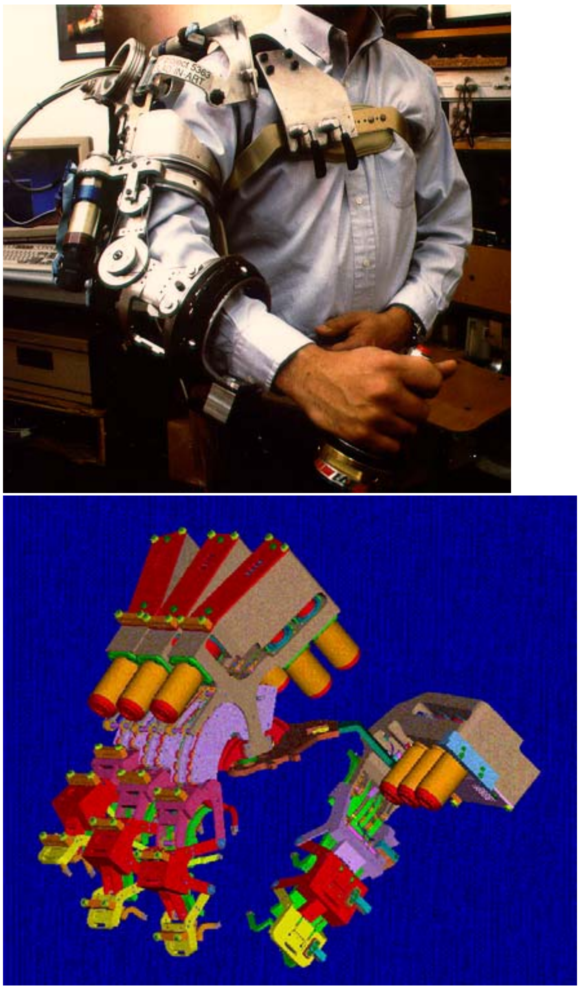


Figure 4: *The EXOSkeleton (up) and the Hand Exos (down) realized at PERCRO*

In force-feedback joysticks the command is forwarded to the system acting on the stick by changing it slope. It is very usual to associate to the stick slope a sort of movement information inside of the virtual space. This association, which is not completely natural, has been named as metaphoric paradigm of interaction. In the metaphoric paradigm, space movement information such as the impossibility of reaching some point due to a collision are forwarded to the user by a proper force feedback. The essence of this force feedback which is not directly related to the effective collision since no 1:1 relation between the position/events in the virtual and in the real space exists, characterize the metaphoric communication.

One point attached haptics are LDOF# or HDOF# devices that interacts with humans by means of 1 haptic contact. Since they have no constraints in the contact with hu-

Figure 5: *The MORIS simulator*

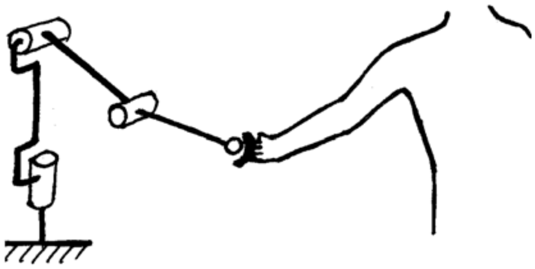


Figure 6: *A scheme of one point attached device*

mans other than those imposed from the contact, they can generally be optimized in design for high performances. One point attached interface are generally external to the operators.

The most common one point attached device for haptic rendering is the PHaNToM interface [16]. The nature of the force that can be exchanged in such type of devices make them well suited for simple VE applications in which the user needs to explore the environment by means of simple probing.

Since the one point attach can render forces as they were produced in one "virtual space", point they are usually employed for rendering surface profiles or the objects consistency (stiffness).

Some haptic devices have special end-tools attached to their extremity. These end-tools can be shaped as generic handles as well as a copy of a specific instrument. We named these kind of interfaces **Task Replica**. The design complexity of task replica devices may be different depending on the kind of task they try to replicate. For writing (See figure 3) two or three active force feedback information are needed while the remaining movement are left free (This kind of system required at least five DOFs for allowing completely writing related movements).

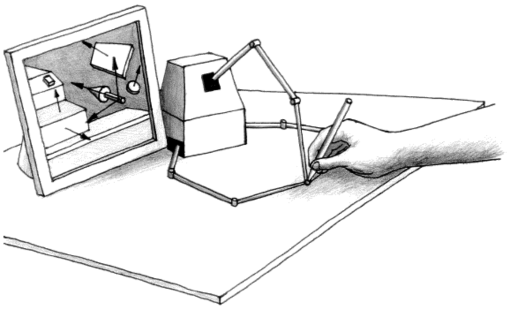


Figure 7: *A task replica example: an haptic interface for writing and virtual prototyping in course of development at PERCRO*

Even if task replica interface can be less complex than HDOF# or VHDOF#, they allow the user to share a complex experience with the system limited to the field of application the interface has been developed for.

Since the task replica devices are specifically designed for a task, they can be optimized with respect to that task and their design can be made simpler that is requested for HDOF# or VHDOF#.

A **Multipoint Attached** interface shares more than one contact with the operator. Multipoint attached are designed for sharing complex experience such as manipulation of objects. With respect to the other types of HIs, the multipoint attach interfaces show much more design constraints on mechanical development and control synthesis:

- from a mechanical point of view since this kind of interfaces is "strictly" connected to the operator it is no more conceivable the "separation of the links working spaces". This design concept is usually adopted in the case of simple LDOF#/HDOF# devices for improving user safety during the motion of the mechanical device: haptic interface and operator shares only the contact point or tool, but their "bodies" moves in separate spaces such that the collision problems between structures are always avoided.
  Multi point attach interfaces should be designed according to the kinematic structure of the operator and their mechanism should move in such a way of not interfering with the operator movements. This physical constraint is truly hard and often compels developers to complex designs in order to ensure safety of operations;

- from a control point of view when more than one interacting point are taken into consideration, interferences could exist between the forces exchanged in the different contact points. The contact forces generated along one haptic contact can be forwarded into the "Virtual Reality" up to the other contact points. Interference between the attaching points can arise:
    - in terms of coupled-impedance of the contact, the forces applied on a contact can be felt on another contact by means of a physical propagation of the stimulus;
    - in terms of virtual coupling, the forces exchanged at the contact point and measured by sensors can be modeled and propagated in the virtual environment up to another contact where they can produce undesired effects,

  in both cases the control rules should be designed in order to take care of these effects and to provide overall stability. The control algorithms should take care of these relations and avoid all stability problems which could arise when the user is experimenting this feeling.

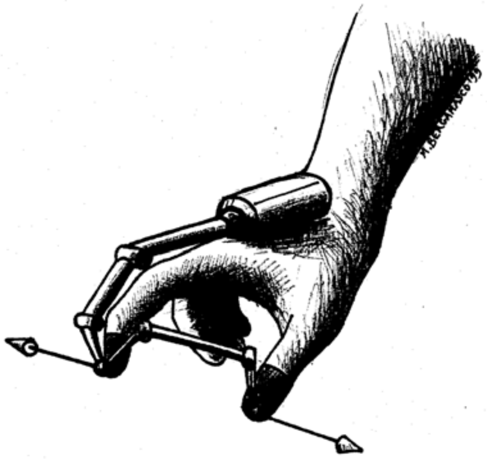


Figure 8: *An example of multipoint attach interface: the concept of PERCRO pincher*

The **Wearable Interfaces** are exoskeleton like interface. They usually present themselves as a kind of VHDOF# multipoint attach interfaces, but their synthesis is much more complicated in terms of mechanics and control. The number of constraints they are subjected is increased due to wearability and safety problems. They should be sizeable, light, easy to fit,…from a control point of view much more complex experience can be shared with these interfaces.

Since this type of interfaces can be worn on the human body they implicitly can figure out the correct posture of the operator and can produce in the virtual environment a more detailed imagine of the operator with respect to other types of interfaces. The environment is consequently capable of fully determining all kinds of contacts between the operator body and the objects which are present in the virtual space. As shown in figure 3 the haptic experience can interest not only the object the user is trying to manipulate but also all other external objects which can constraint the movement.

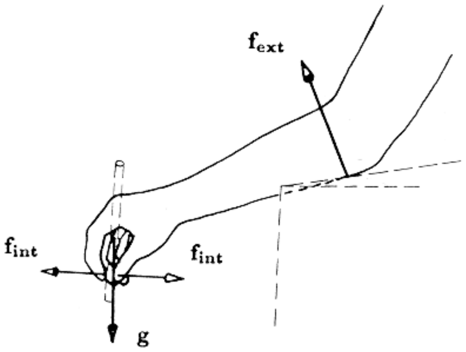


Figure 9: *Wearable interfaces make complex haptic experiences renderable*

4. Force Modelling

Once all contact points have been successfully determined by a collision detection algorythm, the collision response should provide the following steps:

- synthesis of the contact forces for the avatar;
- mapping the forces felt by the avatar onto the contact points with the human by means of torques/forces exerted on the display joints;
- providing the necessary interface joint controls.

4.1. Synthesis of the contact forces

The contact forces are usually generated as a simplified model of the complex contact phenomena. In a first phase, the detailed geometry of the contact is neglected and replaced with a simple description of the Downarrowcontact. For each contact point the operator is modeled by just one collision point c to which a relative inter-penetration with a virtual body is associated. The inter-penetration can be summarized as a vector $\mathbf{d}$ whose versus is orthogonal to the contact surfaces and whose modulus represents the distance from the contact point to the surface.

The contact between the operator and the virtual object generates a reaction forces $\mathbf{F}_{react}$ which is present only in the case of a real contact. If we suppose that the objects in

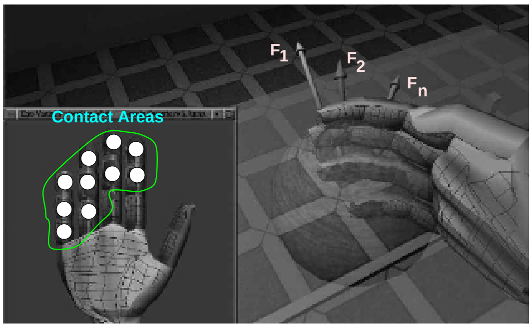


Figure 10: *The contact areas (bottom left) identified in a case of CD and the relative reaction forces.*

contact have their own stiffness, the proper formulation for the contact force is the following:

$$\mathbf{F}_{react} = \begin{cases} -K\,d & \text{at contact} \\ 0 & \text{otherwise} \end{cases} \qquad (1)$$

The above relation supposes that all objects in the virtual space are elastic and that the force exerted during a contact causes a virtual deformation of the object which is proportional (Hook's law) to the contact force itself. Even if the deformation is not graphically represented in most cases, the contact force with the object surfaces is computed proportional to the amount of penetration between objects (See [17]).

Even is this model exactly represents the relative natural phenomena, due to the non dissipative properties of this contact, numerical approximation, errors on force feedback and delays in computation usually make this model unstable at contact and contour following.

For this reason the virtual model usually add to the contact a dissipative component in the form of a viscosity factor which generates forces opposed to velocity, according to the equation:

$$\mathbf{F}_{react} = \begin{cases} -K\,d + B\,v_{op} \cdot \frac{\mathbf{d}}{|\mathbf{d}|} & \text{at contact} \\ 0 & \text{otherwise} \end{cases} \qquad (2)$$

Where the viscosity factor B should be kept as low as possible accordingly with the overall contact stability. Similar models have been used by several researchers who agree in affirming that the introduction of a dissipative factor helps to realize a good quality (stable) feedback.

Colgate [18] verified the influence of such a factor when a sampled-data based system is adopted for the control. He verified that the ranges the dissipative factor should have in order to make the whole virtual system resembling passive (and consequently stable) at human interface.

4.2. Stability and object dynamics in case of multiple contacts

The same dissipative concept can be adopted if a multipoint attached or a wearable interface is used by the operator. The interaction can be modelled by means of a dissipative matrix which contributes to improve the phase margins of the systems. The viscosity force (proportional to the position first derivative) acts with a counterclockwise rotation on the Nyquist plane and therefore improves margins.

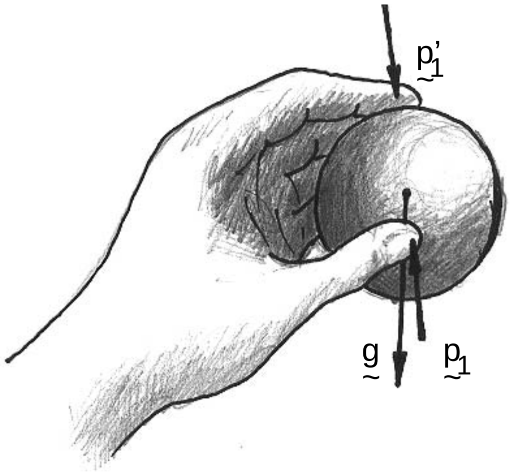


Figure 11: *Contact Forces between the avatar (virtual hand) and the virtual object*

In the case of multiple contacts between the operator and a virtual object, it is necessary to solve the dynamic equations which determine the environment dynamics. The solution of such equation requires the solving for the friction forces.

This issue has been investigated by several authors and a wide set of solutions has been found. The existence and uniqueness of the result is provided and algorithms are available for implementing the proper collision response.

We will illustrate the bases on which this computation can be made. Suppose in a first step only to consider contacts with fixed bodies. In this case we proceed to determine the normal component of the contact forces the user is exerting. This can be done in the same manner we have seen before, by modeling each contact with an associated stiffness.

Once the forces are known for each contact point i, we will form the following set of data:

$$(F_i, P_i, r_{xi}, r_{yi}, d_i)$$

where, F_i is the normal estimated force, P_i is the contact point spatial position and (r_{xi}, r_{yi}, d_i) is a spatial frame xyz having the z axis along the contact normal.

In the statical case (object can be hold) the contact force are the solution of this constrained problem:

$$\begin{cases} \sum(P_i \times F_i + P_i \times r_{xi} + P_i \times r_{yi}) = 0 \\ \sum(F_i + r_{xi} + r_{yi}) = 0 \\ r_{xi}^2 + r_{yi}^2 < \mu^2 F_i^2 \end{cases} \tag{3}$$

where μ is the friction factor. In case of movement we have:

$$\begin{cases} M\ddot{x}_b = \sum(F_i + r_{xi} + r_{yi}) \\ I\dot{\omega}_b = \sum(P_i \times F_i + P_i \times r_{xi} + P_i \times r_{yi}) \\ r_{xi}^2 + r_{yi}^2 < \mu^2 F_i^2 \end{cases} \tag{4}$$

Where P_i represent the contact point coordinates expressed with reference to the object center of mass, x_b represents the object center of mass position with reference to an inertial frame and ω_b represents the object angular velocity with reference to an inertial frame.

Frictional reaction forces, which belong to a cone, are often replaced with a pyramidal approximation such that the non linear constraint:

$$r_{xi}^2 + r_{yi}^2 < \mu^2 F_i^2$$

can be replaced with the set of linearities:

$$\begin{cases} r_{xi} < \mu F_i \\ r_{yi} < \mu F_i \end{cases} \tag{5}$$

The deficiency occurring in this approximation is that during slide motions the force feedback is not exactly opposed to the direction of sliding. Despite this deficiency the pyramidal approximation introduce enormous benefits in the contact computation by significantly simplifying the contact model.

The replacement of the exact Coulomb friction law with the pyramidal approximation allows us to reformulate the contact problem by replacing all non-linearities. Examples on about the detailed solution of the 4 can achieve are reported in the reference.

4.3. Creating the haptic Rendering

Once all forces generated into the virtual environment and felt by the avatar have been determined, it is necessary to translate them into physical forces to be presented to the display operator.

This rendering phase translates forces generated into the virtual environment onto real forces that can be reproduced by the interface and defines the mapping procedure for achieving these results.

Not all the forces can be reproduced by means of the haptic interface. In an haptic device we have two types of limitations connected with the haptic contact:

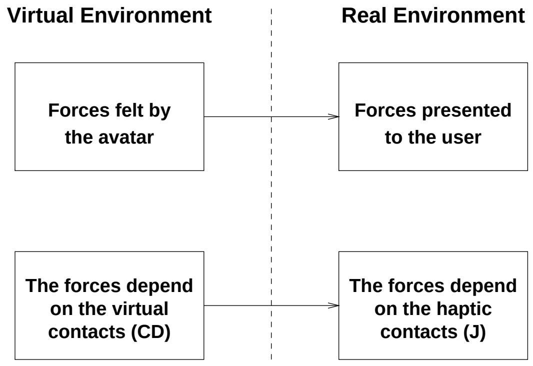


Figure 12: *Forces generated into the VE should be mapped into forces on the haptic display*

1. the limitations due to the nature of the haptic contact;
2. the limitations due to the kinematic of the interface at the contact.

The contact between the operator and the interface can be realized according to different solutions. It is not our interest to examine here all types of techniques for ensuring contact, we limit our discussion by evidencing that not all contacts can allow forces and torque to be transmitted along all directions (6 DOF contacts). In some cases (string contacts, rings,. . .) forces or torque cannot be exerted along particular directions.

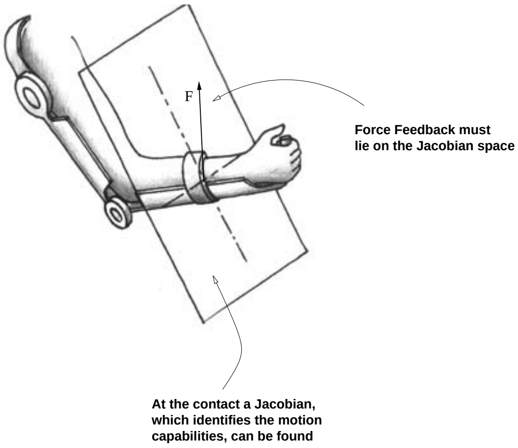


Figure 13: *haptic contacts constraint the force replication. Force feedback must lie on the contact-jacobian image*

As shown in Figure 13 the force can be transmitted to the operator only along the direction the haptic contact allows.

Once the haptic contact has been satisfactorily ensured the quality of the haptic feedback is moreover limited by the interface kinematic at the contact point.

If we computed the manipulator Jacobian matrix J_c at the contact point, c we know that all the forces which are exertable (F_{set}) belong to the vector subspace generated by the columns of J_c:

$$F_{set} = Im(J_c)$$

The forces outside F_{set} are “controlled” by the joint reaction-forces. They cannot be programmed or controlled from the virtual environment and are outside of the interface-mobility space. In such directions the control is completely left to the operator. The force feedback information produced are such that they cancel the user efforts in order to produce no movements along that directions.

The following result due to the force mapping can be fixed:

1. not all forces can be replicated by means of the haptic contacts;
2. when the rank of the Jacobian matrix is equal to 6, the force feedback presented to the operator can be an approximation of the virtual force computed into the VE. For example with reference to figure 14 the force $textbfF$ is not exactly reproducible.

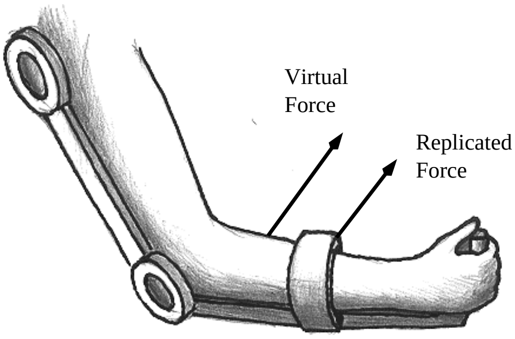


Figure 14: *Not all forces are exactly reproducible*

If we decompose the force components along the two orthogonal spaces: $F_b \in Im(J_c)$ and $F_a \in Im(J_c)^{\dagger}$ only the F_b component can be reproduced by the contact. Let consider the force mapping rule which determines the effective component at joints (see next paragraph):

$$M_j = -J_c^T F = -J_c^T (F_a + F_b) = -J_c^T F_b$$

3. the cases in which an approximation is present can be distinguished into:
   - kinematic singularities due to the posture. Such kind of singularities are generally avoided when designing an exoskeletric structure;
   - due to the mechanical structure (DOF at the contact $<$ 6).

4.4. Mapping Forces into Contacts

In virtual environment forces can be generated between any couple of movable objects. With reference to the virtual representation of the operator body, the contact point usually does not match with the correspondent points of the haptic contacts except that in the case of a simple interaction context (one point attachment and metaphoric interfaces).

The strategy of generating force on the operator hand should consider that the system can never exactly replicate the avatar sensations whenever they have been generated by forces applied in points which are different from the haptic contacts.

In these cases the mapping strategy will introduce an error of replication.

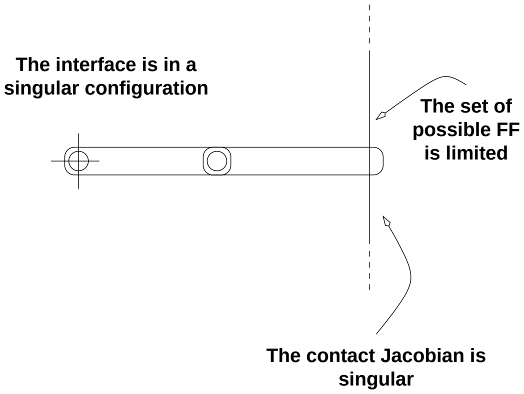


Figure 15: *Singularity position in the interface can reduce the set of replicable and controllable forces*

When the contact force should be applicated exactly on the mechanical contact between the operator and the interface, if no contact singularities are present, the required force at joints can be computed as:

$$M = -J_c^T F_c$$

which produces on the contact the exact reaction force, in fact multiplying both sides by a small joint-angular change, we obtain:

$$\delta\omega M = \delta L = -\delta\omega J_c F_c = -\delta x F_c = L$$

that satisfies the virtual work principle for the reaction force.

When the contact force is generated outside the haptic contact (C) of the operator with the mechanical interface, in an external point (A) there are two different strategies for computing the proper contribution to the motors:

1. the simplest strategy does not take care of the contact constraints and assumes that the attachment rigidly holds the link by allowing the force and torque exchange along

all directions. In this case we can determine the proper torque as an additive attach point is placed where the contact force is applied (see figure 16). This operation applies at the contact a force $F_c = (J_c^T J_c)^{-1} J_c J_a^T F_a$.

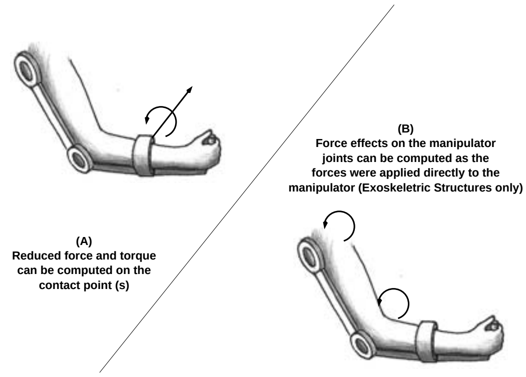


Figure 16: *Forces can be Mapped in two Different Ways*

2. alternatively it is possible translating the contact forces reducing them to the contact point. $F_c = F_a + \vec{F_a}(A - C)$.

The present paper analyses the design methods and choices which have been required to implement the concept of anthropomorphic haptic interface for the human arm.

Several studies in the field of haptics focus on determining the requirements for master arms and force feedback haptic interfaces; others focus on quantitative measurements of their performance.

On the contrary, when coming to the problem of designing haptic interfaces, most of the analyses available at the state of the art are, unfortunately, of little use. In fact, even if the optimal device performance is known in advance (and we believe the state of the art has not reached this point yet), an aware design process requires to put in quantitative relation the design alternatives with the final performance. As a consequence, models representing a suitable abstraction of the system, models specifically intended to evaluate each design alternative, must be developed and implemented. Often their predictions need to be validated experimentally on simplified hardware setups.

5. State of the Art

There are several arm masters designed to provide force feedback from a virtual environment. A small set of very different devices can be identified by the common idea of resembling in their design the kinematics of the human arm. It is interesting to review the approaches underlying the design of the SARCOS Dextrous Arm Master and the FREFLEX Master, which can be both regarded as attempts towards a no compromise solution to feedback forces on the human arm.

The SARCOS Dextrous Arm Master, by SARCOS Co., is composed of a 7 d.o.f. arm and of a 3 d.o.f. hand. The kinematic chain of the arm has three perpendicular, intersecting d.o.f. forming a shoulder, then an elbow joint and, at the end, a spherical wrist. The joints ranges of movement are 180° at the shoulder, 105° at the elbow, $105^\circ \times 180^\circ \times 100^\circ$ at the wrist. The SARCOS Master shoulder is positioned close to the operator shoulder; during operation, the elbow and the wrist of the device remain only approximatively next to the human arm. Hydraulic actuators, equipped with servo valves and potentiometers, are used for joint level position control. The force exchanged with the user hand is measured with load cells. The hydraulic pipes and electric wiring are routed inside the links. The maximum torque available at the joints ranges from 98 Nm, at the shoulder, to 22 Nm, at the wrist.

The FREFLEX (Force REFLecting EXoskeleton), developed by Odetics Co. for the Wright-Patterson Air Force Base, is an electrically actuated, seven d.o.f. device, whose kinematics is similar to that of the SARCOS Master. Direct current servomotors are located on the ground and the joints are driven by bidirectional cable transmissions. Each transmission cable is routed over idlers to reach the joint. The axes of the idlers and of the joints are designed to be either perpendicular or parallel to each other. Gearboxes are present at the motors. The maximum exertable force at handgrip is 25 N.

5.1. Anthropomorphic Devices

Human joints are not lower-pair joints but are composed of non-conforming smooth surfaces that are constrained in their motion by elastic ligaments and compliant tissues. Even just the kinematic simulation of such mechanisms is mathematically quite complex. On the other side, mechanics is, at present, mainly confined to the construction of mechanisms with lower-pair joints. Moreover in robotics, there is undoubtedly a preference for the usage of pure rotary joints which, for several reasons, guarantee a better performance in motion control with respect to translational ones.

These considerations led to the chioce of building an anthropomorphic haptic interface with a kinematics composed of seven rotary joints, which approximates the kinematics of the arm of the operator (see Figure 5.1). The first three joints are intersecting in a point in the operator shoulder and account for the shoulder adduction/abduction movement, the shoulder flexion/extension movement and the arm rotation. The fourth joint is associated to the elbow flexion/extension; the fifth to the forearm pronation/supination movement. The third, fourth and fifth joint axes intersect in a point in the operator elbow. The two last joints account for the wrist abduction/adduction and wrist flexion/extension. In order to better approximate the wrist movements these two axes are some millimeters apart.

An anthropomorphic design, which is "coincident" with

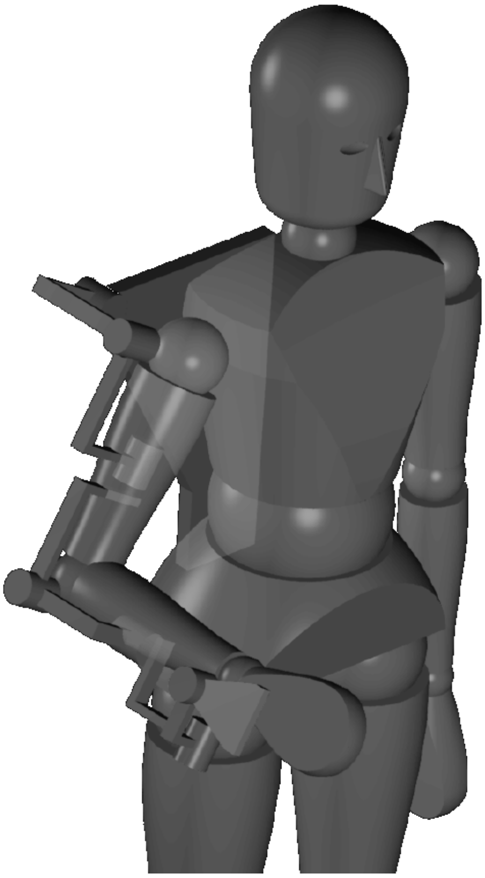


Figure 17: *Anthropomorphic kinematics*

the human kinematics in the sense just specified, offers several advantages and peculiarities which are discussed in the following. It is worth noticing that, in this sense, the SARCOS and the FREFLEX devices are not really anthropomorphic.

5.2. Device-Body Interface

Matching the kinematics of the haptic interface to that of the human makes the arm, forearm and palm links of the device always integral with the respective human arm links. It becomes then possible to have three points of attachment between the device and the human arm, using fixtures positioned at the center of the arm, forearm and palm. In other words, the interface braces the whole arm of the user letting his fingers free. In this way, by adopting an appropriate control strategy, the interface can exert forces on the three main segments of the user arm.

5.3. Monitoring of User Body Posture

The measurements of joint rotation angles of an anthropomorphic interface offer an estimation of the posture of the whole user arm; such estimation is coherent with the approximated kinematic model chosen for the human arm. The ability to record the whole human arm posture, instead of recording just the hand position, has several advantages both for teleoperation applications and virtual environments. In teleoperators, the operator can control not only the slave "end-effector" position but also its posture, especially the elbow position which in many arm manipulators is not uniquely determined by the end effector position. In Virtual Environment applications, the monitoring of the human arm posture is necessary to represent the artificial body of the user in the VE.

5.4. Set of Reproducible Forces

An anthropomorphic haptic interface for the arm with the kinematics depicted in Figure 5.1 can exert forces applied on the arm, forearm and hand of the user. An arbitrary wrench can be applied by the interface on the user palm; four independent components of a wrench can be applied on the user forearm, while only three independent components of a wrench can be applied on the arm link. For example, forces aligned with the arm link rotation axe cannot be applied on the arm and forearm links. Moreover, since the device has in all seven degrees of freedom, only seven components of wrench can be controlled independently at the same time. For instance, a wrench can be applied on the user palm and at the same time a single force component can be applied on the user elbow.

Forces on the arm and forearm arise in many cases during manipulation procedures in complex environments. When the operator is working in a cluttered space, it can collide with obstacles in any point of the upper limb. During manipulative operations, the operator can deliberately lay his arm/forearm on surfaces or edges. Inserting the arm in objects having deep hollows gives also rise to patterns of forces applied on the arm. It is clearly very interesting to handle these cases in the simulation of a realistic Virtual Environment.

In teleoperation, the ability of an anthropomorphic master to feedback forces not only at the level of the operator hand, but also on his arm and forearm, makes possible to think of master-slave systems which can perform “whole arm” manipulation procedures (i.e. manipulation with several link surfaces in contact with the environment or manipulandum, instead of interactions exclusively at the level of the end-effectors). Moreover, anthropomorphic master arms, which can constrain the motion of the whole operator arm and not only of his hand, can be used to enforce the avoidance of known objects in the remote environment.

5.5. Human-like Workspace

In order to preserve the user arm dexterity, the workspace available when wearing the device must match that of the free human arm. The available workspace is the intersection between the human arm workspace and the device workspace. An anthropomorphic interface is in the best conditions to maximize such intersection because the two workspaces tend to coincide if the device's joints ranges of movement are matched to the human joints ranges of movement.

5.6. Mechanical Design Challenges

The mechanical design of an anthropomorphic interface presents several challenges.

First of all, the kinematics of an anthropomorphic interface is determined by anthropometric considerations. From statistical data expressing the lengths of human upper limb as percentiles, the links lengths have been computed to ensure, on the 95 percentage of population, a maximum telerated joint axes misalignment. Kinematic parameters are not degrees of freedom in the design but rather constraints. As a consequence, the stiffness and the inertial properties of the interface cannot be improved by optimizing kinematics parameters.

Secondly, an anthropomorphic device is like a robot which the human operator wears on his body (on his arm in this specific case) and therefore it must be tailored on the operator body. The elementary requirement of avoiding interferences between the device and the human arm and trunk in every configuration gives rise to big difficulties about "where to place the links" with respect to the human body. The link design is greatly affected by the problem of wearability too. The links should be slender and close to the human limb so that both the operator and the space around him is as unencumbered as possible. For the same reason, the links should have their surfaces free of protrusions, which could hurt the operator coming in contact with his arm or trunk during movements.

Finally, aligning the joint axes of the device with the approximated anthropomorphic kinematics is particularly difficult from the mechanical design point of view. In fact, it is necessary to design joints whose axes intersect *inside* the human arm at the level of the shoulder, elbow and wrist. The case of the arm and forearm rotation joints is even more critical, because they must have their rotation axes completely *inside* the human arm and forearm (see Figure 5.1).

5.7. Precedent Work

At PERCRO, Scuola Superiore S. Anna of Pisa, Italy, a Force Display Device, consisting of two exoskeleton systems devoted to replicate forces at the level of the palm and of the operator's fingers, has been designed and realized. In particular the two systems are:

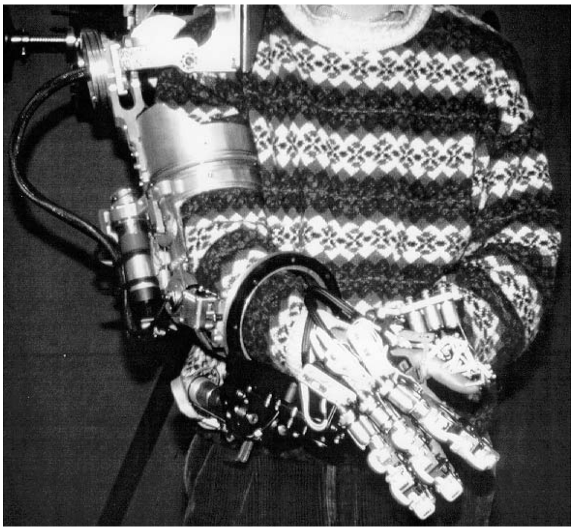


Figure 18: *Arm and Hand Exoskeletons*

- an Arm Exoskeleton, or External Force Feedback (EFF) system, with 7 d.o.f. which are coincident with the principal joint axes of the human arm. The EFF is attached to the user arm at the level of the palm (see Figure 5.7);
- an Hand Exoskeleton of Hand Force Feedback (HFF) system, consisting of 4 independent finger exoskeletons wrapping up four fingers of the human hand (little finger excluded) and each one possessing 3 actuated d.o.f. in correspondence of the finger flexion axes, while fingers abduction movements are just sensed. The HFF is connected to a base plate located on the user's metacarpus and corresponding to the end -point of the Arm Exoskeleton (see Figure 5.7).

The EFF and the HFF are both anthropomorphic haptic interfaces in the sense specified in the precedent section. The present work has its origins in the analysis and the experimental work done on the EFF. Some limitations of the Arm Exoskeleton mechanical design have been highlighed.

First of all, the workspace available to the operator is limited by the reduced range of motion available at the shoulder joints: the maximum shoulder adduction and extension are respectively 73° and 49°. These limitations don't allow to take full advantage of its anthropomorphic design.

Secondly, the exoskeleton structure, wrapping completely the human arm, forces the user to wear the system inserting his arm through the shoulder hollow. This has proved to be cumbersome to the point that unexperienced or impaired users may require external help. Moreover a exoskeleton around the arm, even if compact, is anyway an hindrance to bringing the arm laterally close to the trunk, a position which we have noticed to be the most natural for resting.

Thirdly, although the EFF is fully anthropomorphic, it does not exploit the possibility, discussed in Subsection 5.4, to replicate forces also on the users arm and forearm link.

The actuation system of the EFF is dimensioned to apply a $20N$ force on the user palm positioned still at the center of the workspace with the HFF (weighting around 1.4 kilos) mounted on the seventh link. Such performance is realized using small DC servo motors, designed for linear torque output, gearboxes with reduction ratio of 66, and a cable transmission allowing for a further reduction ratio of around 3. The presence of gearboxes causes friction which affect negatively joints backdrivability. The reduction of friction by means of closed loop joint torque control has proved successful but it has been implemented only on the wrist joints, where torque sensors are available.

The joint position sensing obtained with optical encoders on the motor axes gives a satisfactory resolution, also because of the reduction rate, but it doesn't allow to derive a clean velocity signal by numerical differentiation. The need of a noise free velocity signal, especially for the implementation of interactions with virtual rigid surfaces, has experimentally demonstrated by Prisco.

The EFF control strategy is based on driving the joints with a 7-dimensional torque vector $\tau_{control}$ which compensates the weight of the device and balancea the wrench $\mathbf{F}_{react}$ desired on the user's hand. The torque vector $\tau_{control}$ is computed according to the relation:

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

where $\hat{G}$ indicates an estimate of the gravity effects at the joints and $J(\mathbf{q})$ is the jacobian matrix.

6. Objectives of the Research

The scope of the present research is to proceed towards the realization of a satisfactory implementation of the concept of anthropomorphic haptic interface, as it has been outlined in Section 5.1, by designing a device which exploits the advantages of the anthropomorphic approach and at the same time overcomes some of the limitations of the Arm Exoskeleton described in Section 5.7.

Costs and development time have played no role in the system specifications; reliability has been considered of secondary importance at this stage of the project. In fact, our effort has aimed at demonstrating the system feasibility and its usefulness; we rely on technology advance and industrial re-engineering to cut on costs and realization times and to increase system reliability.

Apart from the requirements associated to the anthropomorphism of our device, our design has been influenced by two other functional requirements:

- adjustability. It is particularly important for an anthropomorphic haptic interface to be adjustable to accommodate to different sizes of the user arm (different arm and forearm lengths and circumferences);
- wearability. From our experience with the Arm Exoskeleton, easiness of wearing is a key issue for the acceptance of a device among users which are not specifically trained.

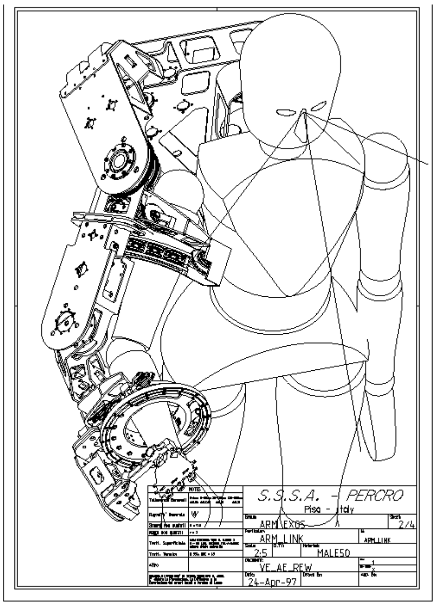


Figure 19: *Anthropomorphic haptic device for the upper limb in reference posture*

6.1. Dynamic Requirements

The dynamic properties, which we have chosen as design requirements for our device, are the exertable peak force (transient and continuous value) and the force resolution (both specified at the palm). The maximum velocity and acceleration have been specified defining a set of reference arm trajectories, as discussed in Section 8.1.

The backdrivability, i.e. the impedance of the controlled device measured at the palm, and the force bandwidth have been judged very important requirements too. It is very difficult to translate into design indications such requirements since they depend also on the joint torque control laws. Therefore the open loop joint torque bandwidth has been used as reference criteria for the dynamic properties of the final controlled system.

7. Design Innovations

The main innovative design solutions which we have introduced in our system are related to the design of the tendon transmission and to the mechanical solution which permits lateral wearing of the device.

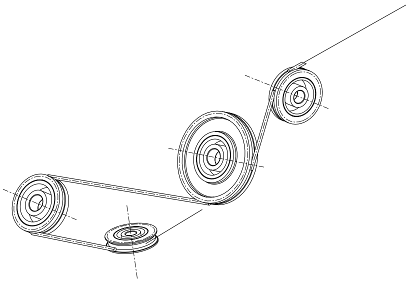


Figure 20: *Spatial placement of idlers*

7.1. Tendon transmission

We have designed a tendon based driving system which permits to place the motors away from the joints. Our goals have been to achieve reduced link weight (especially for the distal joints), increased joint compactness, reduced encumbrance in the workspace of the moving parts of the device. Moreover, such solution allows the usage of grounded actuators with high peak torque and consequent reduction or elimination of gearboxes (with the associated friction and torque transmission problems).

The main drawbacks of tendon transmissions are associated to the tendon elasticity and routing. The elasticity between the motor and the link, which is inevitably introduced by tendons, tends to lower the stiffness and the mechanical bandwidth of the device. Therefore these values have been kept under control during the design as described in Section 10.

The routing of the tendons from the motor to the joint becomes complex in multi d.o.f. systems. If the tendons are guided by sheaths the routing is simplified but severe problems arise in force control due to dry friction. In our design, the tendons are routed over idlers mounted on ball bearings. Such a method has been used in several other robotic structures. Usually such type of transmission is planar, that is to say, all the idlers lay in a common plane. A variant to this approach has been proposed in [19] and it allows for a small skew angle between an idler and the following. In other designs, such as the WAM from MIT and the Arm Exoskeleton from PERCRO, the axes of two successive idlers can be perpendicular in order to route the tendon between two orthogonal planes.

The innovative design solution introduced inthe anthropomorpic haptic interface is that the idlers of tendon transmissions are arbitrarily placed in the space; just the constitutive condition that two successive idlers share a common tangent line, as shown in Figure 20, is respected. This is the most general type of tendon transmission guided over pulleys and, to our knowledge, it has never been adopted in other designs. In this case, it has been a key technology which has allowed to route the tendons around the human arm and forearm.

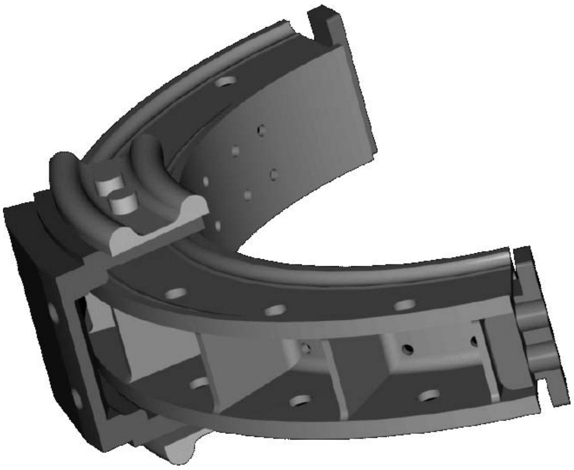


Figure 21: *Anthropomorphic kinematics*

7.2. Lateral wearing

In the aim of achieving a comfortable wearability, ‘open’ links for the arm and forearm have been designed. This means that the links do not wrap completely the user limb like in an exoskeleton, but instead just adhere to the external part of the arm. This solution allows easiness of wearing, since the user arm enters laterally into the device (while an arm exoskeleton has to be worn just like a sleeve) and it adapts to a broader range of user arm circumferences. Fast lateral wearing/unwearing gives also a greater intrinsic safety and a broader acceptance among users. Moreover such solution allows the user to bring his arm very close laterally to his trunk.

The design of open links around the user’s arm and forearm, while meeting the constraint of coincident anthropomorphic kinematics, has been possible thanks to an on purposely developed a partial (semicircular) rolling ball bearing. Such a mechanical component, depicted in Figure 7.2, has the same performance in terms of stiffness, weight and friction of a precision ball bearing of the same diameter.

The lateral wearing is only partially allowed by the present design, in fact only the arm link is open (while the forearm link wraps the user forearm as can be seen in Figure 19). This is only due to time/budget constraints.

8. Design tools

The mechanical design of the anthropomorphic haptic interface for the human arm has been possible only thanks to a set of software tools, which have given to the mechanical designers a better control of their work.

First of all, a key element has been the adoption of a fully associative, 3D, parametric CAD environment, integrated with a structural analysis tool. This has allowed to draw and

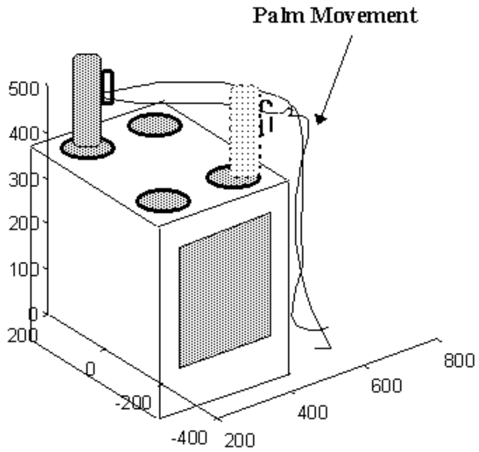


Figure 22: *An example of arm trajectory recorded to derive quantitative requirements for the actuation system*

analyse intrinsically 3D solution, such as the transmission system described in Subsection 7.1. Moreover, it has been possible an iterative process of design, by changing the dimensional parameters of a part in consequence of the results of the analyses performed on the whole system.

Secondly, a software tool has been developed in order to evaluate the lowest resonant mode associated to the multi DOFs, coupled transmission system. Such tool implements the dynamic model of such type of tendon driven robot.

Finally, a dynamical simulation software application has been developed to evaluate quantitatively the performance required to the actuators (see Section 8.1.

8.1. Dynamical simulation tool

The derivation of quantitative requirements for the actuators has been based on the following specifications:

A the kinematics and dynamics of the device, in terms of joint variables;
B the transmission structure, in terms of the relationship it introduces between joint variables and motor variables;
C a description of the arm free movements workspace, in terms of joint positions, velocities, accelerations during the expected usage of the device. Since the haptic device has no repetitive usage, a quite large set of typical operation has been chosen and arm trajectory acquisition has been done using infrared markers attached on user arm (see Figure 22 for an example trajectory).
D a specification of the peak forces the haptic device is requested to apply on the human arm.

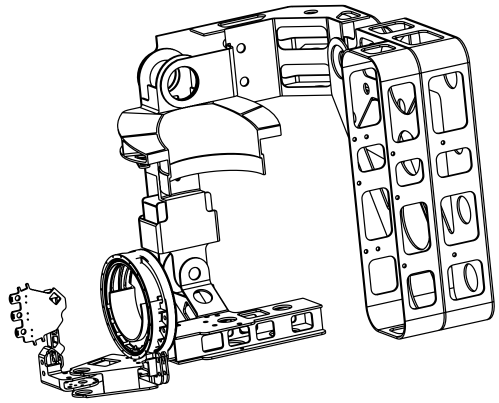


Figure 23: *Anthropomorphic haptic device for the upper limb in reference posture*

Given the complexity of the anthropomorphic haptic device, the first two items have been determined with confidence only thanks to the adoption of a 3D CAD environment capable of computing masses and inertia of the complex assemblies of mechanical parts, which forms the links of the device.

Items A,B,C and D have been used as inputs to the dynamical simulation software tool (see the precedent Section) which solves the inverse dynamic problem along all the arm trajectories and computes the associated motor trajectories, under the hypothesis of rigid transmissions. From the motor trajectories, a set of indexes, such as peak continuous and rms values of motor torque, velocity, acceleration and mechanical power output are computed. These values have been used to select the motors (see Table 3).

9. Design solutions

The device closely follows the human arm from the shoulder to the palm; it features 7 rotational joints in order to fully preserve the freedom of movement of the user arm (see Figure 23 for an global view).

The choices, already experienced in the Arm Exoskeleton, of a totally anthropomorphic kinematics and of the usage of electrical actuation, cable transmission and joint torque control approach, have been renewed.

The kinematic congruence of the device to the user arm kinematics is guaranteed by means of a regulation system for the arm and forearm links. The lengths of the arm link and the forearm link are continuously adjustable within a range of $0.05m$ and $0.03m$. The adjustments induce no rotation on the actuators and they can be performed with the device powered and controlled by a special software.

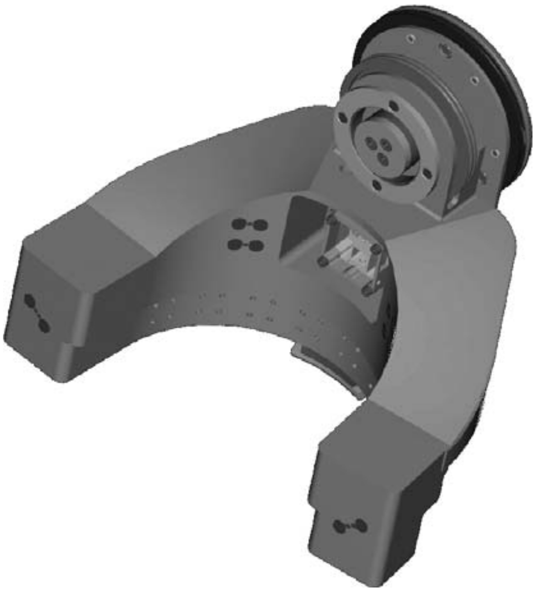


Figure 24: *Link 2*

The device is fixed to the user upper link at the level of the medium part of the arm, of the forearm and of the palm (see Figure 19).

The wearability, for users with arm circumferences of a wide range of values, is guaranteed because the arm link of the device just surrounds half of the user arm (see Figure 24). This has been realized using the semicircular rolling ball bearing described in Subsection 7.2, and guiding the transmission tendons around the joint 3 using a spatial transmission, as explained in Subsection 7.1. The same solution could be implemented for the forearm link.

9.1. Kinematics

The joints ranges of movement with respect to the arm reference position of Figure 23 are reported in Table 2.

Joint	#1	#2	#3	#4	#5	#6	#7
θ_{min}	0	−180	−60	−90	−60	−70	−45
θ_{max}	90	0	60	20	60	60	15

Table 2: *Joint rotation limits (in degrees)*

The shoulder d.o.f. have a range of movement which is wider with respect to the Arm Exoskeleton described in Section 5.7. This allows the user to raise his hand over his shoulder and head. The range of movement of the arm and forearm rotations are limited by the presence of the semicircular ball bearings.

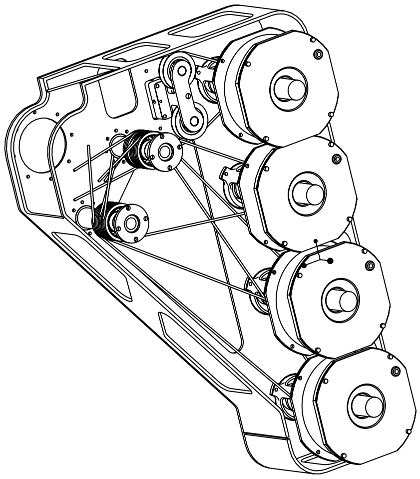


Figure 25: *Link 0 with 4 motors*

9.2. Actuators

Motor	#1	#2	#3	#4	#5	#6	#7
τ_{cont}	13	13	13	2	0.8	0.8	0.8
τ_{peak}	21	21	21	3.5	1.5	1.5	1.5

Table 3: *Available torques at motors' axes (Nm)*

Current controlled DC electric motors, designed for high peak torque (i.e. pancake shaped motors), with one stage gear boxes or no gear boxes at all, have been used. The actuators for the first 4 joints are placed on the back of the user (see Figure 25), while the 3 actuators for the wrist joints are placed under the forearm with a similar mechanical design.

9.3. Transmissions

The basic design choice for the transmission system is that of using a $2N$ tendon configuration, in which a pair of opposed tendons drives each single joint and one rotary actuator is used to drive a pair of tendons (see Figure 26). Multistage transmissions are used whenever the motor is not

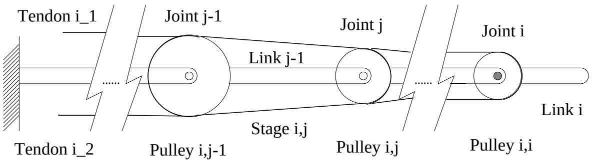


Figure 26: *A multi stages transmission with pairs of opposed tendons*

Figure 27: *Differential tendon tension sensor*

placed near the joint (see Figure 26). In such cases, the fact that the tendons driving a joint are routed over the preceeding joints, causes a coupling in the relationship between motor variables (angular displacements and torques) and joint variables. Multi strands, steel cables, with a diameter of 2 mm, are used as tendons; the tendons are routed over pulleys mounted on ball bearings. Pretensioning is obtained with a regulation mechanism located at the driven pulleys.

9.4. Sensors

Resolvers, mounted on the motor shafts, are used in order to have high resolution in the position measurement and in order to have a direct velocity measurement available to implement damping control.

On purposely developed, differential tendon tension sensors are employed, in order to measure joint torques (see Figure 27). Such sensors use strain gauge full bridges as sensing elements. They are equipped with local electronics for signal conditioning in order to improve signal to noise ratio. The performance of the sensor module is summarized in Table 4. The sensing resolution is adapted to the requirement of each joint, by varying the incidence angle of the cables on the sensor frame.

10. Design analysis

An analysis of the global results of the design has been performed iteratively during the design process, in order to evaluate the impact of some solutions on the most critical global performance indexes. Three sets of global properties of the haptic interface have been kept under control:

- the masses and inertia tensors of the links;
- the worst-case end point stiffness of the device;
- the worst-case mechanical bandwidths of the joints.

10.1. Link inertial properties

The estimation of the mass and inertia tensors of the links has been obtained directly by the 3D CAD design environment. In this way, every single mechanical part, up to the screws, has been taken into consideration; we have also been able to evaluate the gain in mass which is realizable by using special materials, such as composite material or carbon fiber, instead of aluminium, for the structural parts.

The results of the analysis have shown that the greatest impact on link masses is due to the actuator modules, each integrating an unhoused pancake rotor/stator, a resolver and a mechanical frame. In fact, from Table 5, it is noticeable the high masses of links 0 and 4, which house respectively four and three actuator modules. A second significant contribution to the link masses is represented by the steel parts, such as torque sensor frames, ball bearing, idlers and pulleys.

10.2. Stiffness

The estimation of the worst-case end point stiffness of the device has required a special care, because of the complexity of the mechanism. From a methodological point of view, the correct computation of the end-point stiffness has required to take into account the contribution of both the link structural parts and the tendons. The worst case has been identified as occurring when the human arm is completely stretched in the front (the joint angles values in such case are reported in Table 6). In Figure 28 and 29, the diagrams representing the displacement magnitudes, under a general load condition, are reported. The elastic constant along z, which is by far the worst direction, is $1.8N/mm$.

References

[1]. Lederman S.J., Klatzky R.L., “Haptic Exploration and Object Representation,” in M.A. Goodale (Ed.), *Vision and*

Transversal force	Max	200 N
	Min	-200 N
Transversal torque	Max	2 Nm
	Min	-2 Nm
Overload factor	1.5	
Force resolution	0.1 N	
Force accuracy	2.0 N	

Table 4: *Performance of the torque sensor module*

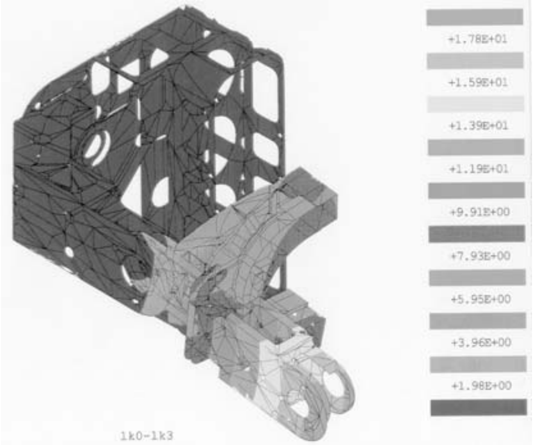


Figure 28: *Displacement magnitude of the assembly composed of the first four links, including cable transmission contributions, under a generic load condition*

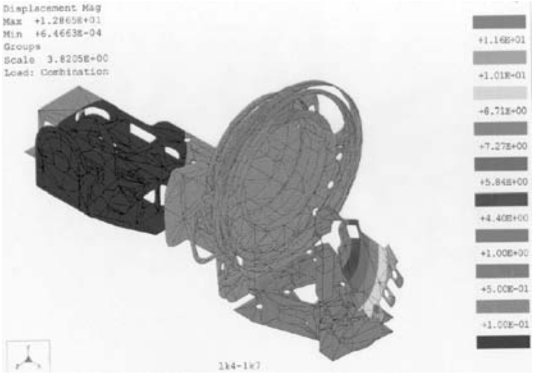


Figure 29: *Displacement magnitude analysis of the assembly composed of the last 3 links, including cable transmission contributions, under a generic load condition*

Action: the Control of Grasping, Ablex Publishing Corporation, Norwood, NJ, 1990.

[2]. Loomis J.M., Lederman S.J., “Tactual Perception,” in K. Boff, L. Kaufmann, J. Thomas (Eds.), *Handbook of Perception and Human Performance*, J. Wiley, New York, 198+6.

[3]. Gibson J.J., “The Senses Considered as Perceptual Systems,” Greenwood Press Publishers, Westport, CT, 1966.

Link	#0	#1	#2	#3	#4	#5	#6	#7
Mass	8.1	2.6	3.2	1.4	5.1	0.64	0.28	0.07

Table 5: *Link masses (with structural parts made of aluminium)*

[4]. Sheridan T.B., “Telerobotics, Automation and Human Supervisory Control,” MIT Press, Cambridge, MA, 1992.

[5]. Bergamasco M., De Micheli D.M., Parrini G., Salsedo F., Scattareggia Marchese S., "Design Considerations for Glove-like Advanced Interfaces,"Proc. of ICAR’91, Pisa, Italy, 1991.

[6]. Bergamasco M., "Design of Hand Force Feedback Systems for Glove-like Advanced Interfaces, Proc. of the First IEEE Int. Workshop on Robot and Human Communication ROMAN92, Hosei University, Tokyo, Japan, 1992.

[7]. Iberall T., MacKenzie C.L.,“Opposition Space and Human Prehension,” in S.T. Venkataraman, T. Iberall (Eds.) *Dextrous Robot Hands*, Springer-Verlag, New York, 1990.

[8]. Bergamasco M.,” Different Inter-Action Modalities Between the Human and the Virtual Environments,” in preparation.

[9]. Millman P., Colgate J.,”Design of a Four Degree-of-Freedom Force Reflecting Manipulandum with a Specified Force/Torque Workspace,” Proc. of IEEE Int. Conf. on Robotics and Automation, Sacramento, CA, 1991.

[10]. Hayward V., Choksi J., Lanvin G., Ramstein C., ”Design of Multi-Objective Optimization of a Linkage for a Haptic Interface,” Proc. of the 4th Workshop on Advances in Robot Kinematics, Ljublijana, Slovenia, 1994.

[11]. Allotta B., Bergamasco M.,"The Range of Wrenches that can be Statically Applied by a Force Replicating Device," Proc. of IEEE Int. Workshop on Robot and Human Communication ROMAN94, Nagoya, Japan, 1994.

[12]. J.K. Salisbury, “Teleoperator Hand Design Issues”, Proc. of IEEE International Conference on Robotics and Automation, S.Francisco, April 1986.

[13]. William T. Townsend, “The Effect of Transmission Design on Force-Controlled Manipulator Performance”, thesis published by the Artificial Intelligence Laboratory, Massachussetts Institute of Technology, 1988, Boston.

[14]. J.E. Colgate, “On the Inherent Limitations of Force Feedback Compliant Controllers”, International Journal of Robotic Research, ASME publ., (12)1989.

[15]. Thurston L. Brooks, “Telerobot Response Requirements”, STX Coorporation, Rep. N. STX/ROB/90-03, Lanham, 1990.

Joint	#1	#2	#3	#4	#5	#6	#7
θ	0	−90	0	−90	0	0	0

Table 6: *Joint angle in test configuration(in degrees)*

[16]. T. H. Massie and J. K. Salisbury, “The PHANToM Haptic Interface: a Device for Probing Virtual Objects”, asme, Chicago, IL, 1994.

[17]. William R. Mark and Scott C et Al., “Adding Force Feedback to Graphics Systems: Issues and Solutions”, siggraph, 1996.

[18]. J. E. Colgate and G. Schenkel, “Passivity of a Class of Sampled-Data Systems: Application to Haptic Interfaces”, Proc. of American Control Conference, 3236-3240, 1994.

[19]. S. Hirose, “Biologically Inspired Robots”,Oxford University Press, Oxford (UK), 1993

Design of Haptic Interfaces

Avizzano, C.A., Raspolli, M., Fontana, M, Frisoli, A., Bergamasco, M

PERCRO
Scuola Superiore S.Anna
Pisa, Italy

Abstract

Haptic Interfaces can be widely applied to a large set of interactive applications. The design of these devices differs from classical robotic approach and requires a specific competence on HCI and applications. The present paper reports the results achieved at PERCRO in the design of new haptic devices. A specific care has outlined on the design of Kinestetic Haptic Interfaces. The most relevant devices are briefly classified and described. Low DOF and High DOF devices (according to [1]) are presented. All these devices follow the approach of impedance control and they are the result of accurate optimizations of kinematics, structural components shape, transmissions and actuation. Keywords Haptic Interfaces, Virtual Reality, Human Computer Interaction

---

1. Introduction

The advent of Haptic Technologies (HT) has changed the concept of robotic system [2] in fact Robots were originally introduced into the industrial environment for replacing human activities while HT has introduced robots in VE for enhancing the sense of presence by reproducing the contact forces and other specific forces on user (Emery [3]). The use of such systems improves the interaction with the VE and increases the sense of presence and the dexterity of the users with the virtual objects. Reach-In [4] for example, integrates a 3D graphic system with a PHANToM device [5, 6]. With few exceptions [7] almost all the existing VE, the haptic interfaces work in cooperation with a visual feedback for integrating the contact information with complementary visual information. It is commonly accepted the position that the visual interaction is dominant in this type of interaction as well as it is known that haptic feedback can be used to improve the interaction of people with visual impairments. Some time can be useful to create a system with not only force feedback and visual but also audio feedback. Haptic feedback also offers the possibility of using robotic system as a training tool (i.e. eEducation [8]) or as a therapeutic tool (i.e. reducing tremor [9]). The present paper reports the current results achieved at PERCRO in the design, the development and integration of haptic devices for immersive Virtual Reality application system such as: Computer Aided Surgery, Rehabilitation, Cultural Heritage, Automotive, Entertainment and Technological Aids for disabled and elderly.

2. Desktop Devices

Several classifications of haptic devices could be done according to complexity, kinematics, transmission, application and several other features. In the present work we would like to show the achieved results accordingly to kind of interaction modality. We have identified two main types of devices: desktop and wearable haptic. Desktop haptic could be used at user's workplace as an interaction devices enabling to augmented computer access, while wearable interfaces are ideal for being immersed into complex VE environments such as 3D wall and/or CAVE like virtual environments.

2.1. 2 DOF Haptic Interfaces

2DOF haptic is the simpler haptic device that can show complex VE interaction. In this kind of interfaces the end-effector has 2 degrees of freedom, usually it moves along a plane. Being the computer desktop bi-dimensional, such kind of devices is ideal in designing computer like interaction that animates things that happens on the computer screen. These Haptic Interfaces can also be employed as under-actuated systems in three- dimensional exploration and navigation. Low DOF HIs represent an alternative choice, when it is not requested to sense the posture of the entire human arm and the nature of the performed task can be carried out with a single contact point.

2.2. Haptic Pen

The haptic PEN is the more intuitive haptic display for hand-based interaction. The system is a 2+1 DOF Haptic Interface having its end-effector shaped in the form of a pen. The Force Display has been designed in order to exhibit the higher kinematic isotropy over the worskpace. A specific parallel linkage structure is actuated by an innovative transmission [10]. The system has been designed in order to allow users working in the same space defined by a letter size. It can measure and control the motion on the paper plane, while measuring the pression of the pen exerted by the user along the pen axis. The device is composed of two rotary actuators, driving a closed 5-bar linkage by two pairs of opposed tendons realized through steel cables. The actuators are located apart from the linkages of the mechanism. Each motor has two tendon transmissions in order to realize a pre-tensioned bi- directional tendon drive. The tendon drive couples linearly the angular displacements of all the joints to the motor displacements such a feature allows distributing actuation torques to all joints, moving in such a way the singular condition outside of the operating workspace. By actuating one motor, while the other one is locked, the mechanism motion is kinematically constrained by the tendon drive. The particular nature of the tendon drive allows shaping the force response of the system to achieve high value of kinematic isotropy over the workspace. Two high-resolution encoders are placed on the motor joints for sensing the position of the end-effector in the workspace. The HI can exert forces up to 10 N in its plane.

Although the system possesses a plane geometry, it can be used for rendering 3-dimensional intermediate scale shapes (holes or bumps) too, by the principle of Lateral Rolling Finger Deformation [11] i.e. exploiting vector fields of lateral forces: a force resistant to the motion of the operator's hand and lying in the plane of motion is perceived as a positive slope, while a force pushing along the motion direction as a negative slope. This property allows displaying 3D shapes by using low dof planar devices with the main advantage of increasing reliability, easy of use and reducing cost with respect to higher DOF HIs. This Haptic Interface is suitable for applications where high accuracy is required such as teaching of drawing/handwriting abilities, rehabilitation of human hand, or for easy access to computer for special user groups, such as people with sight or sensomotorial disabilities.

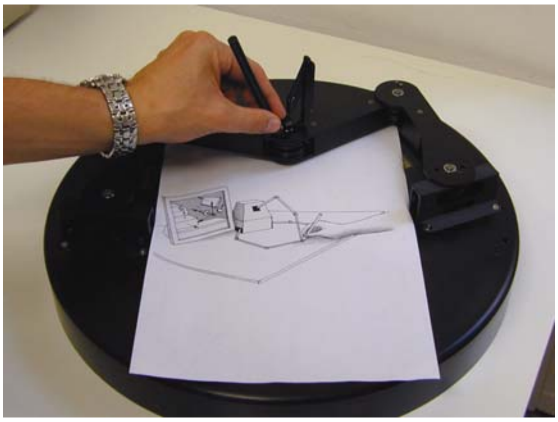


Figure 1: *The desktop 2 DOF HI*

2.3. Haptic Desktop

By following the interaction concept identified in the haptic pen, another 2DOF HI has been developed. The Haptic Desktop integrates in the desktop planes all the haptic functionalities together with an office automation workstation. To this end several component have been assembled under the desktop surface including: an embedded PC, a slim LCD, IO boards, motor, drivers and power supply group. Only the linkages of a 2-DOF parallel planar haptic structure have been left over the desktop surface. The layout of the whole system has been shown in figure 2. The layout of the system has been arranged in such a way that the operator has no other object on the desktop and he can also see trough the desk plane in the LCD.

Figure 2: *The Haptic Desktop system*

The design of the HD aims to reduce the mental workload required to users during the interaction with VE. This capability has been achieved with the adoption of two functional solutions: a coherent kinematics and collocated feedback. The linkages of the HD hare made of transparent plastic material with low refraction index, so that the visual information is not disturbed or distorted while the operator is manipulating the end-effector of the device. The workspace of the device has been designed to have optimal manipulation capability all over the surface of the LCD. Furthermore the system design and control allow the user to feel and control haptic interaction just below his fingertips, while directly viewing the effects of his actions on the computer screen. Coherence and collocation have been implemented according to these principles: the user can operate with his fingers onto the computer screen controlling the pointer while directly seeing through the haptic device. In fact, the haptic device has been calibrated in order to collimate the position of the usage tool, with the computer pointer. Specific state of the art analyses [12] have verified that co-location greatly enhance the user performances in HCI while reducing the mental load of the interaction. The developed system, besides guaranteeing the complete interaction offered by traditional systems, allows accessing the computer resources by controlling the graphical cursor that is coincident to the interaction point. The second functionality is the possibility of creating through the sense of "touch". Such kind of interaction offers the possibility of using the system as a training tool (i.e. eEducation) or as a therapeutic tool (i.e. reducing tremor). Features:

- Workspace 430 x 320 mm;
- Force continuous: 3 N;
- Force Peak: 5 N;
- Zero Backlash kinematic;
- Reflected inertia: 0.07 Kg;
- Typical Stiffness: 4 N/mm;
- Position resolution: 0.01 mm.

2.4. 3 DOF or more Haptic Interfaces

3 Dof or more Haptic Interfaces are used for tracking user's position and to exert forces on it in a three-dimensional environment. This kind of interfaces allows the user to interact with virtual three-dimensional objects with one or more contact points.

2.5. 3DofJoy

The 3 DofJoy (figure 3) is a desktop haptic pen designed to exert forces of arbitrary direction [13]. Its innovative parallel kinematics provides a purely translating platform [14] that is suited to be used as a base module for more complex devices.

High performance in terms of stiffness and dynamic bandwidth has been obtained. The coupler is a fully parallel translating platform realized by connecting a base and a moving platform (coupler) via three independent legs. Each leg is characterized by an open serial kinematics composed of 2 links and presents 5 DOF: the two universal joints at the ends and an actuated revolute joint at the elbow. The actuation is composed by three PM DC motors located closed to the ground in order to reduce moving masses. Torque transmission is achieved by a tendon system. The translational motion is obtained by proper joints positioning and orientation; therefore a not redundant actuation characterizes the parallel mechanism. Recently 3Dofjoy has been completely re-designed introducing significant improvements of performances in terms of exertable forces, gravity auto-compensation capability, backlash and constructive simplification. The main improvement consists in a new arrangement of motors locations that leaded to an auto-compensated configuration. The 3 Dofjoy system has the following characteristics:

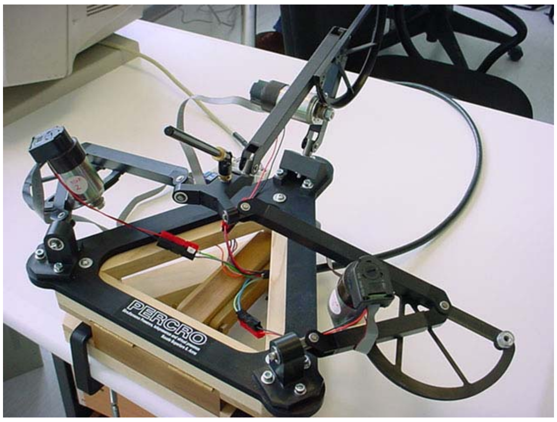


Figure 3: *The 3 DOF Joystick device*

- Maximum continuous force at coupler in the workspace center equal to 18 N;
- Maximum stiffness in the worst configuration equal to 8 N/mm;
- Reflected inertia (according to model type) equal to 0.2 - 0.4 kg;
- Zero Backlash kinematic;
- Peak Force (according to model type) equal to 18 Ű 36 N;
- Zero backlash transmission.

Possible applications of the system include: teleoperation and interaction with virtual environments (drilling, carving, cutting, etc.).

2.6. GRAB

The GRAB [7] is a dual points haptic device expressly conceived for the simulation of grasping and manipulation of objects with two fingers. The system is composed of two haptic interfaces, a control unit and a visualization system (figure 4).

Each haptic interface is composed of two identical robotic arms. Each arm has 6 Degree of Freedoms (DOF's), of which 3 are required to track the position of the fingertip in 3D space and the remaining 3 are required to track its orientation. The arms will interact with the user's fingers by means of a couple of thimble the user can suit. Due to the large workspace requirements, a serial kinematics has been selected. In this implementation, only the first 3 DOF's have

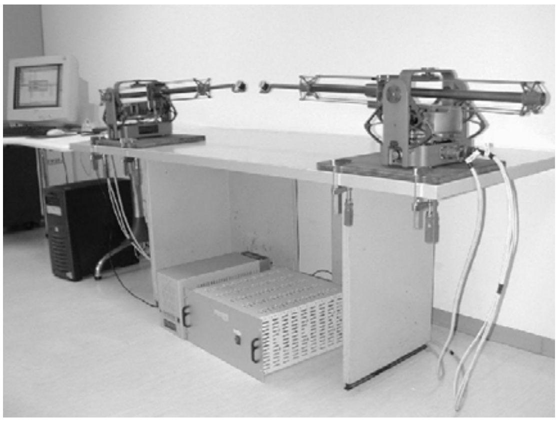


Figure 4: *The Dual point HI: GRAB device*

Figure 5: *The L-exos first configuration*

to be actuated (by three DC motors and tendon transmissions) in order to exert forces of arbitrary orientation at the fingertip, while the last DOF's can be passive because it is not required to exert moments. This solution allows a very high degree of isotropy of the device w.r.t. other kinematics solutions, like that used for the PHANToM. A high degree of isotropy is important in order to achieve a uniform use of the actuators in the workspace of the device and to have a uniform reflected inertia. The realized system has the following characteristics:

- A wide dual point Workspace (600x400x400mm);
- Large Peak and continuous force: 10-15N peak, 4-6N continuous;
- High stiffness: 3-7N/mm;
- Low Mechanical friction: 20mN with active friction compensation and 200mN without compensation;
- Zero backlash kinematic;
- Reflected inertia: 0.4kg.

3. Wearable devices

Wearable haptic interfaces have a kinematics similar to the human body. The design of these components is very complex due to both kinematics constraints as well as size and weight limitations. Two types of wearable devices will be presented here, one for the arn, the latter for the hand.

3.1. L-Exos

The L-Exos (Light EXOSkeleton) is an innovative Haptic interface wearable on the arm that allows the user to experience a direct interaction with a Virtual Reality System. L-Exos has a versatile design with two interchangeable configurations. In the first one it can exert a force on the hand's palm through a handle; in the second one it can be coupled with another device (Hand Exoskeleton) that is able to exert forces independently on two fingertips (typically thumb's and index finger's).

L-Exos is a serial robotic structure, with 4 primary sensorized and actuated dofs to which may be added respectively 1 sensorized dof in one configuration (figure 5), or 3 sensorized and actuated dofs and 3 idle dofs in the coupled configuration (figure 6). All the primary DOFs are rotational joints connecting in series 4 movable links to a fixed one (Link 0), which can be rigidly connected to a fixed or movable support. Its particular open structure (thanks to an open circular bearing on third joint) ensures the safety of the user that, in any emergency case, can immediately undoff the system. The first three rotational joints emulate the kinematics of a spherical joint (human shoulder joint) while the fourth joint of the robotic device coincides with the human elbow joint. From a structural point of view a high stiffness with reduced mass (i.e. weight and inertia) is obtained by using composite materials (carbon fibers) in combination with a hollow shell link's morphology, containing within themselves the power transmission system. This one is constituted by a series of steel tendons, two for each joint, transmitting the bi-directional torque to the joint from the remote located actuators. All the actuators are in fact situated in the fixed link (link 0) in order to reduce again the movable mass. Each transmission carries out an overall gear ration between the torque output of the motor an the torque transmitted through the actuated joint, by means both of motor/driven pulleys radii ratio and of joint-integrated epicycloidal gearheads. Mechanical custom subsystem, like the open- structure circular guide [15], the joint-integrated reduction-gear [16] and the motor-group, have been designed and developed by PERCRO. In the configuration with the handle the L-Exos can exert a continuous force of 50 N and a peak force of almost 100 N to the hand palm in every direction of the space. The L-Exos has a mass of 11 kg, of which approximately 6 kg distributed on the link 0, i.e. the fixed part, and mostly due to the mass of the 4 motor-groups. This means that in this configuration the robotic interface can achieve the desirable very low value of weight /payload ratio of almost 1. The applications of this interface can be the field of Teleoperation (deming, manipulation of toxic or radioactive materials, inspection of dangerous zones, maintenance of satellite or space stations) or in the field of Virtual Reality (virtual prototyping, medicine and rehabilitation, ergonomic assessment, art and cultural heritage [17] e [18]).

3.2. Hand-Exoskeleton Haptic Interface

The Pure-Form Hand-Exoskeleton [19] (PFHE) is a portable Haptic Interface designed to exert forces of arbitrary direction and amplitude on the index and thumb fingertips

Figure 6: *The L-Exos and Hand Exos integrated configuration*

This interface has been conceived as a modular system, so that it can be used either independently fixed on a desktop or mounted and totally supported on the terminal link of the arm exoskeleton (figure 6). Assembling these sub-systems, it is possible to achieve a better HI that combines the greater workspace of the arm exoskeleton with higher degree of manipulation provided by the PFHE. The PFHE was used to simulate the contact with virtual surfaces, while exploring virtual sculptures in the Museum of Pure Form [20]. The final version of the device is composed of two serial limbs, each one with three actuated degrees of freedom. The last actuated links of the two limbs are connected to the respective end-effector (a thimble) by means of a gimbal, which allows the mechanism to reach the user's fingertip with any orientation. The PFHE is actuated by 6 ironless DC motors (three for each one of the two limb) sensorized with high-resolution encoders. A bilateral tendon transmission system with steel cables driven by idle pulleys is used to convert the torque of the motors into the force applied at the end-effector. This solution, joined with the choice of high- performance materials, such as carbon-fibers composite materials and the aeronautic aluminum, has allowed to reduce the total weight of the interface and, in particular, of the moving parts (about 206g per limb). In this way it has been possible to reduce the perceived inertia by the user, increasing the transparency during the free exploration of the virtual environment and maintaining good levels of stiffness and dynamic performances. The main performances of the device are listed below:

- Minimum continuous force at the end- effector in the worst configuration: 3N;
- Maximum peak force at the end-effector auto-limited at 15N in all the workspace;
- Minimum stiffness at the end-effector guaranteed in the worst configuration: 5N/mm;
- Flexion-extension angular excursion allowed to the wrist: +/- 45ř.

4. Conclusion and Acknowledgement

Six new types of haptic devices have been shown. Each of them presents innovative aspects in terms of functionalities, performances, operability and design. A summary of the device performances can be found in table 1. A comparison with existing device has also been provided in the same table. The work of design of these devices has been carried out within the EU project TREMOR, PUREFORM, GRAB while the current application development is supported by the IT project VICOM and the EU NOE Enactive. The authors are grateful to National and European governments whose grants constituted a valid cofinancing of the presented research. The authors also thank the partnership of the mentioned project that provided a valid support in the functionality definition and/or system assessment.

where:

1. Haptic Pen;
2. Haptic Desktop;
3. 3DofJoy;
4. GRAB;
5. L-Exos;
6. Hand-Exoskeleton Haptic Interface;
7. DELTA;
8. PHANTOM 1.5.

5. References

[1]. Hayward, V.; Astley, O.R. *Performance measures for hap-tic interfaces*, RoboticsResearch: The 7th International Symposium, 1996.

	WSpace	Fpeak	Fcont	Resol.	DOF	Stiff.
1	170x120	13.9	3.5	0.03	2	3
2	430x320	5	3	0.01	2	4
3	R=100,H=200	36	18	0.01	3+2	8
4	600x400x400	15	6	0.05	3+3	7
5	N.A.	100	50	0.02	4+1	3
6	N.A.	15	3	0.005	3+3	8
7	R=150,H=300	25	20	0.1	3+3	N.A.
8	195x270x375	6.4	0.03	3+3	3.5	
	Mm	N	N mm	N/mm		

Table 1: *Performance comparison*

[2]. Buredea, G.; Coiffet, P. *Virtual reality technology*, John Wiley & Sons, New York USA, 1994.

[3]. Vitense, H.S.; Jacko, J.A.; Emery, V.K. *Foundation for improved interaction by individuals with visual impairments through multimodal feedback*, Universal Access in the Information Society. Nov. 2002; 2(1): 76-87, Springer-Verlag.

[4]. *Reachin web site: www.reachin.se*

[5]. Massie, T.H.; Salisbury, J.K. *The PHANTOM Haptic Interface: A Device for Probing Virtual Objects*, Proceedings of the ASME Winter Annual Meeting, Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, Chicago, IL, Nov. 1994.

[6]. *SenseAble Technologies Inc*, 15 Constitution Way Woburn, MA 01801, USA, www.sensable.com.

[7]. Avizzano, C.A.; Marcheschi, S.; Angerilli, M.; Fontana, M.; Bergamasco, M.; Gutierrez, T.; Mannegeis, M. *A Multi-Finger Haptic Interface forVisually Impaired People*, RO-MAN03 October 31- November 2. San Francisco.

[8]. Solis, J.; Avizzano, C.A.; Bergamasco, M. Teaching to Write *Japanese Characters using a Haptic Interface*, Proc of the 10th International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, Orlando, FL, 2002.

[9]. Avizzano, C.A., Bergamasco, M. *Technological aids for the treatment of the tremor*, ICORR, Stanford, 1999.

[10]. Frisoli, A.; Bergamasco, M. *Experimental identification and evaluation of performance of a 2 DOF haptic display*, Robotics and Automation, 2003. Proc. ICRA ’03. IEEE International Conference on, Volume: 3, 14-19 Sept. 2003 Pages:3260 - 3265 vol.3.

[11]. Hayward, V. *Display of Haptic Shape at Different Scales*, In Proc. of EuroHaptics 2004, Munich Germany, June 5-7, 2004.

[12]. Jansson, G.; Öström, M. *The Effects of Co-location of Visual and Haptic Space on Judgments of Form*, EuroHaptics 2004.

[13]. Checcacci, D.; Frisoli, A.; Bergamasco, M. *L’Interfaccia aptica master del sistema METAFORE*, Proceedings of XXX AIAS National Congress. September 12-25 2001, Alghero (CA), Italy.

[14]. Frisoli, A.; Checcacci, D.; Salsedo, F.; Bergamasco, M. *Translating in-parallel actuated mechanisms for haptic feedback*, HAPTIC INTERFACES for Virtual Environment and Teleoperator Systems 2000 ASME International Mechanical Engineering Congress and Exposition, November 5-10, Orlando, Florida.

[15]. Dettori, A.; Frisoli, A.; Salsedo, F.; Bergamasco, M. *Analisi e progetto di una guida ad elementi volventi con geometria circolare aperta*, XVI Congresso AIMETA di Meccanica Teorica e Applicata, AIMETA’03 9-12 Settembre 2003.

[16]. Franceschini, M.; Frisoli, A.; Raspolli, M.; Salsedo, F.; Bergamasco, M. *Analisi e progetto di un riduttore integrato per trasmissioni a cavo in tensione di interfacce aptiche di tipo esoscheletrico*, XVI Congresso AIMETA di Meccanica Teorica e Applicata, AIMETA’03 9-12 Settembre 2003.

[17]. Bergamasco, M.; Brogni, A.; Frisoli, A.; Salvini, F.; Vignoni, M. *Tactual Exploration in Cultural Heritage*, XIV Round Table Computer-Aided Egyptology Pisa 8-10 July 2002.

[18]. Bergamasco, M.; Frisoli, A.; Barbagli, F. *Haptics Technologies and Cultural Heritage Applications*, IEEE Computer Animation 2002 Conference, Geneva - Switzerland, June 19-21, 2002.

[19]. Frisoli, A.; Simoncini, F.; Bergamasco, M. *Mechanical Design Of A Haptic Interface For The Hand*, Asme 2002, Technical Conferences And Computers And Information Montreal, Canada, September 29-October 2, 2002.

[20]. Bergamasco, M.; Frisoli A.; Barbagli, F. *The museum of Pure Form*, Proc. of ICAR 2003, The 11th International Conference on Advanced Robotics June 30 - July 3, 2003 University of Coimbra, Portugal.

Haptic Desktop for Office Automation and Assisted Design

Carlo Alberto Avizzano, Mirko Raspolli, Simone Marcheschi and Massimo Bergamasco

PERCRO
Scuola Superiore S.Anna
Pisa, Italy

Abstract

The present paper describes the conceptual and technical design of a new multimodal device named Haptic Desktop System (HDS). Haptic Desktop System is an integrated system, which merges haptic functionalities, and VDT systems into one. Specific care has been given to HDS design for enhancing and improving human-computer interaction from the following points of view: esthetical, ergonomic and functional. In order to improve the quality of the interaction, the HDS fully integrates proprioceptive, visual, audio and haptic functionalities, into a desk while minimizing the visual interference of the physical components. In the proposed approach classic input devices (i.e. keyboard and mouse) have been replaced by new features integrated within audio and haptic. Such features allow commanding and rendering natural force stimuli in such a way that they are completely coherent and co-located with respect to the visual information. The new features of the HDS are designed for reducing considerably the mental load from users during interaction operations. In the present paper the design guidelines and the achieved results are reported.

Keywords *Haptic desktop system, Office Automation*

---

1. Introduction

The concept of Office Automation appeared during the second part of the sixties as an unexpected phenomenon and collateral and synergic effect of two parallel activities: the development of intuitive graphic systems and the reduction of cost for accessing computer resources. One of the first tools used to access such resources was introduced by Engelbart Douglas, who designed the first prototype of the mouse with the purpose of "augmenting human intellect" [1]. However the mouse was firstly used in 1973 by a manufactured machine, the Xerox Alto Computer [2]. The main processing unit, the size of a small refrigerator, was designed to sit under a desk or table, while the display, mouse, and keyboard sat on the tabletop. The display was shaped like a piece of letter-sized paper and in conjunction with the mouse employed a graphical user interface (GUI). This was the most farsighted feature of the machine, as it took another twenty years for GUI's to become standard on desktop computers. Actually, the Office Automation tools are the result of the sudden growth of this field. The development of new tools to access multimedia resources has considerably increased the space needed to place them on the desk (monitor, mouse, keyboard, joystick, etc.). Even if such tools have been conceived absolutely necessary to interact with the computer, in some way such devices alters and/or limits the ability of users to manage the interaction. Therefore, new tools for an easier and natural interaction between human and computer have been designed in last ten years.

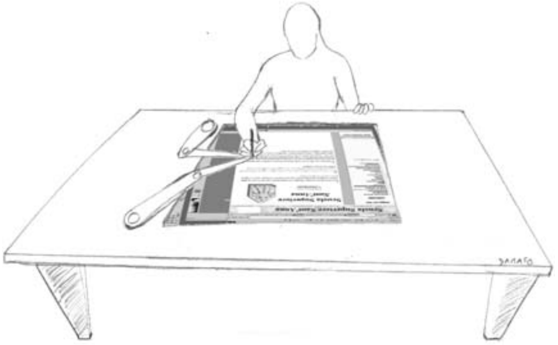


Figure 1: *The concept of the HDS system*

In 1991, Wellner proposed for the first time the concept of a digital desk [3, 4], which enables users to seamlessly handle both digital and physical objects on the desk by using a conventional video projector and CCD camera. Leibe proposed the Perspective Workbench [5] that is additionally equipped with infrared illumination lamps and infrared CCD cameras to import the object's shadows to reproduce its shape digitally. The Enhanced Desk and Augmented Desk [6, 7] by Koike were also equipped with an infrared camera to capture the user's hand motion as command input. The Smart Skin [8] by Rekimoto was equipped with a unique array of sensors to detect the user's hands motion on a table without cameras. The sensor used an electric capacitance meter that was affected by user's body, and many sensors were embedded under the desk. In all these systems, the virtual environment image is projected onto a common physical desk where the visual channels acts simultaneously as input/output device. Other studies have tried to introduce the force feedback information not only for replacing the conventional input devices but also for introducing novel output devices. In fact Dennerlein and Yang [9] suggested that the addition of force-feedback can improve operator's performance, and it potentially reduces the musculoskeletal loading caused by the use of the mouse, which may be a possible risk factor for chronics musculoskeletal disorders of the upper extremity. Then, some mouse-like devices with a force feedback mechanism were developed to reduce such load. Ramstein's Pantograph [10] employed a 2-DOF parallel link mechanism. Kelly proposed the Magic Mouse [11] using a 2-DOF linear DC motor. There are also commercial products such as the penCAT/Pro (Haptic Technologies Inc. [12]) and the haptic mouse (FEELit mouse) patented by Immersion [13] and Logitech [14]. In most of all these devices, the motion range is quite limited and even if they are able of exerting force feedback, mental load is not reduced and visual and haptic information is not co-located. The term co-location has been used to describe a haptic and a visual display that is calibrated such that visual and haptic coordinate systems are coincident. This means that the user can visually perceive an object in the same position in space as the haptic simulation [15, 16]. This criterion simplifies the required human perception process and facilitates its natural integration for allowing fast reflexive motor responses to the haptic stimuli. In fact, as it was presented in our previous research [17], which implemented a planar 2-DOF haptic interface with non-colocated haptic and visual information [18], when users must perform higher-level cognitive tasks, in that case Japanese Handwriting, the operator's performance can be significantly affected when the visual and haptic information is not coincident. Also Ware and Rose [19] noted that co-location between the hand and the virtual workspace improved performance in tasks involving object rotation. Up to now, few systems have been designed to provide co-located haptic/visual information to the operator. Reach-In [20] for example, integrates a 3D graphic system with a PHANToM device [21, 22]. Another example is the DaVinci system [23], which offers a collocated teleoperation environment able to lead surgical instruments to be remotely controlled through images obtained from optical sensors and presented by means of a system based on fixed screens. Although both systems described above allow users to interact with 3D environments, the limitation of the number of contact points and the complexity of the images displayed may demand a high level of skills for processing all the information. In fact, such systems are used only by specialists (i.e. doctors, designers, etc.) restricting the access to this technology. Furthermore, the need of special requirements for visualizing the 3D images and for providing the haptic information increases considerably the cost of such systems and the workspace required for placing the whole system. On the other hand, some solutions for integrating 2D systems have been proposed. Brederson proposed the Virtual Haptic Workbench [24], which integrates a PHANToM with a planar screen. Although the dimension of the workspace is quite big, the system requires a complicate calibration procedure. Moreover, the complexity of the haptic interface does not match with the requirements of the visualization system (2D). A different solution is based on linear induction motors fixed under the desk, which produce forces on a metallic plate fixed to the user's finger or to the end part of the tool [25, 26]. The disadvantage of this solution is that the visibility of the graphical system can be obstructed by the operator's arm. In fact the projector is not under the desk but is above user's head.

2. DESIGN GUIDELINES

Two types of design guidelines have been employed during the preliminary definition of the system: qualitative and performance guidelines. According to qualitative guidelines the device had to show ergonomic features, which make the use of the system very comfortable. These guidelines have regarded: the workplace, the quality of the visual feedback, the aesthetics of the system, and the modality of interaction. Another very important guideline was the reduction of mental load during the use of the device. The system design and control allow the user to feel and control haptic interaction just below his fingertips, while directly viewing the effects of his actions on the computer screen (co-location). Specific state of the art analyses [29] have verified that co-location greatly enhances the user performances in HCI while reducing the mental load of the interaction. The haptic device has therefore to be calibrated in order to collimate the position of the usage tool (end-effector), with the pointer within the computer screen. The accuracy provided in design, has to ensure that the sensitivity of the system is far beyond the pixel resolution of the screen. These guidelines have steered the main design choices of the system: the presence of the haptic interface has to minimally interfere with the visual feedback in fact it was decided to make use of transparent materials for building; all cables and connections has to be hidden to the user; the device has to offer the possibility of using a common pen as an interaction tool or the possibility of changing the end part with different tools; the device has to be able in any case to replace and substitute the mouse in all its basic functions (point, select, click,Ě); the kinematic of the device has to be designed in order to not interfere with the user limbs, it has to preferably move in the opposite space with respect the user; the device, whenever unused, has to be closable in order to left the desktop free. According to performance guidelines the device must have the following characteristics: a comfortable workspace wide enough to allow user to interact in writing operation: the workspace estimated had to cover at least the same dimensions of a notebook (270X360mm); for design and writing related applications a typical position resolution well below 1 mm was identified. Backlashes were not allowed in kinematic design. A set of preliminary experiments, carried out with pens in writing-and-contour-following-tests suggested a target continuos force of about 1-1.5N. Similar tests outlined a maximum residual mass of 0.2Kg. A high isotropy of the mechanical parameters (manipulability ellipsoid 1) was required all over the workspace in order to reduce the distortion effects and to maximize the exploitation of the motors. In order to achieve high control bandwidth and facilitate the system maintenance and development a high degree of integration with the hosting OS was required. Finally, in order to reduce the cost related to the system manufacturing two features were required to the system design: simplicity and possibility of manufacturing with low precision (low cost) technologies such as the laser cutting.

2.1. DESIGN OF THE HAPTIC DEVICE

According to the previous Design Guidelines, thefollowing design choices were made. An LCD monitor of the proper size and resolution 34x27 cm (1024x768 pixels) was chosen and integrated within a desktop plane. The haptic device is a 2DOF system, which employs a hybrid serial/parallel kinematic structure. This solution behaves an end-effector, which slides over the monitor and desk plane in correspondence with the computer pointer. The specific kind of materials adopted has chosen in order to reduce the friction factor among surfaces. In order to improve the performances of the haptic device (transparency, manipulability, workspaces, reflected mass), the following design choices have been adopted:

- Both actuators have been grounded and attached to the base link. As in parallel manipulators, the grounding of the motors allows to reduce the amount of movable masses and to increase the overall stiffness. The specific serial parallel design was used to transmit the actuation to the end effector and to solve the typical workspace limitations of parallel devices [30];
- Brushed DC motors have been selected: the amount of target force in this kind of applications is limited to few newtons; therefore the iron-less construction of the rotor allows the best compromise of performances;
- Capstans and metallic in tension tendons have been used as means of transmission of forces from the actuators to the joints. This solution allows completely avoiding geared transmission for the reduction of the transmission ratio, and therefore to avoid the backlash and friction issues related to this kind of solutions.

The structural parts have been realized with light materials (aluminium, plastic) and the used specific design allows the system to correctly operate even in presence of medium tolerance manufacturing. The whole system has been designed to be integrated with the work-plane of a desk: the computing unit, the power supply, the motors and the electronics for the control of the haptic interface have been placed under the desktop so that the desk plane is completely free and the operator has direct access only to the visual and haptic systems.

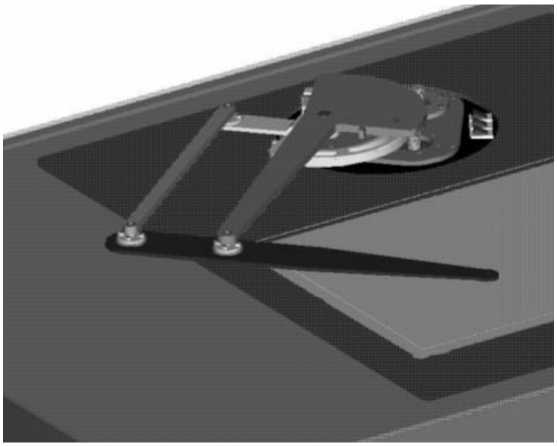


Figure 2: *Assonometric view of the haptic interface.*

Fig. 2 shows an assonometric view of the design prototype: in this system, on the desk plane only the required mobile parts of the interface are present; a new design of the prototype allows moving even the capstans and motor pulleys below desk plane. Three buttons have been left near the base of the haptic devicein order to control the computing-unit power, to enable force feedback, and to switch on/off the desk light.

3. OPTIMIZATION OF THE DESIGN

In order to evaluate the proper length of link 1 and link 2, a preliminary analysis was set. As basic assumption we required that the device should cover the whole workspace of the LCD while maintaining a good factor in the manipulability ellipsoid. The variation of the condition number of the manipulability ellipsoid (while the system moves over the workspace) was considered in this design phase. A script procedure was initially set up to estimate the conditioning number all over the workspace when links' sizes and interface position were changed. In Fig. 3, the best-case solution is graphically represented. The workspace areas have been coloured by the value of the condition number (c). The colour type changes at each tenth of unit. Central area has values between 0.9 and 1, second area values range between 0.8 and 0.9 and the third area values range between 0.7 and 0.8. More than 90% of the overall workspace has c>0.9

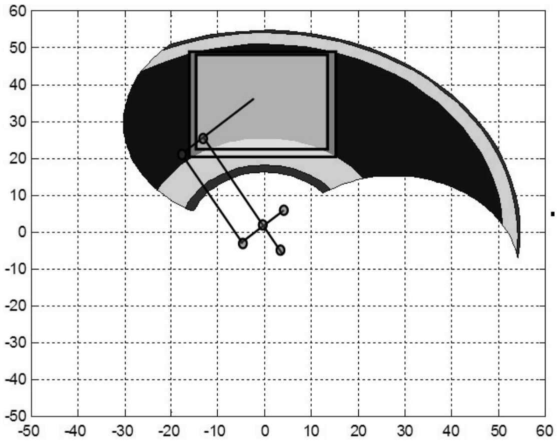


Figure 3: *Workspace evaluation*

In Fig. 4, the haptic desktop workspace in case of length of link 1 equal to 300mm and length of link 2 equal to 270mm is shown. Two capstans are used for reducing the inertia of moving masses and for introducing a reduction ratio. These reduction ratios have been dimensioned to obtain a condition number in the middle of the workspace equal to 1.

4. COMPONENT CHOICE AND CONTROL DESIGN

The kinematics of the haptic interface has been determined according to the chosen link lengths and the following equations describe end-effector's coordinates referred to the central pivoting joint:

$$X_{ee} = -L_2 \cos(q_2) + L_1 \cos(q_1) \tag{1}$$

$$Y_{ee} = -L_2 \sin(q_2) + L_1 \sin(q_1) \tag{2}$$

From (1) and (2) and are the lengths of link 1 and link 2 while and are the angles referred to the joints. On the other hand, the end-effector's coordinates referred to the motors, and can be computed as follows:

$$q_1 = \frac{r_1}{R_1}\theta_1 \tag{3}$$

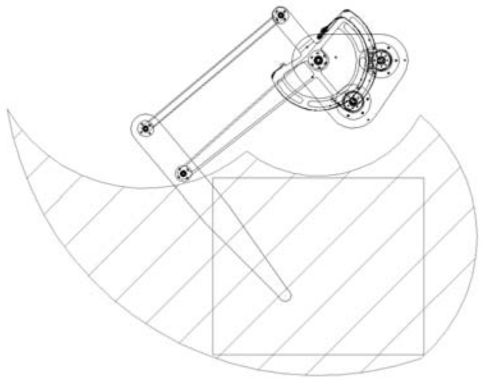


Figure 4: *Workspace of the haptic interface.*

$$q_2 = -\frac{r_2}{R_2}\theta_2 \tag{4}$$

From (3) and (4) and are the rotations of the two actuators, and are the radii of motor pulleys and and are the radii of the capstans. Using the above relationships it was possible to identify the commercial components to be used within the haptic device (motor type and size, sensors,Ě). The homogeneity of the conditioning number has allowed us to size out the design by using the workspace centre as reference point. Maxon motor 3557024CR was used for actuation. With this solution the Haptic Interface can generate on user's hand up to 3 N of continuous forces and 5 N of peak forces. To detect device motion 1024cpr optical encoders with a 4X decoding were adopted. Such a choice leads to a spatial sensitivity of about 30um at workspace centre (pixel size is about 300um).

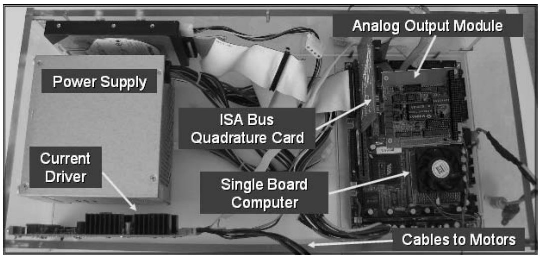


Figure 5: *Square box with all electronic components inside.*

This control system was implemented on the same architecture of the target application system. This device was made by an embedded PC (PIII 1.4GHz 256Mb RAM). Specific I/O board for detecting the encoder position and for generating the DAC command to be forwarded to drivers were implemented on the ISA and PC104 busses offered by the embedded board. The desktop backside was designed in order to host motors, power supply, hard disk, power drivers, mother boards and IO boards, all within a minimal regular square box as shown in figure 5. The high integration achieved has allowed us to implement all control procedures

a
fi

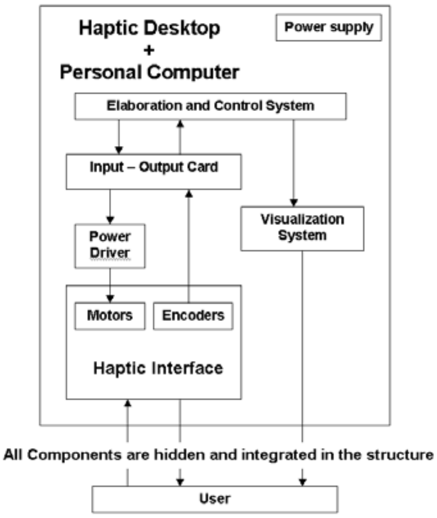


Figure 6: *Architecture of the system.*

Figure 7: *The Haptic Desktop system.*

Figure 8: *Device end-effector is made of transparent plastic material.*

Several functional control solutions are available for using the system: a basic mouse replacement toolkit allows making use of the system interface for controlling the pointer position within the screen and for interacting with the GUI; it is also possible to directly control the hardware device by software and/or control CAD; a set of functionalities libraries also implement main features for facilitating integration within application.

5. COMPONENT CHOICE AND CONTROL DESIGN

The HDS layout presents the device as a multifunctional desk (as shown in figure 7): the transparent haptic interface being designed using a plastic material with low refraction index can be grasped directly with the finger or manipulated by means of a sensorized pen.

The use of the haptic interface, as a bi-directional device, allows users to interact with the computer without any other interfaces: mouse and/or keyboard; this last functionality has been achieved by integrating specific commercial handwriting recognition tools on the operating system. At present the device can display haptic information according to specific control procedures written in a specific environment. It is foreseen to develop a wide set of programming libraries in order to exploit the system capabilities within several office automation application: this enlarges and reinforces the information exchanged between the human and the computer compared with the traditional ways of accessing the computer resources.

Several tools can replaced the end effector in order to perform different kinds of task, for example:

- Virtual pen tool: a cylindrical part handled by the user like a common pen;
- A barrel made of transparent material on which the user can grasp the interface by using his/her finger;
- A real pen for writing directly on sheets of paper.

6. EMPLOYMENT OF THE SYSTEM

The developed system, besides guaranteeing the complete interaction offered by traditional systems, adds at least three new functionalities:

- The possibility of accessing the computer resources by controlling the graphical cursor that is coincident with the interaction point [27] (Fig. 8). By attaching a pen stylus, the writing and designing tasks (Fig. 9) becomes easier than using the conventional input devices (mouse, track-ball, etc.).
- The possibility of interacting with the software resources of the computer by adding force feedback information to the operator's imputs. This makes possible the creation of a new kind of interaction with the user so that users can "touch" buttons, "feel" and "move" lines and the haptic device can replace the use of compasses, squares and/or other drawing instruments. This kind of interaction offers the possibility of using the system as a training tool (e.g. eEducation [17]) or as a therapeutic tool (e.g. reducing tremor [31]).

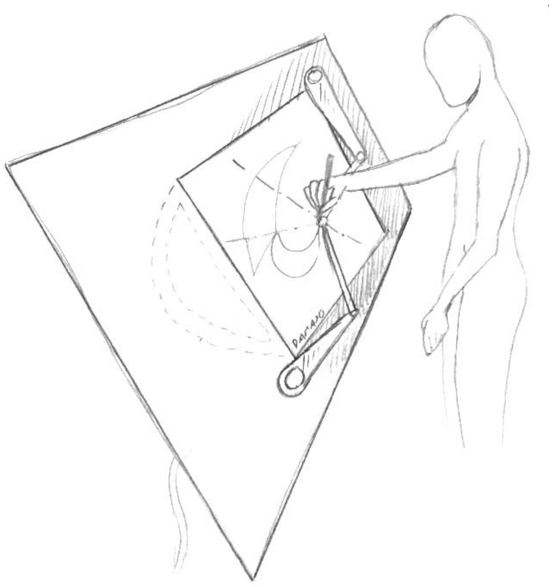


Figure 9: *An example of how to use the system for designing*

- The possibility of using the instrument to produce internal/external stimuli while the operator interacts with real elements such as pens, pencils, papers, etc. (Fig. 10). For example, the operator can use the device with his/her own pen and paper for verifying the improvement of the student after a training process programmed on the haptic interface (e.g. technical drawings).

7. ACKNOWLEDGEMENTS

The activities described in this work have been carried out within the EU NoE Enactive. The authors are grateful to European governments whose grants constituted a valid cofinancing of the presented research. The authors also thank the partnership of the mentioned project.

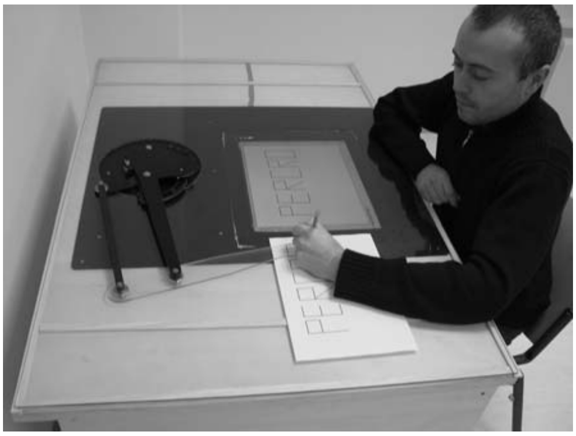


Figure 10: *Haptic Desktop system can interact with operators by means of different tools such as pens, pencils, paper, etc.*

8. CONCLUSION & FUTURE WORK

The Haptic Desktop reduces the actual workspace needed for accessing computer resources. Thanks to the integration of electronic devices, the encumbrance related to the connectors of the conventional devices has been disappeared. The novel interaction approach of the HD leads to the satisfaction of the following objectives:

- The coherence and collocation between the haptic and graphical information is assured;
- The addition of force feedback as an additional perceptual channel for enhancing the interaction between user and computer;
- The possibility of integrating real instruments for rendering more natural means of interaction, i.e. pen, sheet, etc.;
- The access to computer resources is more simple, as the interaction point is coincident with the graphical cursor of the system;
- The introduction of haptic information linked to operator movements and/or events can be programmed.
- The use of the system as a transfer skill system for enhancing human skills and/or as a rehabilitation tool for disable people;
- The integration of different perceptual channels (i.e. haptic, visual, and audio) makes possible to generate real immersive experiences for the user;
- The replacement of conventional drawing instruments is possible by using the haptic device.

We are actually developing applications on the system for verifying the added functionalities of the system for enhancing the interaction between the human and the computer. There are two main application fields already under development: a transfer skill system for teaching [28] how to design to unskilled persons (e.g. children) and a system for aiding people affected by tremor. The first type of application will address the ability of achieving nice drawing of objects from the collection of digital images which are preprocessed for detecting the principal features of the objects (i.e. edges, size, etc.), the focus of the application is centred on the ability to transfer the design skills from the application to the user; in the second type of application a specific filtering strategies [31] is applied as a force controlled feedback to the user hand in order to damp involuntary vibratory movements.

9. References

[1] Engelbart Douglas, X-Y Position Indicator for a Display System, Patent Number: US354154, Publication Date: 1970-11-17.

[2] C.P. Thacker, E M McCreight, B.W. Lampson, R.F. Sproull, and D.R. Boggs, *Alto: A Personal Computer*, Tech Rep CSL-79-11, Palo Alto CA: Xerox Palo Alto Research Center, August 1979.

[3] Wellner, *Tangible manipulation on a desk top display*, ACM Symposium on User Interface Software and Technology '91, pp. 27-34, 1991.

[4] Wellner, *Interacting with paper on the Digital Desk*, Communication of the ACM, Vol. 36, No. 7, pp. 87-96, 1993.

[5] Leibe, Starner, Riarsky, Wartell, Krum, Singletary and Hodges, *The perceptive workbench: toward spontaneous and natural interactive in semi-immersive virtual environments*, In Proceedings of IEEE Virtual Reality '00, pp. 13-20, 2000.

[6] Oka, Sato, and Koike, *Real-time tracking of multiple fingertips and gesture recognition for augmented desk interface system*, In Proceedings of Automatic Face and Gesture Recognition '02, pp. 411-416, 2002.

[7] Koike, Sato and Kobayashi, *Integrating paper and digital information on enhancedDesk: a method for real time finger tracking on an augmented desk system*, ACM Transactions on Computer-Human Interaction, Vol. 8, No. 4, pp. 307-322, 2001.

[8] Rekimoto, *Smart skine: an infrastructure for freehand manipulation on interactive surfaces*, In Proceedings of ACM Conference on Human Factors and Computing System '02, pp. 113-120, 2002.

[9] J.T. Dennerlein and M. Yang, *Perceived Musculoskeletal Loading during Use of A Force Computer Mouse*, In Proceedings of Human Factors and Ergonomics Conference, Houston, 1999.

[10] Ramstein and Hayward, *The Pantograph: A Large Workspace Haptic Device For A Multi-modal Human-Computer Interaction*, In Proceedings of Conference on Human Factors and Computing System '94, pp. 57-58, 1994.

[11] Kelly and Salcudean. *The Development of a Force Feedback Mouse and its Integration into a Graphical User Interface*, In Proceedings of the International Mechanical Engineering Congress and Exposition, DSC-Vol. 55-1, pp 287-294, 1994.

[12] Haptic Technologies web site: www.haptech.com.

[13] Immersion web site: www.immersion.com.

[14] Logitech, Ltd. www.logitech.com.

[15] S.A. Wall, K. Paynter, A.M. Shillito, M. Wright and S. Scali, *The Effect of Haptic Feedback and Stereo Graphics in a 3D Target Acquisition Task*, In Proceedings of Eurohaptics 2002, University of Edinburgh, 8-10th July, pp 23-29.

[16] C.A. Avizzano, S. Marcheshi, and M. Bergamasco, *Haptic Interfaces: Collocation and Coherence Issues*, In Proc. of Multi-point Interaction in Robotics and Virtual Reality, IEEE International Conference in Robotics and Automation, 2004.

[17] J. Solis, C.A. Avizzano, and M. Bergamasco, *Teaching to Write Japanese Characters using an Haptic Interface*, In Proceedings of the 10th International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, Orlando, FL, 2002.

[18] A. Frisoli and M. Bergamasco, *Experimental identification and evaluation of performance of a 2 DOF haptic display* Robotics and Automation, 2003, In Proceedings of ICRA '03. IEEE International Conference on,Volume: 3, 14-19 Sept. 2003 Pages:3260 - 3265 vol.3.

[19] C. Ware, J. Rose, *Rotating Virtual Objects with Real Handles*, ACM Transactions on CHI., 6(2), 1999, pp.162-180.

[20] Reachin web site: www.reachin.se.

[21] Thomas, Massie and Salisbury, *The PHANTOM Haptic Interface: A Device for Probing Virtual Objects*, In Proceedings of the ASME Winter Annual Meeting, Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, Chicago, IL, Nov. 1994.

[22] SenseAble Technologies Inc. 15 Constitution Way Woburn, MA 01801, USA, www.senseable.com.

[23] Intuitive web site: www.intuitivesurgical.com.

[24] Bredson, Ikits, Johnson and Hansen, *The Visual Haptic Workbench*, In Proceedings of Fifth PHANTOM Users Group Workshop ’00, pp. 46-49, 2000.

[25] Pangaro, Maynes-Aminzade and Ishii, *The actuated workbench: computer-controlled actuation in tabletop tangible interfaces*, In Proceedings of ACM Symposium on User Interface Software and Technology ’02, pp. 181-190, 2002.

[26] Noma, Yanagida and Tetsutani, *The Proactive Desk: A New Force Display System for a Digital Desk Using a 2-DOF Linear Induction Motor*, In Proceedings of the IEEE Virtual Reality 2003.

[27] H. Margrethe, H. Olson and C. Lucas, *The impact of office automation on the organization: some implications for research and practice*, Communications of the ACM, Vol. 2, Issue 11, 1982, pp. 838-847.

[28] P. Baumgarter and I. Bergner, *Categorization of virtual learning activities*, Eden Conference, Oldenburg, 2004. [29] G. Jansson and M. Öström *The Effects of Co-location of Visual and Haptic Space on Judgments of Form* EuroHaptics 2004.

[30] A. Frisoli, M. Prisco, F. Salsedo and M. Bergamasco, *A two degrees-of-freedom planar haptic interface with high kinematic isotropy*, Robot and Human Interaction, 1999. RO-MAN ’99. 8th IEEE International Workshop on , 27-29 Sept. 1999. Pages: 297 - 302.

[31] C.A. Avizzano and M. Bergamasco, *Technological aids for the treatment of the tremor*, ICORR, Stanford, 1999.

Dynamic modeling of primary commands for a car simulator

A. Frisoli *, C. A. Avizzano *, M. Bergamasco *, S. Data **, C. Santi **

PERCRO - Scuola Superiore S. Anna - Pisa - Italy
** Vehicle Dynamics Division - Centro Ricerche Fiat- Orbassano (Turin) - Italy

---

Abstract

Simplified dynamic analytical models of primary commands of a car, i.e. steer wheel and gearshift, are identified and developed in the paper. The dynamic models are used to design the control law of force feedback devices, which will be integrated in a car simulator. The model simulation results match satisfactorily with the experimental available data. An experimental partial assessment of control law for the gearshift simulation has been performed with a commercially available force-feedback joystick. The gearshift simulation control is implemented with an hybrid model, based on a state machine. The results are presented and discussed.

---

1. Introduction

Vehicle simulators, and in particular aircraft simulators for use in training pilots, are generally equipped with various control devices such as acceleration pedal, brake pedal, clutch pedal, gear change lever and steering wheel, to enhance the realism of the simulation.

In most of such simulators [SGEa95, AJ94, PMea94], control commands are employed as passive sensorized systems, which measure the commands executed by the user. In such systems the force behavior is regulated by the mechanics of the control commands, designed to replicate the force response of real commands.

The adoption of Haptic Interfaces (HI) within simulator systems appears to be an added value which improves the functionalities of the simulator. The mechanical response of HI can be logically programmed and controlled. In such a way in tests within simulator users can evaluate the vehicle by changing either kinesthetics or Haptic parameters. This is particularly useful when ergonomics aspects are taken into consideration [vir99, RR99].

In [WJHJ98] the steer wheel was replaced with a force controlled Haptic Interface, whose behavior was based on an internal numerical model of the vehicle.

The ATARI corporations patented two inventions regarding the simulation of a gearshift [LMJDa, LMJDb]. The devised systems are based on a mechanism which allows the gearshift lever to pivot around at least two axes. In the first invention [LMJDa] the mechanism is equipped with electrically operable clutches, that can cause only resistance to the movement of the lever. Positional sensors and strain gauges coupled to the gearshift lever are used to sense the lever movements and forces. In the second invention [LMJDb] a solenoid is coupled to the pivoting mechanism and controls the amount of force applied.

This paper concerns the dynamic modeling of the primary commands of a car, i.e. the steering wheel and the gear shift. Models have been set up to replicate the forces felt by the driver during a real drive in a car simulator, aimed at evaluating the ergonomics of internals of car in Virtual Environments [vir99]. The mechanical response (i.e. the exerted force related to the displacement imposed by the driver) of these primary controls will be controlled via software.

In this paper the control and dynamics models of the steering wheel and manual gearshift are presented and analyzed. The Haptic Interfaces, to be used for the simulation of the primary commands, and the simulator mock-up are currently under construction. The results of a preliminary evaluation of the gearshift control model are reported, as obtained with a commercially available force feedback joystick. The control law will be finally implemented on a 2 DOF Haptic Interface prototype, currently under construction at PERCRO.

2. The steering wheel model

The steering wheel torque estimation is based on a simplified model, that allows to perform the simulation in real time, by reducing the computing time required by a complete vehicle model. The solution is calculated through an algebraic formula, instead of a system of differential equations. The steering wheel simplified model calculates the torque τ at the steering wheel as a function of the vehicle longitudinal velocity V_x and the steering wheel angular displacement δ_w. The approach proposed in this section has been validated by experimental data collected for a FIAT PUNTO. The steering wheel torque can be split into different terms to clearly show the physical meaning of the equation:

$$\tau = \tau_i(\ddot{\delta}_w) + \tau_0(A_y) + \tau_1(V_x, \dot{\delta}_w) + \tau_2(\dot{\delta}_w) + \tau_3(\dot{\delta}_w) \quad (1)$$

The term τ_i is the inertial torque. Knowing the steering wheel moment of inertia J_w, the value of τ_i is:

$$\tau_i(\ddot{\delta}_w) = J_w \ddot{\delta}_w \quad (2)$$

The term τ_0 is the torque due to the vehicle lateral acceleration A_y, which has been derived from the linear time-invariant bicycle model. However, since it is not correct to consider that the vehicle behaviour is linear in every condition, so the lateral acceleration of the bicycle model $A_{y,b}$ has been adjusted to fit with experimental data. The relation between the A_y and $A_{y,b}$ derived from the bicycle model is:

$$A_y = K \cdot \max(A_y) \cdot tan^{-1}(\frac{A_{y,b}}{K_0}) \quad (3)$$

On the basis of equation 3, the expression of τ_0 determined by interpolation of track data acquisition is:

$$\tau_0 = \frac{K_1 A_y}{1 + K_2 A_y^{K_3}} \quad (4)$$

The term τ_1 is the torque due to the tire spin. The parameter that most influences this torque is the vehicle longitudinal velocity V_x. In order to have the torque sense and avoid discontinuity, the steering wheel angular velocity is also taken into account in the following equation:

$$\tau_1 = \frac{1}{K_4 + K_5 V_x} \cdot tan^{-1}(\frac{\dot{\delta}_w}{K_6}) \quad (5)$$

The term τ_2 is the torque due to the friction present in all the steering system:

$$\tau_2 = K_7 \cdot tan^{-1}(\frac{\dot{\delta}_w}{K_8}) \quad (6)$$

The term τ_3 represents the damping contribute:

$$\tau_3 = K_9 \dot{\delta}_w \quad (7)$$

To sum up, some comparisons between the values of the steering wheel torque, calculated with the proposed method, and the experimental data, collected on the track for an FIAT PUNTO, are represented below. Different kinds of manoeuvres have been used for the model validation: "steady state" manoeuvre (Fig. 1), "steering wheel angle imposed" manoeuvres (Fig. 2 and 4), "trajectory imposed" manoeuvre (Fig. 3)

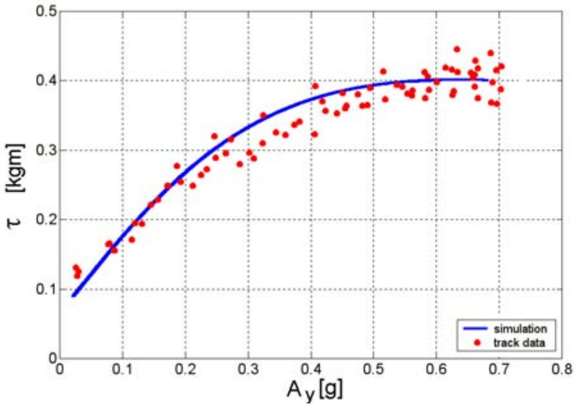


Figure 1: *Steering pad manoeuvre ISO 4138 with radius of 40 m*

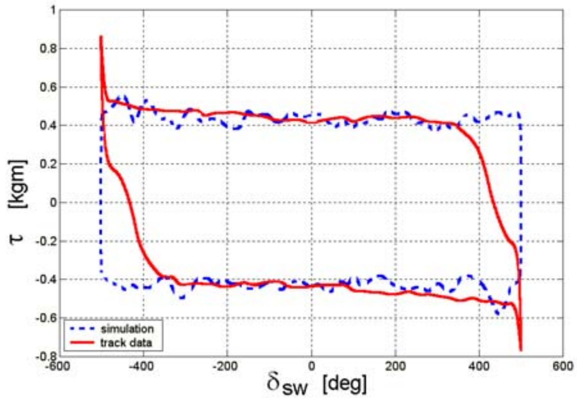


Figure 2: *Complete steer cycle with* $V_x = 0$

The graphics above attest that the algebraic formula proposed for steering wheel torque estimation, only as a function of the vehicle longitudinal velocity V_x and the steering wheel angular displacement δ_w, completely satisfies the design demands of precision and real time calculation. However, there are some situations in which a more accurate and complicate steering wheel system model would be necessary, as for example during steering wheel release manoeuvres, in fast dynamics and near the steering wheel stops (Fig. 2).

3. The gearshift model

Differently from other primary controls, the gearshift force behavior is highly non-linear and unpredictable, since is related to the instaneous collisions that occur in the gearbox.

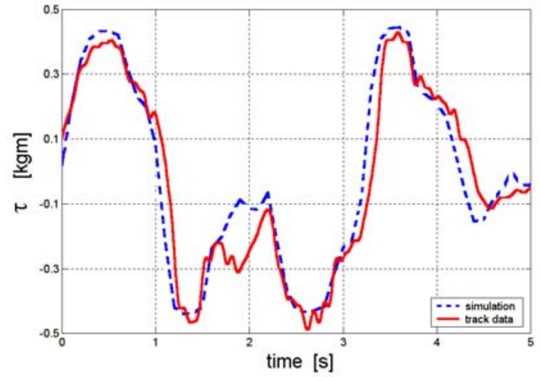


Figure 3: *ISO 3888 lane change manoeuvre with rms(A_y)=0.381 g*

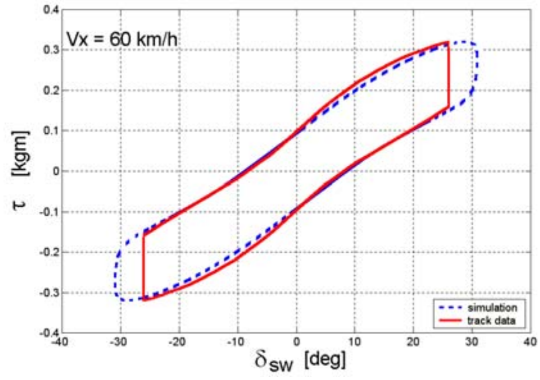


Figure 4: *Sinusoidal steer input manoeuvre ISO 7401 with* $V_x = 60Km/h$

In the following it is presented an analytical approach for modelling the gearshift force response, based on the force contents displayed during the engagement as measured experimentally, and a preliminary assessment of results. Prior to introduce the model implementation, a brief description of the gear engagement is given, considering the involved mechanical aspects.

3.1. Mechanical description of a manual transmission gearshift

The gearshift allows to change the gear ratio between the primary shaft, connected by the clutch to the motor, and the secondary shaft, which conversely is permanently connected to the differential unit, and so to the wheels shaft. In the following the clutch pedal is always considered pushed to the floor. In a manual transmission the driver can move the gearshift lever horizontally (y) to select and vertically (x) to engage the gear. The gearshift lever is connected to the gearbox, placed generally in the front part of the car, through an external command system.

The external command converts the movements of the gearshift lever in movements of a coupling in the gear-box. The couplings in the gear-box are generally sliding keyed either to the primary or to the secondary shaft. For instance suppose that the coupling is keyed to the secondary shaft (this is commonly the case of the coupling that engages the first and the second gear). Two gears are keyed with the primary shaft, and are permanently in mesh with two corresponding gears idle on the secondary shaft. The coupling can engage one of the idle gears on the secondary shaft, with a sliding motion along the shaft (vertical movement of the lever), and so can create the motion transmission between the primary and secondary shafts. Since the idle gears are driven by the primary shaft, the relative angular velocity between the idle gear and the coupling is not null, before the mesh occurs. In order to allow a quiet and smooth engagement, the two gears to be engaged in the actual transmission must be brought to approximately the same angular velocity. This is realized by an intermediate synchronizing ring in two stages: pre-synchronizing and synchronizing. Only after the synchronizing stage the full engagement takes place.

3.2. The gear engagement process

Three different main stages occur during the gear engagement, which characterize the particular force response of a gear-shift: the synchronizing, the engagement and the impact against the mechanical stop. Since the engagement is a multi-body dynamical process, each stage is associated to the interaction of different parts in the gear-box. In the following the forces felt during a gear engagement are explained according to the gear-shift dynamics.

A spring-ball system (placed in the housing of the lever mechanism) constrains the lever in the selected gear position. So an initial preset load must be applied to displace the lever from its equilibrium position.

After the lever has been released, another preset load must be applied to displace the coupling from its neutral position. In fact the coupling is hold in the neutral position by a second spring-ball mechanism (placed in the gear-box), whose function is to accomplish a softer mesh of the synchronizing ring and the coupling. This is the pre-synchronizing stage.

After the pre-synchronizing stage has been achieved, the synchronization can begin. The coupling engages the synchronizing ring and pushes it against the gear. The internal conical surface of the synchronizing ring is brought in contact with the external conical surface of the gear, which is rotating dragged by the primary shaft. The tangential friction forces, which the two bodies exchange in reason of their relative motion, are transformed in axial forces, through the taper of the synchronizing ring, and impede a further sliding motion of the coupling.

Until a relative motion between the synchronizing ring and the gear exists, the coupling (and so the gearshift lever) is blocked into a fixed position and can not go forward. Only when the relative velocity becomes null, the “synchro gate" can open and the coupling can continue its sliding motion.

At the end of synchronization, the block of the coupling is released and so the coupling teeth of the gear and synchronizing ring collide and then mesh. The main feature of the coupling tooth contact is that the generated impact forces are random, depending on the relative position of teeth at the moment of the engagement. After the full engagement, the lever reaches its mechanical stop, based on a spring-ball mechanism also.

The data displayed in figures 5 and 6 reveal typical force characteristics with respect to time and engagement position. Both plots have been collected by sensorizing the gearshift knob aboard an experimental car.

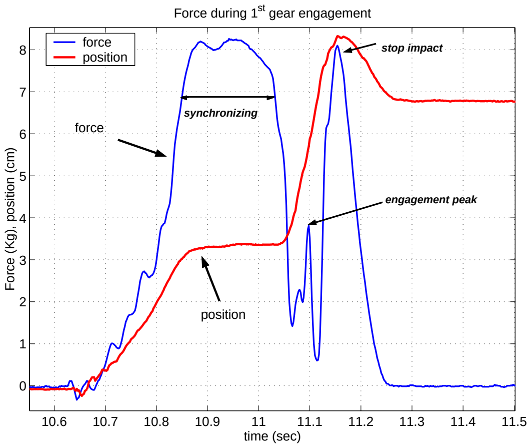


Figure 5: *Force and position vs. time, as measured at the knob during neutral-first gear shift (courtesy of CRF)*

The pre-synchronizing stage can be reasonably rid off in the simulation, since it generates a negligible force peak only.

During the synchronizing phase both the force and the position are held constant, as shown in figure 5. The force reaches its maximum value, and the position is held constant for a definite period of time.

The engagement stage is characterized by an isolated peak force, that is lower than the synchronizing force peak. Moreover the magnitude of such pick force is variable, so that engagement peaks can vary remarkably.

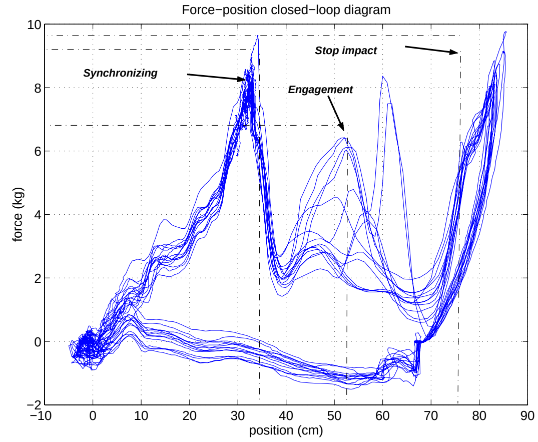


Figure 6: *Force vs. position, as measured at the knob during neutral-first gear shift (courtesy of CRF)*

As shown in figure 6 the synchronizing and the engagement peaks occur at definite values of the x position. In particular the synchronizing stage reaches a peak value of about $8\,Kg$, and has a duration of about $0.3\,msec$. The engagement peak is instantaneous instead, since it is due to the impact of the gears teeth.

The final stage gives raise to the stop impact peak. Since it is mediated by an elastic stop system, there is an overshoot and a following recovery to the equilibrium point, as in figure 5.

The forces that the driver exerts on the lever, when he changes into a gear, are so determined mainly by the stages of synchronizing, engagement and stop impact. A realistic simulation of a gearshift must replicate rigorously these three phases, and it can neglect the pre-synchronizing stage, because of both its low endurance and small forces.

3.3. The gearshift engagement model

An analytical model of the gearshift behavior was synthesized to replicate a correct force-feedback to the operator. The different phases of the gear shift have been modeled through a dynamic model with both continuous and discrete states (each discrete state was associated to a gearshift stage). The gearshift response has been developed as a MATLAB Simulink/Stateflow module, since it represents an hybrid model in itself.

The GEARSHIFT ENGAGEMENT model, shown in figure 7, takes as input the user forces exerted on the knob and provides as output the knob position and velocity. The model can be divided in two parts:

1. A time varying continuous dynamics which depends on the gear stage (GEARSHIFT DYNAMICS).
2. A discrete state machine (GEARSHIFT STATE-FLOW) which determines the gear stage on the basis of the knob position, the user’ s force and the previous machine state.

The GEARSHIFT DYNAMICS has been implemented

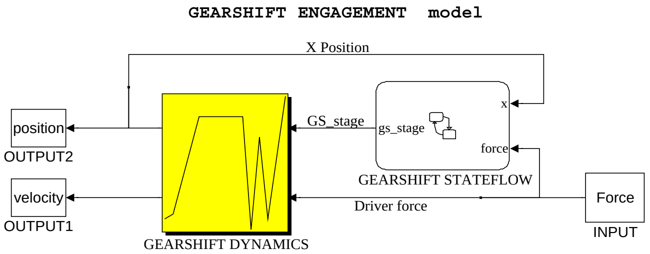


Figure 7: *The GEARSHIFT ENGAGEMENT module in the gearshift model*

as a parametric mechanical system composed of a mass m, spring k, damper c with a stick-slip friction:

$$F_{dr} = m\ddot{x} + c\dot{x}s + k(x - x_0) + F_{fr} \tag{8}$$

where F_{dr} is the driver force, x the position and the friction force F_{fr} is given by:

$$F_{fr} = \begin{cases} F_{dr} & \text{if } F_{dr} - c\dot{x} - k(x - x_0) <= F_{st} \\ & \text{ and } \dot{x} = 0 \\ \text{else} & F_{sl} \end{cases} \tag{9}$$

with F_{st} and F_{sl} respectively the static and dynamic friction coefficients. The parameters $m, k, c, x_0, F_{st}, F_{sl}$ are set to different values for each stage by the GEARSHIFT STATEFLOW module, according to the current stage.

The GEARSHIFT STATE-FLOW module receives as inputs the x position of the knob and the force exerted by the user. The discrete states of this module represent the different gearshift stages outlined in previous subsection, and so the synchronization, the engagement and the end impact. Moreover free motions states have been added to model the lever behavior out of these stages. Figure 8 shows a simplified scheme of the state machine, which simulates the engagement process.

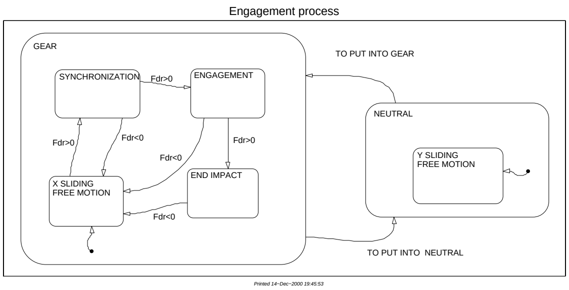


Figure 8: *Simplified scheme of the stateflow for the gear engagement*

The input information are used to manage the transitions among different states. For instance if the user is pushing forward during the synchronization state, a transition is activated to reach the engagement state. Conversely if the force is suddenly reverted, an in-transition to a free motion state is activated.

The conditions under which the transitions can occur are based not only on position and force, but on time also. So the duration of the synchronization stage is imposed by a time-dependent out-transition from this state.

Actions and events broadcasting are associated both to the transitions and to the states. In particular different assignments to logical variables are executed according to the active state. The logical variables, containing the information about the active state, are then output to the GEARSHIFT DYNAMICS module, to control the current values of the simulation parameters.

3.4. Simulation of the engagement model

To test the efficiency of such a model, a driver module was also implemented in the Simulink environment.

The driver has been modeled assuming that his force behavior is inversely linear related to the gearshift knob velocity:

$$F = F_{max}(1 - \frac{\dot{x}}{V_o}) \tag{10}$$

where V_o is the target velocity and it is assumed equal to the maximum one measured during the engagement movement, while F_{max} corresponds to the maximum force that the user can apply. Such a force model with a velocity feedback of the driver can be adapted to fit the behavior of different drivers.

The driver module has so been interfaced to the GEARSHIFT ENGAGEMENT module in a velocity closed-loop (the position output of the GEARSHIFT ENGAGEMENT module has not been used in this simulation).

Figure 9 shows numerical results achieved during the simulation. As shown in the figure all main stages of engagement are replicated by the model. Model parameters have been regulated in order to match maximum forces, position and reference times to those of the experimental results.

3.5. Experimental validation of the gearshift model

A 2 dof force feedback joystick has been employed for carrying out an experimental validation of the engagement model. For such purpose we adopted the "Wingman Force Feedback Joystick" by Logitech, a commercially available device with proper drivers and control board.

The Joystick is equipped with two DC motors and two analog potentiometers, which are connected to the handle through a 2 DOF parallel pivoting mechanism. Such a mechanism allows the lever to pivot around two co-planar axes. The motors transmit the torque through a capstan tendon

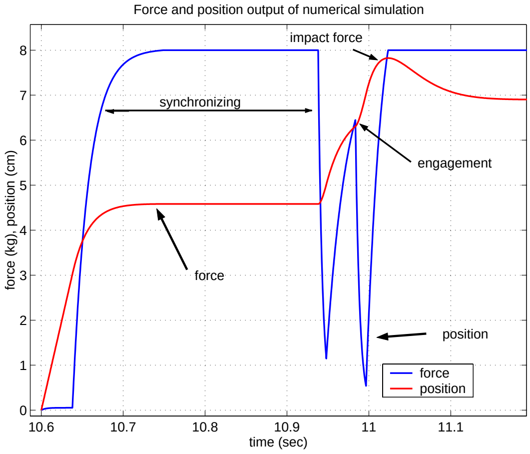


Figure 9: *Force and position vs. time output by the numerical simulation*

transmission system, both to increase the motor torques and to reduce the mechanical plays between motors and potentiometers.

Since our aim was to test the efficiency of the algorithm, we excluded the built-in control processor, and connected the Joystick to a high performance control board (DSP DS1102 dSPACE). By a rough estimation of the maximum actuated force at the knob with the DSP arrangement, we found a value of about $\sim 10N$, that is one tenth of the target force of $10\,Kg$ we wished to replicate. Also the workspace dimensions were smaller than the required ones. So the presented results was scaled to the experimental ones of figures 5, just to test the validity of the control algorithm.

We interfaced the Joystick to the Matlab environments through the Real Time Workshop toolbox. The model was downloaded and run directly on the DSP board. A GUI interface panel was developed to control and capture the data of the simulation.

All simulations were performed at a frequency of 1 KHz to avoid problems related to simulation sampling time.

First we tested the force feedback during pure engagement operations. The force-feedback control scheme was based on a admittance force-display [RB99], which measures force and displays motion. The forces were estimated by the current inputs, sent to the motor drives, while the positions were read by two analogical potentiometers.

During simulation the y position of the joystick was constrained to zero to simulate a 1 DOF sliding constrain.

The following plots show the obtained results. The error on the force signal was determined by the electric noise produced by the analog potentiometers. Plot 10 shows the filtered (with a low pass Butterworth filter and a cut-off frequency of 20 Hz) and the non-filtered signal. The curve matches satisfactorily the experimental one, and also the feeling during the engagement was realistic and similar to a slow gear engagement during drive. The hardware restrictions did not allow to improve further the performance of the system (position signal resolution and noise, internal mechanical play, friction), but the devised control law seemed to work properly.

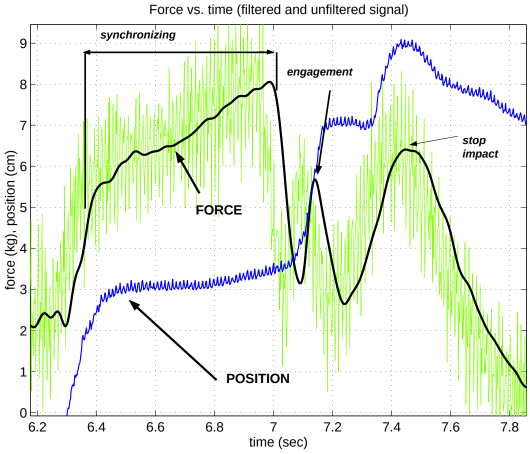


Figure 10: *Force signal estimated from the position error*

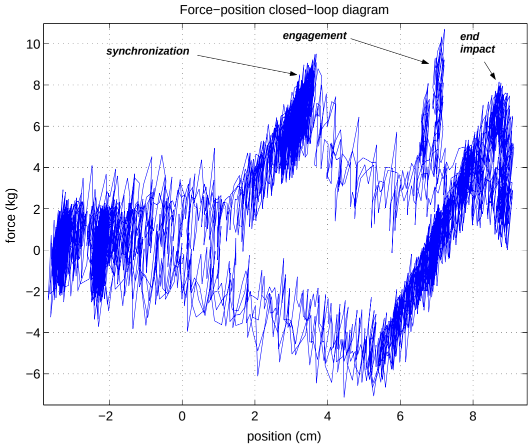


Figure 11: *Force vs. position loop diagram during neutral-1^{st} gear shift*

After the simulation of a single gear engagement, we stepped to the development of a complete gearshift. The model was extended to consider the constrains imposed by the slides of each gear. The y axis was controlled by using a parametric module similar to that of the x axis, but with a lower number of states. In particular the workspace of the gearshift was divided, according to the x and y, into numerous areas, associated to a different state of the gearshift. A main state-flow module, called STATE-FLOW MANAGER, identifies the current area, and forwards this information to the X and Y controller modules. Inside these modules, the action executed, either selecting horizontally a gear or engaging vertically a gear, is recognized, and the corresponding state behavior is activated. For instance when the user is engaging a gear, the previously analyzed model of a single gear is activated. The slides constrains were replicated as mechanical impedances, which restrain the knob into rectilinear trajectories.

The final simulated workspace is shown in figure 12.

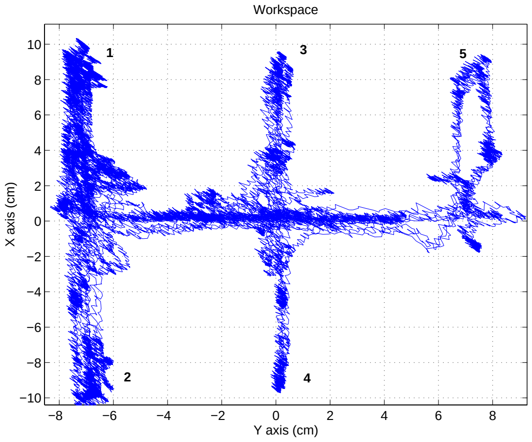


Figure 12: *The simulated workspace (scaled)*

4. Future Developments

The haptic interfaces dedicated to the primary commands simulation are currently under construction at PERCRO and successively will be integrated in the mock-up of the system. The limitations encountered in the gearshift simulation control of a commercial joystick will be overcome by the new HI, specifically designed to satisfy the requirements of a gearshift simulator.

5. Conclusions

In the present paper an analytical model of the primary commands for a car simulator have been presented. The models are based on experimental data and simplified in order to accomplish a real-time simulation of the real force response in a Virtual Environment.

6. Acknowledgements

The authors are grateful to CRF (Centro Ricerche FIAT) for the provided technical support. This research was supported by European Commission “GROWTH” Programme Research Project “Virtual” (Virtual reality systems for perceived ergonomic quality testing of driving task and design) under contract nr. 1999-RD.11030.

References

[AJ94] A. G. J., J. P. T.: Driving simulation at ford. *Automotive Enginneering* (1994). 1

[LMJDa] L. M. R., M. B., J. D. E., D. A. J.: Gearshift for a vehicle simulator having a solenoid for imposing a resistance force. Patent US5197003. 1

[LMJDb] L. M. R., M. B., J. D. E., D. A. J.: Gearshift for a vehicle simulator using computer controlled realistic real world forces. Patent US4949119. 1

[PMea94] P. B. G., M. J. C., ET AL. K. J. W.: Driving simulation at general motors. *Automotive Engineering* (1994). 1

[RB99] R.J. A., B. H.: Stable haptic interaction with virtual environments. *IEEE Trans. Rob. Autom.* (1999). 6

[RR99] R. N. M., R. L. G.: Virtual dynami prototyping for operator interface design. In *Proc. of IEEE Ro-Man* (September 27-29 1999), pp. 357–361. 1

[SGEa95] S. F. J., G. W., E. P. Y., AL.: The iowa driving simulator: an implementation and application overview. *SAE paper 950174* (1995). 1

[vir99] *Technical Annex of 1999-RD.11030-ViRtual project*. Tech. rep., GROWTH Programme, 1999. 1

[WJHJ98] W.S. L., J.H. K., H. C. J., J L. S.: Driving simulator as a virtual reality tool. In *Proc. of IEEE ICRA* (May 16-20 1998), pp. 71–76. 1

A novel fingertip haptic device

G. Cini, A. Frisoli, S. Marcheschi, F. Salsedo, M. Bergamasco

PERCRO Scuola Superiore S. Anna, Italy

Abstract

This paper presents a new concept of fingertip haptic device for the display of local contact geometry on the user's fingerpad. We propose an extension of the encountered haptic interface concept [YY04], in order to build an active haptic thimble, that is portable and can be fixed to the user's finger. The device is endowed with an actuation system that controls the motion of a platform, that can come in contact with the fingerpad with different orientations and at different fingerpad locations, simulating the contact with a virtual surface. A prototype of the device has been built and tested and is presented throughout the paper.

1. Introduction

Haptic interaction with virtual environments is ideally meant to provide an intuitive method of exploration. In [KLM85], it was shown that haptic perception by free exploration with hands can be accurate and fast. This type of performance, however, has not been duplicated in experiments with constrains on the number and natural movement of fingers. In [Ka93], it was found that free hand exploration is more efficient than outstretched five-finger exploration, which was subsequently more efficient than one outstretched finger. G. Jansson [Jan00] in discovered a significant detriment in performance when only one finger was available for exploration of common objects. In an earlier experiment, also reported in [JM03], he found that numbers of fingers had a great effect on the efficiency in identification of real objects, the largest difference appearing between the One finger and the Two fingers conditions.

A further experiment conducted by the G. Jansson involved an haptic display condition with not differentiated information within the contact region, simulated by a hard sheath attached to the finger(s) in contact with the objects, similar to the one used by [KL99] when studying some other haptic functions. A personal communication from the same author, supported by experimental data reported in an internal report [Jan04], confirmed that in the Sheath conditions there was no difference in Exploration time at all between the One finger and the Two fingers conditions, according to the experimental findings. This suggested that the effect of restrictions on the fingerpad contact region can limit the added value of having multiple contact points on more fingers. In [AF04], Frisoli et al. performed an experiment to explore the difference in performance for object recognition as the number of contact points of an haptic interface is increased using either the right hand or both. The conditions with two fingers did not show up any substantial improvement in the recognition task, and on average the one finger condition results performed better than the two conditions, contrary to the expectations that performance, in terms of exploration time and response error, should improved as more contact points were provided to the participant. Further analysis suggested that some specific factors can account for lack of haptic information observed in these experiments, and they are the following:

- Absence of physical location of the contact on the fingerpad;
- Inhomogenous perception of dynamic properties at the fingertip level, due to differences of reflected inertias among different haptic interfaces;
- Absence of any geometrical information related to the orientation of the contact area.

These points suggested new criteria and guidelines for the design of multipoint haptic interfaces.

Recently several new conceptual schemes have been proposed to solve some of the problems arising during the direct exploration of virtual environments. In particular two new approaches have been proposed for the exploration of shapes. The first one hypothesizes [KJK04] that the shape recognition is due either to the perception of slipping of the fingerpad over the object surface or to the displacement of the contact area over the fingerpad. In [MAS02] preliminary tests reveal that relative motion can be used to render haptic sensation; rotating a drum beneath the finger, effectively recreates the sensation of moving one's finger along a surface.

In [KJK04], a new haptic device is presented which integrates grounded point-force display with the presentation of contact location over the fingerpad area. Basically forces are applied to the user's finger through a roller, which can move along the length of the finger pad and determines the display of contact location.

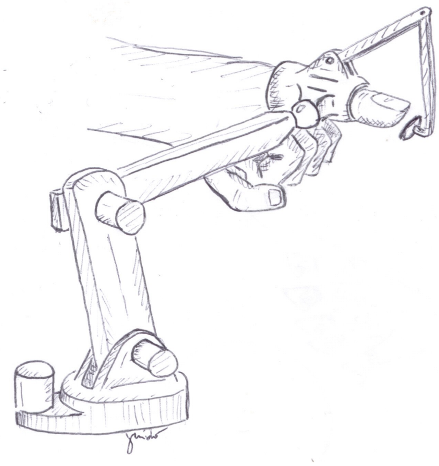


Figure 1: *A conceptual scheme of the device*

The second one consider that recognition of shape is linked to the perception of the orientation of the object surface at the contact points. This concept was further exploited to build a robotic system that can orient mobile surfaces on the tangent planes to the virtual object that is simulated, only at the contact points with the finger [YY04]. This concept has been called encountering haptic interface since the end effector comes in contact with the finger only when a collision is detected in the virtual simulation. In this way the device is completely transparent when no contact is occurring with the environment. In the encountering haptic devices, it still remains open the problem of implementing an accurate tracking of the fingerpad and a correct path planning of the moving platform, avoiding unwanted collisions with the fingerpad.

Hayward [Hay04] brilliantly observed that during typical movements, the exploring finger orientation remained largely invariant, presumably to maximize the acquisition of shape information and showed how a flat plate in rolling contact with the finger tip according to exploratory movements provides the desired moving patterns of normal finger deformation. This led him to the implementation of a prototype device that allowed him to evaluate the hypothesis that contact location trajectory on the fingertip provides sufficient perceptual contribution to create the experience of large objects.

2. A new fingertip haptic display

Analogously to [Hay04], we propose an extension of the encountered haptic interface [YY04], in order to build an active haptic thimble [†], that is a portable device, can be fixed to the user's finger and is endowed with an actuation system that controls the motion of a platform,to bring it in contact with the fingerpad with different orientations and at different fingerpad locations. According to [Hay04], in this way it should be possible to provide a sufficient feeling of curvature of objects. As a main difference with respect to [YY04], it is assumed that the mobile surfaces are connected to a device that is fixed to the hand of the operator rather than being grounded. In this way by fixing a link around the phalanx of the user's finger, we can design an encountering haptic device where the path planning problem is no more an issue, since the relative position of the phalanx with respect to the base link does not change over time. The actuation system of such a device should have all the degrees of freedom that are needed to positioning and orienting a plane in the space.

Figure 2 shows a scheme of concept of the device. At it can be seen, the contact with an arbitrary surface can be easily simulated.

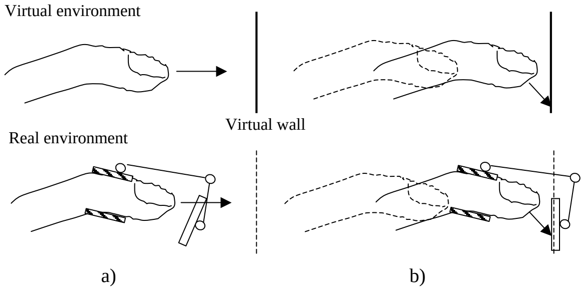


Figure 2: *The general principle of working of the interface*

If additional kinesthetic feedback should be provided to the user, the active thimble can be mounted on the end-effector of an haptic interface according to the scheme in Figure 1. In this way the user is provided with information both on the local geometry through the elicitation of tactile receptors and on the global geometry through elicitation of proprioceptive sensors. In the rest of this paper, the design of the fingertip haptic display and preliminary results from the control are reported.

[†] patent pending

3. Design guidelines

In order to allow the user to support the weight of the device on its finger and to avoid interference of the device with the rest of hand, reduction of bulk and weight was addressed in the design of the device.

4. Kinematic analysis

4.1. Kinematics

The kinematic structure should be able to position the final plate in a predefined workspace around the finger, such that in any position, the final plate could be oriented with respect to the finger in a given range of angles. These requirements can be satisfied if the structure has at least 5 DOF. Three possible kinematic solutions have been considered:

Fully serial mechanism In this case a suitable kinematic chain can be based on an anthropomorphic manipulator for the positioning task, supporting a spherical joint. It should be mentioned that a fully serial solution is suitable for obtaining large translations and rotation of the end-effector, while in our application only large rotations are requested. Major drawbacks of this solution are due to the transmission system. In fact, a cable transmission can reach the actuated joint n in two possible ways:

- through all the $n-1$ joints placed before joint n. This is possible if an idle pulley is placed at each joint preceding the n one; requirements of simplicity and reduced encumbrance lead to reject this solution;
- by sheathed cables directly connected to the actuated joint. In this configuration, the load generated by the sheath bending would act directly on the moving parts of the mechanism, thus introducing a force disturbance; moreover, the relative orientation of the end-sections of the sheathed cables would depend on the mechanism configuration, and consequently the resulting friction between sheath and cable too.

Fully parallel mechanism Parallel kinematic mechanisms are stiffer than serial ones and also allow to easily locate motors in a remote position, i.e. at the base frame. However a 5-dof fully parallel solution would involve high complexity in the design. Moreover in fully parallel mechanisms the range of reachable orientation of the platform is usually limited by the kinematic constraints.

Hybrid mechanism Hybrid solutions are generally composed by two or more subsystems, with serial or parallel kinematics, that are put in succession. In our application, we considered to use two subsystems, one to generate the translation displacements and the other one the orientation rotations of the end-effector.

4.2. Translational stage

In [AF00a] and [A.F00b] all possible parallel kinematics mechanisms that allow only translational movements of a mobile platform have been found. From these ones, the best kinematics fitting with the requirements of our problem, was found to be the one shown in Figure 3. It is composed of three legs with two universal joints and one rotational pair on the elbow joint (equivalent to a prismatic pair, see Figure 4), that is supposed to be actuated for each leg. The axes of the two universal joints are parallel to each other, as shown in Figure 3. To achieve the best isotropic kinematic performance the legs were symmetrically placed around a central axis at 120 degrees.

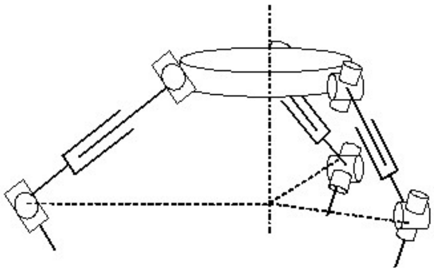


Figure 3: *The kinematics of the translational stage*

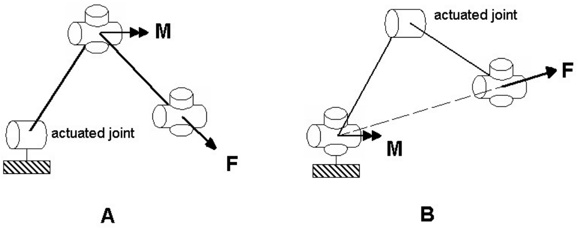


Figure 4: *The Leg Actuation Axis for each leg*

When the rotational pair on the elbow joint is actuated, an actuation force F is generated directed through the centers of the two universal joints (Leg Actuation Axis, see Figure 4). The constraint moment M generated by each leg is perpendicular to the plane of two rotational pairs composing the universal joints. It is possible to align the Leg Actuation Axis with the force applied by each motor to the leg through the transmission system, in order to increase the mechanical stiffness of the device and make the force transmission ratio independent of the configuration. This has been accomplished by implementing the actuation system for each leg as shown in Figure 5. A cable connected to the motor and a compression spring are mounted aligned with the Leg Actuation Axis: clearly since the tension cable should be always positive, the compression spring works in a opposition with the motor, so that a minimum pre-load is always guaranteed on the cable. The constraint moment M for each leg (balancing the external moment applied on the upper platform) is transmitted to the base only through the links 1 and 2, while the external forces are equilibrated only by the cable or the spring action.

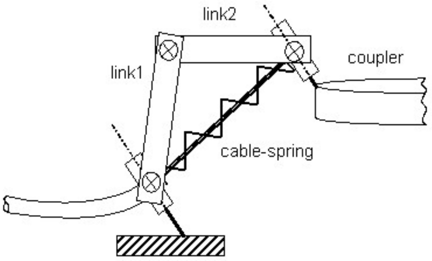


Figure 5: *The implementation of the leg for the translational stage*

4.3. Workspace of the device

The reachable workspace of this kinematics is represented by the intersection of three spheres. The shape and the extension of the reachable workspace clearly depend on the range of motion of the actuators. The internal radius R_{min} and external radius R_{max} depend on the maximum and minimum distance admissible between two universal joints of the same leg. Figure 6 shows the reachable workspace of the translational stage of the device, with the current dimensioning.

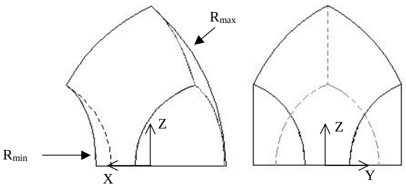


Figure 6: *The reachable workspace for the translational stage*

4.4. Rotational stage

The kinematics adopted for the rotational stage is shown in Figure 7. With the same notation of figure, the orientation requirements suggested to adopt two rotational axes allowing a rotation around the axis Z' fixed to the mobile platform, and around an axis X.

4.5. Actuator group

In the implementation of the first prototype all the actuators were placed distant from the part of the device worn on the finger, in order to reduce the moving masses and bulk of the device. To transmit the actuation forces from motors to joints, addressing zero backlash in the transmission, a solution based on steel tendons was adopted.

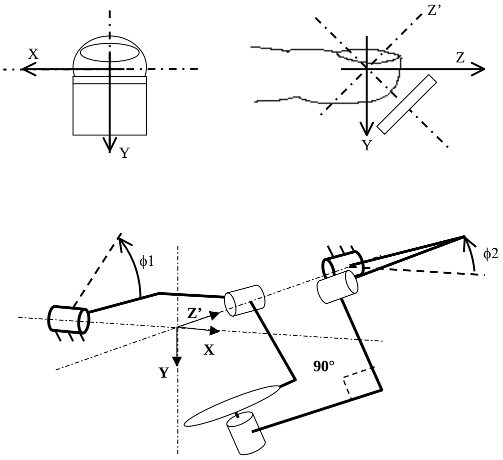


Figure 7: *The rotational stage of the device*

For driving the transmission cables from the motors to the driven joints, two solutions have been considered:

- ***Cable routed over idle pulleys:*** all cable pathways are completely determined by the positions of the pulleys; motors are fixed on the base link of the kinematic chain;
- ***Sheathed cables:*** motors are freely placed at any position (see Figure 8).

While the first solution needs a specific support device, in the second one the motor group can be placed on a fixed external support far from the hand, reducing at the same time the bulk and the perceived inertia. The major drawback of solution 2 is constituted by the higher friction due to the slipping friction of the steel cables inside the sheaths: notwithstanding this point, solution 2 was considered preferable for the implementation of a first prototype.

5. Description of device

Based on the above choices, the final device presents the following architecture, see Figure 9:

- the kinematic structure is realized as an hybrid kinematics with two different stages, a translational and a rotational one;
- the motor group is constituted of five (one per joint) brushed DC motors, placed in a remote position with respect to the structure (see Figure 8);
- the actuation of structure is realized by sheathed cables, which start from motor pulleys and reach driven joints.

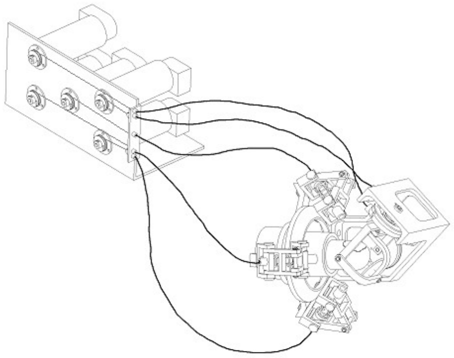


Figure 8: *The device is driven by a set of a sheathed tendons connected to the motorization group*

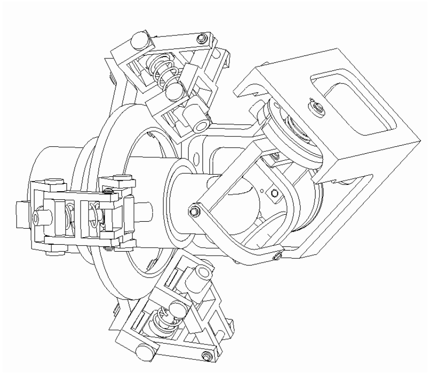


Figure 9: *The CAD model of the final design*

6. Control of the device

The scheme in Figure 11 represents the actuation system of one leg, composed of of one motor, the sheathed tendon, the actuation cable and the return spring for each leg.

The dynamic equations of the motor for each leg were assumed as follows:

$$\begin{cases} \tau_m - T_{in} r = J_m \ddot{\theta} + b_m \dot{\theta} \\ T_{out} = K_m x + m\ddot{x} = r(K_m \theta + m\ddot{\theta}) \end{cases} \quad (1)$$

where J_m and b_m are respectively the motor inertia and damping constant, τ_m is the motor torque, T_{in} and T_{out} represent the cable tension, τ_m the motor torque, K_m the spring axial stiffness, while x_0 is the length at rest of the spring K_m.

The friction of the sheath has been modeled according to the theory of belt (β and f representing respectively the winding angle of the tendon on the pulley and the friction coefficient between the groove and the cable) plus a viscous coefficient b. The relation between T_{in} and T_{out} was determined by the direction of motion, according to the drive either by the motor or by the spring.

$$\begin{cases} T_{in} = T_{out} e^{f\beta} + b\dot{\theta} = T_{out}(1+\mu) + b\dot{\theta} & \text{if } \dot{\theta} > 0 \\ T_{in} = \frac{T_{out}}{e^{f\beta}} + b\dot{\theta} = \frac{T_{out}}{(1+\mu)} + b\dot{\theta} & \text{if } \dot{\theta} < 0 \end{cases} \quad (2)$$

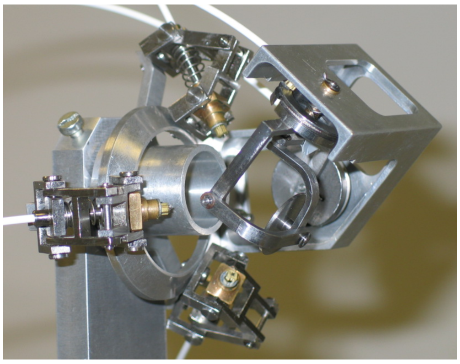


Figure 10: *The final implementation of the first prototype*

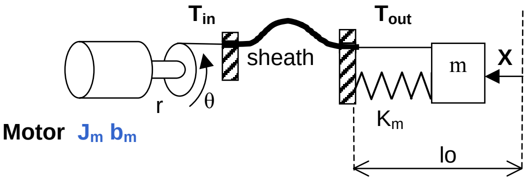


Figure 11: *Scheme of the actuation system of one leg*

The control was implemented with local position controllers at the joint level. An inverse kinematic module was used to convert the desired position expressed in cartesian coordinates to the corresponding joint coordinates. The non-linear term due to the spring pre-load $K_m x_0$ was pre-compensated, by adding it in feedforward to the motor torque τ_m in the control loop.

In order to compensate the friction generated by the sheath, a simple experimental apparatus was set-up to measure the values of the friction coefficients between the steel cable and the sheath in different geometric configurations (for different curvature radii). The cable was fixed on one side to a position-controlled DC motor and on the other one to a weight of known mass. The motor was then moved on a trajectory with constant speed, in order to lift the weight at constant velocity.

6.1. Experimental results from control

Figure 12 reports the step response of the translational stage of the system in two opposite directions. The observed difference in the response of the system is due to the fact that either the spring or the motor is active according to the selected motion direction.

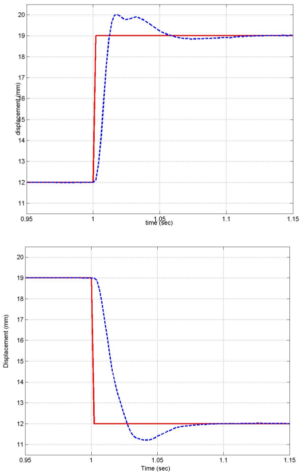


Figure 12: *The difference of the time response in the two directions is due to the different response of the motor and of the antagonist spring*

Figure 13 reports the tracking of a circular trajectory of the central point of the translating stage.

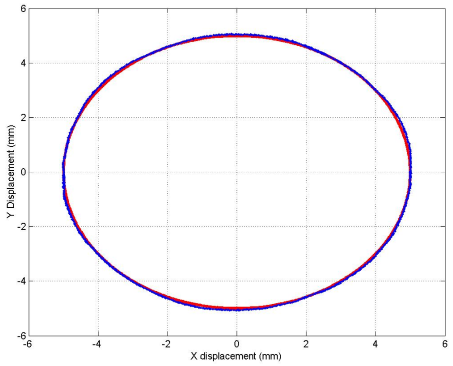


Figure 13: *Tracking of a circular trajectory*

6.2. Preliminary evaluation

In this first phase, only a preliminary evaluation of the device is being conducted. The trajectories to be followed by the device have been defined off-line. Two tests have been carried out to evaluate the ability of the user to perceive the influence of direction and orientation of approaching of the plate The two schemes that have been adopted are reported in table 1:

	Direction	Orientation
Condition 1	Variable	Fixed
Condition 2	Fixed	Variable

Table 1: *Representation of the preliminary tests currently on-going*

- The plate is brought in contact with the fingerpad with the same orientation but along different directions.
- The plate is put in different orientations and brought to contact with the fingerpad with the same direction.

The two tests have still not completed, but preliminary results show the efficacy of the device for the haptic display of virtual surfaces with different orientation.

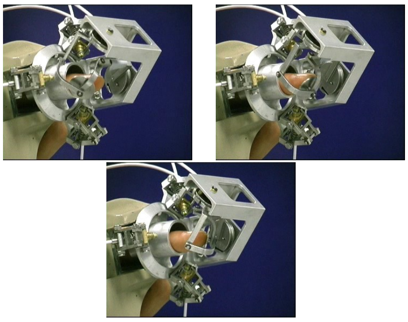


Figure 14: *The approach of the plate to the fingerpad with different orientations.*

7. Conclusion

A new concept of fingertip haptic display has been proposed in the paper. A prototype of the device has been constructed and tests are currently on going for the assessment of the capability of the device and further more will be required for the assessing the validity of this new concept of haptic display.

References

[AF00a] A. Frisoli D. Checcacci F. S. M. B.: Synthesis by screw algebra of translating in-parallel actuated mechanisms. In *Proc: ARK2000* 7^{th} *International Symposium on Advances in Robot Kinematics* (2000), Kluwer Academics Publ, pp. 433–440. 3

[A.F00b] A.Frisoli D. Checcaci F. M.: Translating in-parallel actuated mechanism for haptic feedback.

In *Proc. of ASME (American Society of Mechanical Engineers) IMECE, International Mechanical Engineering Congress and Exposition, Orlando* (2000). 3

[AF04] A. FRISOLI F.BARBAGLI S. L. W. E. R. M. B. K. S.: Evaluation of multipoint contact interfaces in haptic perception of shapes. In *Symposium of Multi-point Interaction in Robotics and Virtual Reality, in IEEE ICRA 2004* (2004). 1

[Hay04] HAYWARD V.: Display of haptic shape at different scales. In *(Keynote Paper) Proc. Eurohaptics 2004* (2004), pp. 20–27. 2

[Jan00] JANSSON G.: *Effects of Number of Fingers Involved in Exploration on Haptic Identification of Objects. Excerpt from PURE-FORM: The Museum of Pure Form; Haptic Exploration for Perception of the Shape of Virtual Objects.* Tech. rep., EU-PURE FORM, 2000. 1

[Jan04] JANSSON G.: *PURE- FORM 4th period 6-monthly report*. Tech. rep., Upssala University, 2004. 1

[JM03] JANSSON G., MONACI L.: *Touch, Blindness and Neuroscience*. UNED press, Madrid, 2003, ch. Haptic identification of objects with different numbers of fingers. 1

[Ka93] KLATZKY R. L., AL.: Haptic identification of objects and their depictions. *Perception & Psychophysics 54*, 2 (1993), 170–178. 1

[KJK04] K. J. KUCHENBECKER W. R. PROVANCHER G. N. M. R. C.: Haptic display of contact location. In *Proceedings of the Symposium on haptic interfaces for virtual environment and teleoperator systems* (2004). 1, 2

[KL99] KLATZKY R. L., LEDERMAN S. J.: Tactile roughness perception with a rigid link interposed between skin and surface. *Perception & Psychophysics 61*, 6 (1999), 591–607. 1

[KLM85] KLATZKY R. L., LEDERMAN S. J., METZGER V. A.: Identifying objects by touch: An “expert system”. *Perception & Psychophysics 37*, 4 (1985), 299–302. 1

[MAS02] M. A. SALADA J. E. COLGATE M. V. L. P. M. V.: Validating a novel approach to rendering fingertip contact sensations. In *Proceedings of the 10th IEEE Virtual Reality Haptics Symposium* (2002), pp. 217–224. 1

[YY04] Y. YOKOKOHJI N. MURAMORI Y. S. T. Y.: Designing an encountered-type haptic display for multiple fingertip contacts based on the observation of human grasping behavior. In *Proceedings of the Symposium on haptic interfaces for virtual environment and teleoperator systems* (2004). 1, 2

Computer Graphics Access for Blind People through a Haptic and Audio Virtual Environment

C.A. Avizzano, S. Marcheschi, M. Bergamasco, PERCRO, Scuola Superiore S. Anna

R. Iglesias, S. Casado, T. Gutiérrez, J.I. Barbero, Fundación Labein

Abstract

This paper describes a new Haptic & Audio Virtual Environment to allow blind and visually impaired people to have access to the three-dimensional graphic computer world through the sense of touch (using a new dual-finger haptic interface) and augmented by audio input and voice commands. Such system has been developed within the European project "GRAB". The new system provides an integrated platform for the design and development of audio-haptic applications in different fields (architecture, art, aeronautics, medicine,..) as well as their fruition in a realtime interactive manner. In order to demonstrate the validity of the approach, the project was specifically focused on the development of three applications selected for their promising positive impact on the life quality of visual impaired people: an adventure game, a city map explorer and a chart explorer. Both the new environment and the new applications were tested by visually impaired people with different profiles (congenitally blind people, advantageously blind people, partially sighted people,..) to evaluate the usefulness and potential of these developments. The results of this validation confirm the validity of the system. Overall, it seems the GRAB system is feasible for these kinds of applications, although some features require some adjustments to create future usable tools.

Keywords *Haptic desktop system, Office Automation*

1. Introduction

The convergence of Information Society Technologies (IST) and markets is leading to new products and services that are increasingly transforming our lives. The impact of IST on every-day's activity is also raising people's expectations for a better quality of life. As technology is becoming part of our normal surroundings, new tools provide individuals with powerful means to express ideas and develop their creativity for professional use or for leisure. However, some collectives need the development of specific tools to facilitate the access of these citizens to the full range of IST applications. To address accessibility issues, interfaces between the information source and the end user have to be accessible as well. In the last few years the software industry, spurred on by legislation in both Europe and the United States, has become increasingly aware of the need to design for all, including people with disabilities. As a result, access for blind and visually impaired users to important software is gradually improving. Some of the obstacles that impede visually impaired people to have access to the IST applications are being solved with the use of: screen reader software, voice synthesis, speech recognition, Braille and tactile displays,… However there are inaccessible fields yet for them such as the access to the 3D computer graphics and their multiple applications (learning, training entertainment systems, working tools,…).

Currently, many researchers are exploring the potential of using innovative haptic interaction mechanisms that exploit the sense of touch as a substitute for vision. Haptic sensing is defined as the use of motor behaviours in combination with touch to identify objects [1]. Many of the haptic interfaces that have been developed in recent years use one-point haptic interaction with the virtual world. In several experiments, it has been shown possible to use these Haptic interfaces alone to recognize basic shapes and textures ([2],[3]). A wide set of applications has been develop to show the added value that the HIs can provide to user with different levels of disabilities ([4],[5], [6],[7],[8]). At present HIs combined with sound feedback [13] have been used to interact with 3D virtual objects in several manners: mathematical graphs[9], diagrams and maps ([10],[11]), and fairly complex environ-

Figure 1: *Overview of the GRAB system.*

ments [12] such as large memory games [14], explorative games [15] and traffic environments [16] have been investigated. At present several commercial 3D Haptic interfaces are available on the market. Some of them have limitations when it comes to the realistic exploration of virtual 3D graphics by touch. Force feedback gloves provide direct feedback independently to multiple fingers but have limited degrees of freedom and are only capable of producing small forces. Being grounded on the hand, they are unable to prevent movements other than in the fingers, so there are a number of effects they cannot produce. Beyond that, in order to fit with the kinematics of the hand, these exoskeleton devices usually behave a very poor mechanical stiffness which make the force feeling at the contact quite unrealistic. Desktop haptic devices, such as the PHANToM (Sensable Technologies), are capable of producing better levels of force in three degrees of freedom, making it possible to realistically represent 3D solid objects. However, the single point haptic interaction mode has still some constraints for blind and visually impaired people, due to persistent difficulties with orientation (miss a reference point), the spatial memory, locating objects, staying in touch with objects and perceiving complex shape and size ([17],[18],[19]). Jansson ([20]) showed that, for shape and form perception, exploration using a single finger falls well short of the utility provided by using ten fingers. However, the same research shows that two-fingered exploration is significantly better than one-fingered and not much worse than ten fingered. Taking into account the difficulty of providing a multi-fingered device that is capable of producing the forces required for realistic 3D haptic rendering, a two-fingered device seems like a good direction to explore. Previous experiences of the partners of the GRAB consortium showed that the employment of two PHANToMs devices is not suitable when problems of manipulation and shape recognition are addressed. The cognitive capacity of the user in recognizing the shape of the object results reduced when the users are deprived of the visual and tactile feedback. Therefore in order to allow visual impaired users to interact with a virtual environment using only the haptic and proprioceptive senses, a reconstruction of the environment with object large enough is required This set of considerations convinced the partners of the GRAB consortium that any approach to develop a novel virtual reality system to enable IST access for visually impaired people could not rely on existing systems like the above cited. So, they decided to proceed in the development of a novel system: the GRAB system

2. The GRAB system

The GRAB system is a new Haptic & Audio Virtual Environment that allows blind and visually impaired persons to have access to the three-dimensional graphic computer world through the sense of touch (using a new dual-finger haptic interface) and augmented by audio input and voice commands.

Instead of displaying just the images of the 3D objects with a visual display, the new environment allows its user to feel with his/her fingers the shape of the virtual 3D objects. This is achieved using a 3D force-feedback Haptic Interface specifically developed to touch 3D virtual objects both with the thumb and the index fingertips or both index fingertips while moving the hands in a desktop workspace. As the user moves their fingers over the virtual object he/she feels contact forces at the fingertips and can recognize its geometric features (such as corners, surface edges, curvature,..), distinguish sizes and distances and understand spatial relationships between elements. During the haptic exploration, the user can also receive audio messages (speech and non-speech) and execute verbal and keyboard commands. The operator screen renders the virtual scene and what the user is doing at each moment (position of the user's fingers, movement of any object,…). The figure 1 shows a work session with the new GRAB system As it shows the figure 2, the new system is based on the integration of three tools:

- A new two-finger 3D force-feedback Haptic Interface.
- A commercial tool, ViaVoice (IBM) to provide speech recognition and voice synthesis
- A new Haptic Geometric Modeller to allow the interaction with any 3D virtual object through haptic stimuli, sounds aids and speech recognition.

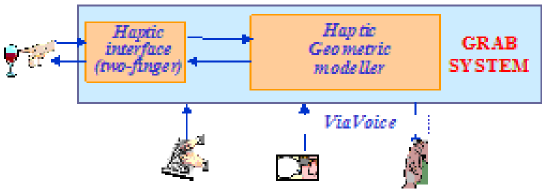


Figure 2: *GRAB system architecture.*

2.1. The GRAB Haptic Interface

From a technical point of view, the GRAB interface is a new high fidelity, two-fingers, 3D force-feedback Haptic Interface. The interface, completely designed and developed by PERCRO, is capable of replicating two independent force vectors on contact thimbles attached to user's fingers (the thumb and the index or both index fingers). The interface consists of two identical robotic arms (fig. 3); each arm has six degrees of mobility and a workspace which covers a large portion of the desktop (600mm wide, 400mm height, and 400mm depth). The first three DOF are actuated by DC motors and allow to display an arbitrary force vector on the relative thimble; the other three degrees of mobility, reproducing a spherical joint, allow any rotation of the fingers. In such a way the user can orient his fingers in any direction of the space while experiencing the force feedback generated by software application. In order to improve the transparency of use of the device, a number of design guidelines have been adopted. Remote localization of the motors, selection of motors with high torque to mass ratio and light materials adopted for the construction of the moving links allow to reduce perceived inertia. For reducing friction and guarantee zero backlash, all transmission systems between motors and mechanical joints are achieved by metallic in tension tendons routed on capstans and pulleys and no geared reducer have been used. Furthermore, the actuation of shoulder is obtained by a differential transmission system which allows to achieve high isotropic control of the end-effector and which helps to cancel spurious and misleading Coriolis effects at high thimbles speed.

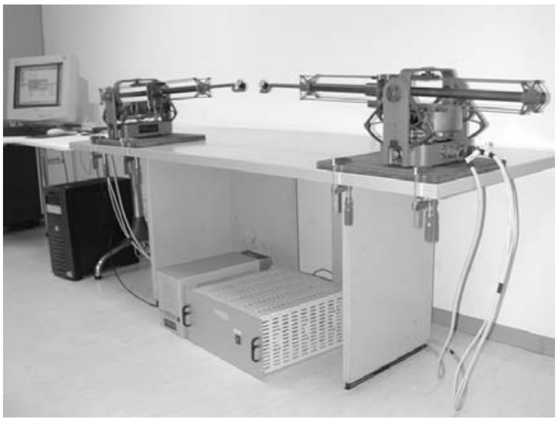


Figure 3: *The new 3D force feedback Haptic Interface.*

The interface is provided with a novel and open control architecture which allow to reduce development costs and facilitate upgrading of the device. The architecture is based on a mix of commercial and custom components: the most important are the motors power supply, which provides the required current to the motors, and the standard SBC which provides the required real time support for running a Real time operating system. The control system kernel will be based on Linux and a real-time micro-kernel which ensures high performances capabilities and allows the integration of sophisticated control procedure to high level control software (such as physical based modelling and force rendering). Connection with the HGM is achieved by means of an ECP parallel port interface which allow high data throughput (>=500 Kbyte/sec), bi-directional communication, low CPU resource request and no latencies. Furthermore the control system identifies, describes and compensates a wide set of non linear features such as the arm kinematics and dynamics, the unbalanced weight effects, the transmission model of the elastic cable, the distributed friction effects, the electrical features of the power supply, the errors due to structural deflection under load conditions. In order to maximize the precision in tracking finger position and ensure coherence between arms, two different calibration procedures are implemented. This feature allows to obtain fingers position expressed respect to a user defined reference frame. Finally, a set of higher level effects (embedded friction, textures, …) have been implemented in control software.

2.2. The GRAB Haptic Interface

The new HGM is a C++ object-oriented toolkit, developed by LABEIN, with all the algorithms that allow the user to interact with any 3D virtual object providing: the haptic stimuli to be rendered by the new haptic interface and sound aids and speech recognition capabilities to improve the interaction. The new HGM is based on DATum: an object oriented variational non-manifold geometric modeller developed previously by LABEIN. Its main role is to analyse the position of the Usert's fingers (provided by the control systems of Haptic interface) taking into account the action required by the user (for example to make zoom or to get a specific help audio) in order to get the corresponding audio messages and calculate the values of the forces to be replicated by the haptic interface on the Usert's fingers. The main functionality provided by the HGM is the following one:

- Creation and rendering of virtual scenes
- Simulation of different types of forces in order to: represent contact with an object, modified by properties such as stiffness, texture and stickiness; constrain the user to the boundary of any virtual object; constrain the user to slide along a trajectory or path; attract or repel a user to or from an object; help the user to find an unexplored object; represent the spring of a virtual button; simulate weight when an object is grasped; detect when objects collide with another one
- Audio feedback (both speech and non-speech) to provide:
  - Static information: general information about the virtual object/environment defined when the environment was designed (for example the name of the object,…)
  - Dynamic information: information related to the user's

actual position within the environment. (for example the distribution of the models around the user)

- Verbal commands
- Haptic effects to be used as controllers (for example the tapping and the pausing)
- Make zoom in/ zoom out of the virtual environment to explore objects whose size is too small or too large.
- Panning the virtual environment to have access to any point of the virtual environment although its size is bigger than physical workspace.

The haptic modeller may also be used in conjunction with or separate from the GRAB haptic interface through a new API (Application Protocol Interface) .

3. Haptic Applications for Blind people

The GRAB system provides an integrated platform for the design and development of audio-haptic applications in different fields (architecture, art, aeronautics, medicine,..) as well as their fruition in a realtime interactive manner. In order to prove the validity of the approach, the project was specifically focused on the development of three applications selected for their promising positive impact on the life quality of visual impaired people.

3.1. An adventurous and searching game

The first application developed on top of the GRAB system was an adventure and searching game, one of the applications most demanded by the users. With this game, the user must move himself inside of a building of two floors (see figure 4.). Each floor has several rooms with different prizes (extra lives, points,..), dangers (bombs, traps, a jail, …), difficulties (random distribution of the elements in each play, find keys to open a door, repair broken keys, cross a maze,..) and interactions (open doors, jump windows, gain objects, use the lift, ask for instructions/inventory…).

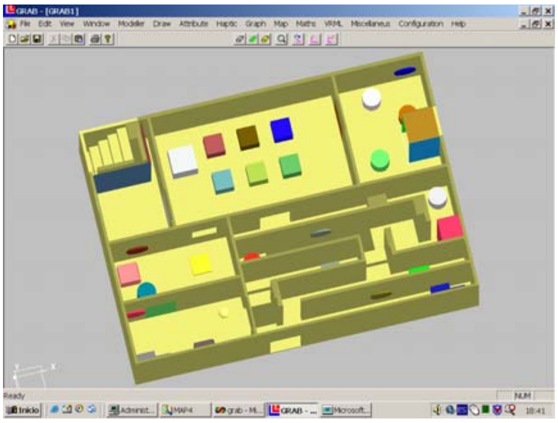


Figure 4: *Scenario of the searching game.*

3.2. A chart data explorer application

The new chart data explorer application allows visually impaired people to access, read and manipulate financial (or other) data using virtual charts with the sense of touch and audio helps (see figure 1). The application imports directly the information from Excel files. In this application the workspace is divided in two areas to facilitate the exploration tasks and the management of the graph. All the operations that change the graph (zoom, panning, activate/deactivate a graph line, change of type of representation,…) will be done in the ”working area”. Meanwhile, the ”overview area” will display the original graph. This application allows:

- Explore simple graphs: lines, bars (columns) and pies
- Explore composite graphs: set of lines and set of bars (columns)
- Explore other elements: trendlines (moving average)
- Haptic and/or audio tickmarks (along the x axis), zero gridline and gridlines
- General features: activate/deactivate graphs, change of representation, zoom, panning and re-scaling the chart between two points or along the y axis.
- Multiple User interfaces: keys, audio, buttons and haptic effects (tapping and stopping).

3.3. A city-map explorer appplication

The last application implemented on top of the GRAB system is a city-map explorer to provide blind and visually impaired people with an orientation tool to familiarise themselves with a city map, locate important facilities and destinations ahead of time and plan and rehearse journeys in a city, see figure 5. The main features of this application are:

- Create a new virtual city-map from an existing cartographic map like the cartographic databases (TeleATlas, ESRI,..).
- Add to a city-map new interest points (bus stops, special buildings,..) and create trajectories (paths) to go from a place of the map to another one.
- Explore the maps in different modes, each one of them with a different purpose
  - Grid Mode get ⇒ general idea of the contents of the map
  - Basic Mode (streets and buildings) ⇒ fast exploration of the map
  - Detailed Mode (streets + buildings + interest points) ⇒ detailed exploration of the map
  - Street trajectory Mode ⇒ follow the trajectories defined by the streets (learn streets)
  - User’s trajectory Mode ⇒ learn the path to go from a place to another ones
- At any time the user can change the mode of exploration of the city-map depending on its preferences, and needs.

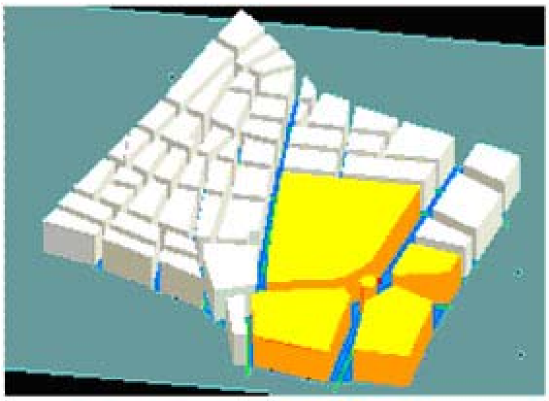


Figure 5: *A 3D city-map in the GRAB system.*

- General features inside of a haptic session: zoom, panning, get inventory of a street and/or a block, get information about the User position,..
- Multiple User interfaces: keys, audio, buttons and haptic effects (tapping and pausing).
-

4. Validating the GRAB system and applications

The GRAB system was tested with a total of 52 participants across the three user organisations of the project (RNIB, NCBI and ONCE). A deep analysis of the features of the GRAB system when applied to visually impaired people was conducted in the project. This analysis enabled to identify a few key features and benefits that the GRAB system can bring to blind and visually impaired people with respect to other current haptic systems. The main advantage is related to the use of two contact points. Observation and user responses indicated that a second finger - on a separate hand - can be vital as a ’anchor’ or reference point that allows the user to orientate themselves in space, more readily understand objects’ relationships (distribution and distances) and makes re-finding objects easier. Other issues that the users most appreciated are:

- Larger workspace than other haptic devices
- Smooth refined movement
- Robustness of the device
- Position accuracy
- High peak forces
- Fidelity, especially in terms of judging sizes and comparative distances
- Interaction and exploration of objects, including features like: weight, stiffness, stickiness, curvatures, attraction forces, following a trajectory, utilities to find, recognise and explore small objects, …
- Audio input and output
- Interaction with a changing environment (buttons, moving objects, organising objects, detecting collisions…)

On average, twelve people tested each one of the above applications. Before starting the validation phase, the application was introduced to each partner through a tutorial specifically designed to familiarise the user with the main features of the application. The results of the validation of these applications, in particular based on users’ comments and evaluators’ observations, confirm the validity and potential of the GRAB system for these kinds of applications, although some features require some adjustments to create future usable tools.

5. Conclusions

In this papers a new Haptic & Audio System (GRAB) interacting within flexible Virtual Environment has been presented. The system is provided with a set of applications that allow visual impaired to access to the 3D graphic computer world through the sense of touch and with audio help. The GRAB system features context aware audio synthesis as well as speech recognition. Haptic interaction can feature object exploration, simple manipulation and control (buttons and haptic recognition). Both modes can be made interacting enhancing in such a way the interaction design. The system has been proved on the field with a wide set of users and in cooperation with different European institutions for blind users. In order to demostrate the validity of the approach, three applications for visual impaired people were implemented: a searching and adventure game, a city map explorer and a chart explorer. Nonetheless, the GRAB system has been conceived openly in order to easily provide a support in the design and development of audio-haptic applications for other fields: architecture, art, aeronautics, medicine,… Both the new environment and the new applications were tested by visually impaired people with different profiles (congenitally blind people, advantageously blind people, partially sighted people,..) to evaluate the usefulness and potential of these developments. The results of this validation confirm the validity and potential of the GRAB system for these kinds of applications, although some features require some adjustments to create future usable tools. An important achievement was the improvement in the understanding of the interaction process of visual impaired people with haptic environments. This will be very useful for the development of future applications in this field. In particular, having evaluated three working applications of very different types has enabled us to build a body of knowledge concerning the finer points of interaction in the virtual haptic environment. This knowledge covers general interaction guidelines, the differences between the virtual haptic environment and the physical world and guidelines for taking into account specific circumstances of the interaction, including the nature of the happtic objects and the requirements of the tasks. Access to computer-generated graphics applications via GRAB system could potentially increase employment opportunities and open up access to jobs which have hitherto been closed to blind users and improve their education, teaching and training opportunities. During the project other potential applications for visually impaired people were also identified in several areas: Employment enhancing applications (editing wave files, painting tool, CAD systems, interior design tools,Ê), Educational applications (Teaching Mathematics, Physics, geography, art history,Ê), Applications that increase social inclusion and independence (building maps, traffic environment, virtual museum, games,..)

6. Acknowledgments

The activities described in this paper have been carried out in collaboration and with the help of the GRAB consortium composed of three European user group: the National Council of Blind of Ireland (NCBI), The Royal National Institute for Blind (RNIB) and the Spanish organization of Blind people (ONCE- Organización Nacional de Ciegos Españoles); two technical developers: PERCRO and Fundación LABEIN; and one commercial partner: Haptica LtD. The authors are grateful the whole consortium for their contribution in the development of the activities. The activities of this project have been carried on with the financial assistance of the EU which co-funded the project GRAB: ”Computer Graphics access for blind people through a Haptic virtual environment”- IST-2000-26151 (www.grab-eu.com) . The authors are grateful to the EU for the support given in carrying on these activities.

7. References

[1] Appelle S. 1991. *Haptic perception of form: Activity and stimulus attributes*, In Heller M, Schiff W (eds). The Psychology of Touch, pp 169-188. Lawrence Erlbaum Associates Inc.,Hillsdale, NJ, USA.

[2] Jansson G., J. Faenger, H. Konig, K. Billberger, 1998. *Visually Impaired Persons’ Use of the PHANToM for Information About Texture and 3D Form of Virtual Objects*, PHANToM Users Group Workshop

[3] Penn P., H. Petrie, C. Colwell, D. Kornbrot, S. Furner, A. Hardwick, 2000. *The Haptic Perception of Texture in Virtual Environments: An Investigation with Two Devices*, Haptic HCI.

[4] Fritz JP, K. E. Barner, 1999. *Design of a Haptic Data Visualization System for People with Visual Impairments*, IEEE Transactions on Rehabilitation Engineering, vol. 7, no. 3.

[5] Fernández J.L., Muñoz J.A., Gutiérrez T., Barbero J.I., Carrillo A, Mendikoa I., 1999. *Haptic Virtual Reality Applications for Blind people*, ”Revista Integración” magazine, vol. 29 pp. 5-11.

[6] Sjöström C.,1999. *The IT Potential of Haptics - touch access for people with disabilities*, Licentiate thesis.

[7] Van Scoy F.L., T. Kawai, M. Darrah, C. Rash, 2000. *Haptic Display of Mathematical Functions for Teaching Mathematics to Students with Vision Disabilities: Design and Proof of Concept*, Haptic HCI.

[8] Yu W., S.A Brewster, 2002. *Comparing Two Haptic Interfaces for Multimodal Graph Rendering*, proceedings of IEEE VR2002, 10th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (Haptics 2002).

[9] Yu, W. and Brewster, S.A. (2003) *Evaluation of Multimodal Graphs for Blind People*, To appear in Journal of Universal Access in the Information Society

[10] Vitense,H.S.; Jacko,J.A.; Emery,V.K., *Foundation for improved interaction by individuals with visual impairments through multimodal feedback*, Universal-Access-in-the-Information-Society. Nov. 2002; 2(1): 76-87, Springer-Verlag

[11] Magnusson C., K. Rassmus-Gröhn, C.Sjöström, H. Danielsson 2002. *Navigation and recognition in complex haptic virtual environments - reports from an extensive study with blind users*, submitted to Eurohaptics.

[12] Lécuyer A., Mobuchon P., Mégard C., Perret J., Andriot C.and Colinot J.P., 2003. *HOMERE: a Multimodal System for Visually Impaired People to Explore Virtual Environments*, IEEE Int. Conf. on Virtual Reality, Los-Angeles, US, 2003

[13] Magennis, M. et Al, 2003. *GRAB - A new haptic and audio virtual environment enabling vision impaired people to access the three dimensional computer graphic world*, (TBP) Advancement of Assistive Technology in Europe (AAATE) 2003, Dublin, Ireland

[14] Van Scoy F.L., V. Baker, C. Gingold, E. Martino, D. Burton, 1999. *Mobility Training using a Haptic Interface: Initial Plans*, Fourth Annual PHANTOM Users Group (PUG99).

[15] Wood J., Magennis M., Cano E., Graupp H., Gutiérrez T & Bergamasco M, 2003. *The design and Evaluation of a Computer Game for Blind in the GRAB Haptic Audio Virtual Environment*, (Eurohaptics 2003).

[16] Magnusson C., K. Rassmus-Gröhn, 2003. *Non-visual Zoom and Scrolling Operations in a Virtual Haptic Environment*, EuroHaptics.

[17] Colwell, C., Petrie, H., Kornbrot, D., Hardwick, A., and Furner, S. (1999) *Haptic Virtual Reality for Blind Computer Users*, Proceedings of The Third International ACM Conference on Assistive Technologies, 1998

[18] Jansson, G. and Billberger, K. (1999) *The Phantom used*

without visual guidance, Proceedings of the £rst Phantom users research symposium (PURS99)

[19] Jansson, G., Billberger, K., Petrie, H., Colwell, C., Kornbrot, D., Fanger, K., Konig, H., Hardwick, A. and Furner, S. (1999) *Haptic Virtual Environments for Blind People: Exploratory Experiments with Two Devices*, International Journal of Virtual Reality, 4, 10-20 (1999)

[20] Jansson, G., Bergamasco, M. & Frisoli, A. (2002) *Tactual exploration of 3D works of art at museums. Abstract Book, Vision 2002*, The 7th International Conference on Low Vision, 21-25 July 2002, Göteborg, Sweden, p.45 (Abstract). Full paper to be published in Vision Impairment Research.

Haptic Interfaces:Collocation and Coherence Issues

C.A. Avizzano, S. Marcheschi, M. Bergamasco

Superiore S. Anna, Pisa, Italy

1. abstract

Multi-modality, collocation and immersive VE nowadays represents the break-trough barrier of human computer interaction. Typical VE systems synthesize the information to be presented to the user by means of different algorithms and present them using different interfaces. On the other hand the human perceptive system is strongly integrated and “fatigues” to interpret these stimuli as belonging to a unique information source.
Collocation and coherence issues may be noticed in any kind of multimodal integration: “visual and audio”, “visual and vestibular”, “audio and haptic”, “visual and haptic”,...
The present paper deals with two speci£c kinds of multimodal integration: “visual and haptic” and “haptic and haptic”. The coherence problem of synchronizing several haptic devices is analyzed and an optimized solution is proposed. The proposed solution has been tested on a dual point HI, behaving a wide workspace realized at PERCRO. More speci£cally the present paper will present a novel algorithm to achieve the absolute coordination of multiple HI working in the same VE. The system performances have been assessed and compared to those of existing solutions. The achieved results have been exploited for the EU project GRAB[†]. The GRAB project investigates to which extent a purely haptic environment can be employed from sightless users.

Index Terms - Haptic Interface; coherence.

2. Introduction

Visual Display Terminal technologies (VDT) i.e. screen, keyboard and mouse, represent the most spread systems for the human computer interaction (HCI). Such technologies are the classical example of non-collocated and non-coherent systems. Collocated feedback required that the information is produced (or given) in the place where the generating action are exerted. Coherent feedback is more related to timing and physical aspects of the interaction and implies that the given feedback is strictly related to the generating action (Fig. 1). Almost all the experiences the user probes in a real world have these two key elements, but the HCI interaction introduces the possibility of altering them. As shown in the scienti£c literature, the missing of these two factors implies that the user brain has to compensate for them resulting in a sort of “mental load” which varies largely according to the application.

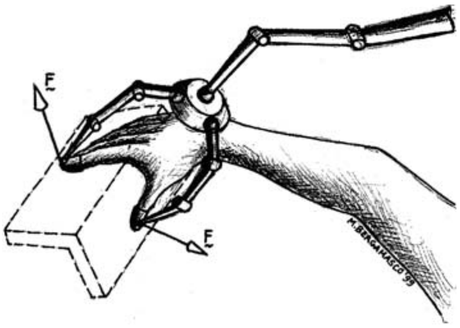


Figure 1: *Collocation & Coherence in multipoint HI*

When the multimodal integration is very strong, as for as the case of vestibular and visual information (typical in vehicle simulator), the presence of incoherent feedback may cause also several physical sickness. Therefore, mouse, video and keyboard are not the optimal way for interacting with computers. In the case of VDT, the popularity of these interfaces is ensured by the fact that the associated mental load is very low because very low is the information content associated to the interaction. This is no more true whenever the degree of interaction between user and computer increases to higher complexities or includes different perceptive channels.

[†] The GRAB project has been carried on within the 5th framework program of the EU. The IST and the European Union are acknowledged for their grants in sustaining the GRAB research.

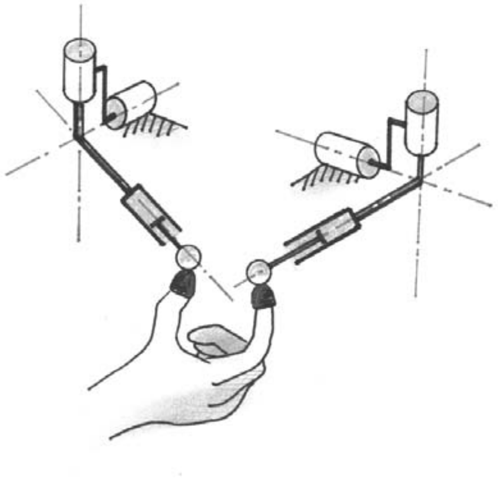


Figure 2: *Double haptic contact concept*

Haptic has proven to be useful during the interaction of users within virtual environment. Within these environment the use of the haptic sense can be employed for enhancing the sense of presence and realism, improve object manipulation, create physical effects, teach handling procedure and much more. The most frequent integration of the haptic feedback is usually done with visual or other haptic feedback. In the first case the visual feedback completes the force information given by the device for a more integrated environment; in the second one the supplementary force information is used to have more dexterous environments.

Some researchers have tested the potentialities of multi-haptic interfaces when addresses in a sightless environment (Fig. 2).

Jansson [Jan01,Jan98] and Klatzky [Kl99,Kl90] conducted some experiments to evaluate the perceptive aspects and the performances when varying the number of contact points and other factors. In [BLSH95] Hirzinger experimented a novel software architecture for improving the sense of presence when teleoperation systems where addressed. A local VE created on the copy of the remote environment, will provide to the user the required collocation and coherence (especially in terms of time delays).

In the present paper a novel algorithm to achieve the mixing of multiple HI in the same VE is considered. The algorithm has been implemented on a novel haptic device and the resulting performances compared to those of existing solutions.

3. Coherence and collocation issues in multiple haptic systems

Even if the principles of collocation and coherence seem to be radicated in the way the interaction is driven, they are not limited to it. The design of the interacting device strongly affects the resulting quality. Even when the interface seems to be well suited for a collocated interaction, sometimes the complexity of the mechanical design, such as in the case of the case of the CyberGrasp [TGTC98], makes the quality of the force feedback very poor and unrealistic the exploration of features. Conversely, when the devices are not thought for being integrated, as in the case of using 2 independent PHANToM devices [HDD99], some drawbacks are present: the available workspace is extremely limited and the resulting mobility is furthermore reduced by device interference problems. Even considering a double “PHANToMed” system, even when subjected to a proper calibration, as did by Heyde [PHB99], the results in terms of position accuracy are very poor. Device internal kinematic provides error as larger as 0.033 mm/mm. Which means that with these system we have a 1 mm error each 30 mm of displacement.

A set of design constraints should be matched from such devices when these issues are taken into consideration:

- Workspace: the mobility of the device should be large enough to match the mobility of the human arm, any reduction in this design criteria will force the user to move according to specific strategies and therefore diminish the naturalism of the interaction.
- Interference: when multiple haptic devices are placed in the same environment, interference between mechanical structures limits the mobility of the user. The interference is mainly related to the kinematics adopted for the device.
- Encumbrance of finger attachments: the type and the encumbrance of the finger attachments can further reduce the quality of the interaction. The recognition of small details in multi finger mode requires that the detail size should be greater than the size of the attachment.
- Force: “force workspace” of the device represents the minmax condition of replicable force all over the dexterous workspace. The human hand/finger as multisensorial receptor is a very complex structure that can perceive and exert force over more than 3 decades (from grams to tenth of kilos). Conversely current design limitation rarely overcomes the 2 decades in terms of maximum force/force resolution.
- Dynamics of the device, structure large enough to cover wide workspace may have serious drawbacks on the rigidity of the structure itself, reducing in this way the bandwidth of the effective controllable forces. The adequate design of large-workspace HI requires that the first oscillating mode of the structure is higher enough to not impact the interaction performances.
- Stiffness of the mechanical structure: the stiffness of the mechanical structure is twice important when considering multi-HI environments. Beside the classical stability issues [CH88,Col93], the deflection of the interface may affect the relative position accuracy.
- Isotropy: non isotropic devices may generate spurious

Table 1: *Summary of GRAB features*

Features	Value		Units
	Worst case	Typical	
Continuous force	4	6-7	N
Peak force	20	30	N
Stiffness	2	6-8	N/mm
Position resolution	100	50	μm
Workspace	400x400x600		mm
Maximum force error	2-4		%
Coherence (max. error)	0.5/100		mm/mm

force/acceleration effects during motion, manipulation and exploration of objects.

- Position accuracy: the accuracy of the spatial position is important in order to achieve an highly collocated system. Objects and distances in a collocated environment should exactly reflect what the interface measure in terms of position. Erroneous measurements will result in distorted environments (curved planes, misaligned object, missing contact during surface exploration).
- Posture calibration: multi-haptic environments requires sophisticated algorithms to detect in an accurate way the relative position of the force display interfaces. Any error in this procedure will result in a “drunk like” representation of the object (i.e. the object position differs according to the exploring finger).

4. The haptic device

In order to overcome these issues, a novel kind of device has been built within the GRAB project. The device kinematics has been shaped in such a way that the available workspace is as large as a desktop environment even when two interacting interfaces are put in the operating environment. The system can be worn on the fingertips by means of thimbles. The device’s shape has been designed in order to limit at a minimum the interference problem even when the user’s fingertips are very close each other. The haptic interface has been described in detail in [AMA03] and has been patent in 2004. In Table 1, a summary of the features is given. The interface is capable of replicating two independent (3D) force vectors on two fingertips, with a workspace covering a large part of the user desktop (400mm x 400mm x 600mm) and with high force feedback fidelity to perceive tiny geometrical details of the objects. The peculiar cinematic of the devices facilitates the integration of multiple devices on the same desktop. A snapshot of the arm device is shown in Fig. 3. Even if the system has been developed with two arm working, several identical robotic structures may be let operating on the same table.

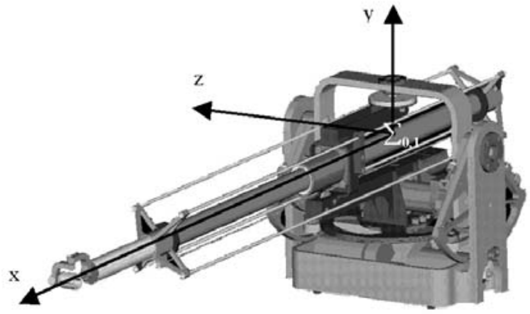


Figure 3: *CAD model of one arm*

Each structure has a total of 6 Degree of Freedoms (DOF’s). The first three DOFs exert the haptic feedback and could be used to track the position of the fingertip in the workspace. These DOFs have been implemented with two rotational joint and one prismatic joint (RRP). The remaining 3 degrees are completely passive and can be used to track the fingertip orientation (degrees of mobility). These degrees of mobility are realized by rotational joints (RRR) in such a way their rotation axes coincides in a common point which is aligned with the axis of the prismatic joint.

5. Integrating the environment

In Fig. 4 is shown the whole GRAB system, composed by following main components:

- two arms, having the same kinematics and symmetrically placed on the same desktop. The user interface of the two haptic interface is a couple of thimbles which can be adapted to any finger size and/or replaced with specific interactive pens;
- a motor driver and supply group including: six miniature PWM servo amplifiers for DC brush motors, custom mixed analog/digital ICs and hybridised power stage, capable to supply the required motors current (continuous current of 10 A, peak current of 20 A);
- a Control Unit, based on a x86 standard, Single Board Computer (SBC) which provides resource for running a Real - Time operating system required by Low Level Controller;
- Haptic Geometric Modeller, which receives the fingers position from Control Unit and provides to sends back the forces for simulating virtual environment.

6. System calibration procedures

System calibration procedures are implemented in order to maximize the precision in tracking finger position. It consists of two different calibration procedures.

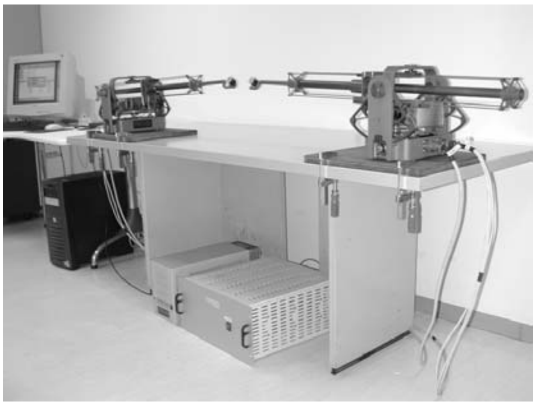


Figure 4: *Grab system*

Table 2: *Finger position vectors*

Symbol	Meaning
Σ_0 Σ_1	Respectively, local frames of right and left arm
$\vec{O}_0$ $\vec{O}_1$ $\vec{O}_W$	Respectively, origin positions of Σ_0, Σ_1 and Σ_W
$\vec{P}_0$ $\vec{P}_1$	Respectively, thimble positions of right and left arm
$\vec{P}_1^0$	position of left arm thimble expressed respect to Σ_0 $\vec{P}_1^0 = \vec{R}_1^0 \vec{P}_1^1 + \vec{O}_1^0$ where $\vec{R}_1^0$ is the matrix rotation between Σ_0 and Σ_1, calculated by $R\vec{P}Y_1^0$ angles
$\vec{P}_0^W$ $\vec{P}_1^W$	position of right and left arm thimbles expressed respect to Σ_W $\vec{P}_0^W = (\vec{R}_W^0)^T (\vec{P}_0^0 - \vec{O}_W^0)$ $\vec{P}_1^W = (\vec{R}_W^0)^T (\vec{P}_1^0 - \vec{O}_W^0)$ where $\vec{R}_W^0$ is the matrix rotation between Σ_0 and Σ_W, calculated by $R\vec{P}Y_W^0$ angles

The first one is been implemented to identify the correct joint positions. In fact, once the system has been turned on, encoder signals indicate a value which do not match the absolute configuration of the mechanical arm. In order to achieve the best force/torque design the position sensors (differential encoders) have been placed on motors' axes and they can only measure the relative motion between a reset angle (at power on) and current position. Such a solution offer the best design solution between position accuracy measurement and low cost sensor choice. In order to find the absolute position of the arms, in this phase, the calibration should find drive the arms in a safe (for the user) and accurate manner. The procedure consists of following steps:

- HI controller provides to control the arm in a speed/torque controlled and saturated operation. Such a control will move each arm towards some mechanical stopper placed in a well known configuration;
- once this position has been reached, the control will provide to register the offsets between actual (real) joint positions and measured read at differential encoders.

This type of calibration allows to minimize finger position errors for each arm separately.

The objective of the second calibration phase if to find the relative posture among the mechanical arms. Even having identical kinematics and being placed symmetrically on the user desktop, the fine placement of the two HIs is left to the user which is free of adapt the device collocation in order to match the constraints of his desktop. In this case, the controller can not anymore assume that the relative position of left and right arms is a fixed pre-computed transformation matrix.

The goal of second calibration procedure is to find the exact content of this transformation matrix in terms of arms' relative position and orientation. This feature will allow to control the two different arms (placed in any relative configuration) as they would share the same coherent system of forces and position. In order to introduce the calibration steps, some information about kinematic model are preliminarily given.

Thimbles coordinates and forces are expressed in control software respect to three different reference systems: two local frames, associated to right (Σ_0) and left (Σ_1) arm (frame shown in Fig. 3) and an independent frame (Σ_W). In order to define the relative position and orientation between two local frames, depending on current arm configuration on the desktop, and the position and orientation of independent frame respect to local ones, Σ_0 is the chosen as the absolute one and Σ_W and Σ_1 are defined respect to Σ_0 by the vector which indicates the origin coordinates (respectively $\vec{O}_W^0$ and $\vec{O}_1^0$) and the three angular rotations of axis respect to absolute one (respectively $R\vec{P}Y_W^0$ and $R\vec{P}Y_1^0$) according to Roll-Pitch-Yaw angles conventions.

Different type of thimble position and force vectors are used in control software, as shown in Table 2 and 3.

The relative positions vectors are calculate for each arm by applying the direct kinematic equations for the mechanical device (3 DOF shoulder) and are rarely used in control scheme. Most important are the positions vectors expressed respect to absolute frame (independent position vectors), be-

Table 3: *Finger force vectors*

Symbol	Meaning
$\vec{F}_0$ $\vec{F}_1$	force to be applied on finger by right and left arm
$\vec{F}_0^0$ $\vec{F}_1^0$	force to be applied on finger, expressed respect to Σ_0 $\vec{F}_0^0 = \vec{R}_W^0 \vec{F}_0^W \quad \vec{F}_1^0 = \vec{R}_W^0 \vec{F}_1^W$
$\vec{F}_1^1$	force to be applied on finger by left arm, expressed respect to Σ_1 $\vec{F}_1^1 = (\vec{R}_1^0)^T \vec{F}_1^0$

cause their values are used to represent current thimbles coordinates for Haptic Geometric Modeler computer (HGM) during the force-feedback task.

The independent force vectors $\vec{F}_0^W$ and $\vec{F}_1^W$, to be applied during the force-feedback, are defined by Haptic Geometric Modeler computer (HGM). Control software provide to transform this forces in vectors $\vec{F}_0^0$ and $\vec{F}_1^1$, expressed respect to local frame, for evaluating the correspondent torques to be applied on joints.

Thus, position and force vectors used in applications implemented on HGM computer can be expressed respect to one reference system (the independent one), without considering the current relative position and orientation of two arm on the desktop (this is only checked by the control software).

Moreover, by changing the values for vectors $\vec{O}_W^0$ and $R\vec{P}Y_W^0$, the position and orientation for independent frame can be set in order to allow the best matching between geometry of graphical applications and users requirements. In fact, control software is defined in parametric way respect to the position and orientation of each frame: HGM software should only issue the correct command for changing position and orientation of independent frame and for activating a control phase which provides to automatically detect the relative arms position on desktop and it returns the correct values for vectors $\vec{O}_1^0$ and $R\vec{P}Y_1^0$.

7. Calibration procedure

Once two arms are placed and fixed on desktop, a simple mechanical device should be applied on thimbles of two arms. As shown in Fig. 5, a little holdfast is applied for constraining thimble axes to be coincident to the barrels' ones and a Cardano's joint is used for linking two thimbles together. If we don't consider singular configuration (i.e. two barrels are aligned), this arrangement leaves only 3 translation degrees of freedom to system and allows the to keep the center of Cardano's joint in a fixed position respect to third body of both arms.

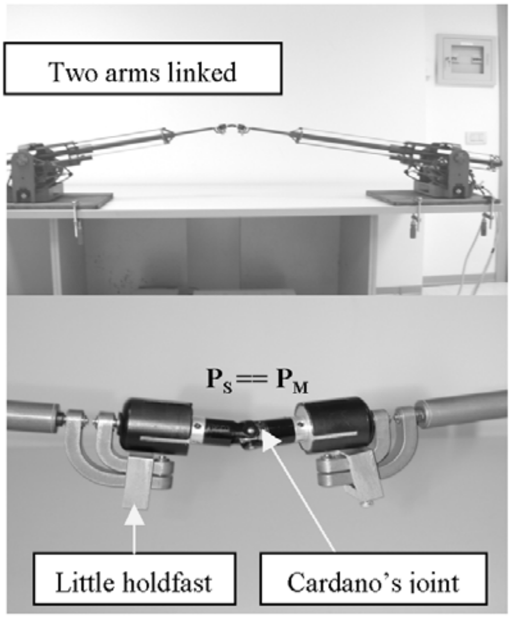


Figure 5: *Mechanical set up for calibration procedure*

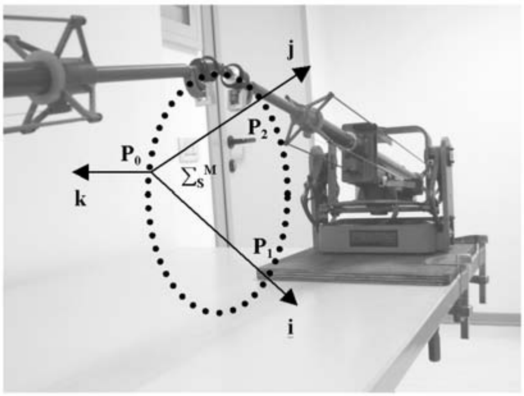


Figure 6: *Movement of linked arms during calibration procedure*

The calibration procedure consists of moving, using a positional control, the right arm along a predefined path while the left one is force-controlled to a zero-resistance. In such a way the right arm can easily drive the other one along the path defined in Fig. 6.

During such a procedure the control software will provide to compute and record the coordinates of Cardanos' spherical-joint expressed in both local reference systems.

Table 4: *Master and Slave position vectors*

Symbol	**Meaning**
$\vec{P}^M$ $\vec{P}^S$	position of spherical joint centre respect to local frame of master and slave arm
$\vec{R}_S^M$	rotation matrix from master's local frame to slave's one
$\vec{O}_S^M$	position vector of slave's local frame respect to master's one

Since the control procedure will provide to use the right arm as motion driver, in the following it will be indicated as master arm and the other one as slave.

As mentioned before, the control procedure will provide to store the positions of the path points expressed respect to local frame of two arms (Table 4).

By using any free set of three among the stored points ($\vec{P}_0^M$ $\vec{P}_1^M$ $\vec{P}_2^M$ respect to master's frame and $\vec{P}_0^S$ $\vec{P}_1^S$ $\vec{P}_2^S$ respect to slave's one), it is possible identify a mobile reference frame which is uniquely identified in both reference systems (Σ_0 and Σ_1).

Such a system can be used to find the rotation matrix between master's and slave's local frames by the following procedure:

1. using stored point it is possible to determine two intermediate frames with versors
   $\vec{i} = (\vec{P}_1 - \vec{P}_0)/|\vec{P}_1 - \vec{P}_0|$ $\quad \vec{j} = (\vec{P}_2 - \vec{P}_0) - ((\vec{P}_2 - \vec{P}_0) \cdot \vec{i})\,\vec{i}$ $\quad \vec{k} = \vec{i} \times \vec{j}$
2. the rotation matrixes between the master's local frame and the intermediate frame and between the slave's local frame and the intermediate frame simply result
   $\vec{R}_I^M = [\vec{i}^M, \vec{j}^M, \vec{k}^M]$ $\quad \vec{R}_I^S = [\vec{i}^S, \vec{j}^S, \vec{k}^S]$
3. the rotation matrix between the master's local frame and the slave's local frame simply results
   $\vec{R}_S^M = \vec{R}_I^M (\vec{R}_I^S)^T$
4. Once rotation matrix is known, by using one of three stored points $\vec{P}0\vec{P}1\vec{P}2$ (for example $\vec{P}0$) it is possible to find the origin position vector of slave's local frame respect to master's one:
   $\vec{O}_S^M = \vec{P}_0^M - \vec{R}_S^M \vec{P}_0^S$

It worths to mention that the procedure is independent from the specific trajectory used to find the six points set ($\vec{P}_0^M$ $\vec{P}_1^M$ $\vec{P}_2^M$ $\vec{P}_0^S$ $\vec{P}_1^S$ $\vec{P}_2^S$). Therefore even in presence of unaccurate position control the calibration procedure can provide exact calibration provided that a synchronized and accurate measure of these points is available.

Errors in evaluating stored vectors position can occur when the procedure is carried on. The reasons could be within the following ones:

- mechanical device could be different from simplified kinematic model:
  - dimensions of mechanical parts may slightly differs respect to design specifications;
  - the mechanical device is not absolutely rigid therefore elasticity of transmissions and of structures may alter the effective measurement;
  - backlash of coupled mechanical parts;
- error in angular offsets evaluation, that will led to imprecise calibration procedure and digital resolution of incremental position sensors can affect computational procedures.

In order to reduce calibration errors, a recursive procedure has been implemented by storing a large number of points and by calculating final relative position and orientation between two frames using average values.

The procedure adopted is the follow:

1. master arm is controlled in order to move the centre of Cardano's joint along a circumference as shown in Fig. 6;
2. a number of circumference points are stored as indicated during the movement;
3. a group of three points $(\vec{P}_0\ \vec{P}_1\ \vec{P}_2)_i$ are considered for determining the correspondent matrix rotation $(\vec{R}_S^M)_i$;
4. from any rotation matrix it is necessary to associate the Roll-Pitch-Yaw angles $(R\vec{P}Y)_i$;
5. the final $R\vec{P}Y$ are calculated as the average values;
6. from the final $R\vec{P}Y$ is calculated the final rotation matrix.

8. Results

Once the calibration has been achieved the control software provides to store it in specific OS registry entries and reuse them whenever the system is restarted.

In this way the user can operate on the systems as the arms belong to unique OS without caring too much (nor in use, nor in SW development) with the organization of mechanics and system control. If the user will notice that collocation of objects within VE appears to be corrupted he can manage a recalibration of the device at any time. This can be achieved by issuing the relative command from the HI control panel. Some extensive tests have been carried out in order to match the effectiveness of the calibration all over the workspace. The procedure works as follows: different "virtual" axes-aligned square-boxes have been placed on several positions of the arms workspace. HIs have then been moved onto the boxes in order to arrange thimbles is a parallel fashion on the same surface. Relative position has been measured according to the normal to the considered surface. Whenever the relative position did not matched the relative difference has been logged.

The resulted error is almost zero at the centre of the workspace and increases as the thimbles are moved away from the center. The error is almost proportional to the distance from the centre. As a result the calibration procedure, joined with the quality of the device, allows to keep the relative error below 0.5 mm (the difference in evaluation of the same position by right and left arm), at a distance of 100 mm from the workspace center.

9. Acknowledgment

The authors would like to acknowledge the EU which contributed to fund the GRAB project as well as all the organizations involved within the project: LABEIN (ES), ONCE (ES), RNIB (UK), NCBI (IE) and HAPTICA (IE).

10. References

[AMA03] Avizzano C., Marcheschi S., Angerilli M., Fontana M., Bergamasco M., Gutierrez T., Mannegeis M., A multi-£nger haptic interface for visually impaired people. Robot and Human Interactive Communication, 2003. Proceedings. ROMAN 2003, 165–170.

[BLSH95] Brunner B., Landzettel K., Steinmetz B.-M., Hirzinger G. Telesensorprogramming - a task-directed programming approach for sensor-based space robots. Int. Conf. on Advanced Robotics (ICAR), Sant Feliu de Guixols, Spain, Sept 20-22 (1995).

[CH88] Colgate J. E., Hogan N. Robust control of dynamically interacting systems. International Journal of Control 48 (1988), 65–88.

[Col93] Colgate J. E. Robust impedance shaping telemanipulation. IEEE Transactions on Robotics and Automation 9 (1993), 374–384.

[HDD99] Howe R., Debus T., Dupont P. Twice the fun: Two phantoms as a high-performance telemanipulation system. In Proceedings of the Fourth Annual PHANTOM Users Group Workshop, Dedham, MA, October 9-12 (1999).

[Jan98] Jansson G. Can a haptic force feedback display provide visually impaired people with useful information about texture roughness and 3d form of virtual objects? In P. Sharkey, D. Rose & J.-I. Lindström (Eds.), The 2nd European Conference on Disability, Virtual Reality and Associated Technologies. Proceedings (pp. 105-111). Reading, UK: University of Reading, Department of Cybernetics. (1998).

[Jan01] Jansson G. The potential importance of perceptual £lling-in for haptic perception of virtual object form. In Eurohaptics 2001 Conference Proceedings (Educational Technology Research Papers, ETRP 12, pp. 72-75). Birmingham, England: The University of Birmingham (ISSN 1463-9394). (2001).

[KL90] Klatzky R., Lederman S. Intelligent exploration by the human hand. Springer-Verlag, 1990, ch. Dextrous robot manipulation.

[KL99] Klatzky R., Lederman S. Tactile roughness perception with a rigid link interposed between skin and surface. In Perception & Psychophysics 1999, 61 (4), 591-607 (1999).

[PHB99] Pelz J. B., Hayhoe M. M., Ballard D. H., Shrivastava A., Bayliss J. D., von der Heyde M. Development of a virtual laboratory for the study of complex human behavior. In Proceedings of the SPIE - The International Society for Optical Engineering, 3639B (1999).

[TGTC98] Turner M., Gomez D., Tremblay M., Cutkosky M. Preliminary tests of an arm-grounded haptic feedback device in telemanipulation. Proc. ASME WAM DSC-64 (1998), 145–149.

Haptic Interfaces for Virtual Prototyping

M. Bergamasco*, A. Frisoli, PERCROScuola Superiore S.Anna, Pisa, Italy

S. Scattareggia Marchese,Signo Motus srl - Messina, Italy
A. Gucciardino, Direzione Generale Armamenti Terrestri - Rome, Italy

---

Abstract

This paper analyzes the general requirements of Haptic Interfaces (HIs) for Virtual Prototyping operations. In particular two different paradigms of interaction with virtual objects are presented, respectively based on an anthropomorphic and a desktop Haptic Interface. The main aspects of mechanical and control system design of HIs and force rendering in Virtual Environments are discussed too. The experimental results of the simulations conducted with a force feedback arm exoskeleton are presented, pointing out the current limits of the existing devices and outlining the future developments.

---

1. Introduction

Virtual prototyping technologies can reduce the time and costs necessary to develop and construct new products and bridge the disciplinary and distance gaps among different collaborators working on the same project [3]. Virtual Prototyping is based on the simulation in a realistic three-dimensional Virtual Environment of the functionality expected from the new product. Before the real construction of the first prototype, it enables designers to evaluate the fulfillment of ergonomics, engineering and design requirements, and the feasibility/adequacy of the product to the foreseen usage [2]. One of the key issues in Virtual Prototyping applications is the capability provided to the operator of interacting in an efficient and sensorially sufficient way with the virtual model of the object. The sense of touch appears to be fundamental to assess the properties of the prototype of a complex system, such as a vehicle. Although CAD systems are becoming widespread, there is still some important information that a CAD program alone cannot supply. The designer cannot see from the CAD how the operator will fit into cab or assess how the controls will feel during operation. During the development of new vehicles the designer must still wait until a mock-up or a prototype is built to find out how the controls feel and whether or not they are easy to use [1]. Vehicle simulators immersed in Virtual Environments [6][4], where either the contact or the inertial forces are replicated to the operator, have been successfully employed for the evaluation of ergonomics aspects in the cockpit. Conceptually the rendering to the human operator of the sensation of a physical interaction with a virtual environment can be achieved by utilizing appropriate interfaces capable of generating adequate sensory stimuli to the operator. Such interfaces, called Haptic Interfaces (HIs), are force feedback devices that can exert a controlled force on the operator's limb as if he was touching a real object. HIs can greatly enhance the realism and the sensation of immersion perceived by the operator in the Virtual Environment, while using CAD tools for the design/assessment of new products. The most important characteristics that an HI must fulfill are high backdrivability, low inertia (related with the transparency during the motion of the device), absence of mechanical plays, mechanical stiffness greater than 5 N/mm, isotropic force response in the workspace (necessary to avoid vibrations and penetration into virtual objects). The low-level control system needs to run with a frequency up to 1KHz and to maintain the coherence with the graphics representation of the simulation. HIs, can be usefully employed for the simulation of virtual assembly and maintenance procedures, with the aim of studying the feasibility of some particular mounting operations in mechanical assemblies and verifying the level of operator's tiredness induced by the task. In particular in order to evaluate the execution of such procedures in complex mechanical assemblies, it is necessary to use HIs with a workspace close to the real one of the human arm and with multiple contact points on the operator's arm. Force feedback anthropomorphic arm exoskeletons, which can be worn by the operator in a natural way with a reduced encumbrance, are the ideal candidate solutions for the simulation of such complex tasks. The possibility of exerting contact forces on different points of the operator's arm allows assessing the feasibility of mounting procedures in huge assemblies. For instance it would be possible to evaluate the reachability of a screwed hole in a motor housing by the operator's arm holding a wrench and to find the interference with other parts along the wrench path. This paper describes two different Haptic Interface systems, which can be employed for the execution of operations of virtual prototyping. The underlying issues related both to the control and the design of such systems are also presented.

2. Characteristics of Haptic Interface systems

Some basic features of Haptic Interface systems can play a relevant role in the execution of Virtual Prototyping operations:

- Number of Points of contact: Haptic Interfaces providing multiple point of contact allow an enrichment of the experience in the virtual environment. Both the time necessary to identify the shape of an object in a virtual environment and the adopted exploratory procedure are directly correlated to this number [10]. Exoskeletons systems generally allow replicating multiple points of contact. In Virtual Prototyping applications this provides the possibility of simulating operations such as assembling and maintenance, by taking into account also the encumbrance of the operator's arm during the execution of operations.
- Grounded vs. Portable Haptic Interfaces. Portable Haptic Interfaces allow the operator to perform a free motion and to touch virtual objects within a large workspace. Grounded Haptic Interfaces have the main advantage of being generally characterized by a reduced encumbrance, which allows to locate them on a desktop, while, as a drawback, the reachable workspace is reduced.
- Capability of replicating torques: Capability of replicating torques is important when operations of assembling have to be replicated. Typically in the case of inserting a peg in the hole, the reaction torques generated by the misalignment of hole/peg axes provide the indication of correct fitting to the operator.
- Mechanical properties of Haptic Interfaces: Haptic Interfaces are traditionally designed according to the following general guidelines: low moving masses and inertia, low friction, high back-drivability, adoption of smooth, low play transmission systems, high structural stiffness, high force and position bandwidth. The fulfillment of such requirements is generally achieved by the adoption of tendon transmissions for remote actuation together with grounding of motors.

3. The arm force exoskeleton

The PERCRO arm force exoskeleton [7] (see Figure 1) is a 7 degrees of freedom (DOF) HI, tendon actuated with DC brushed motors. The system can be configured with 5 DOF only, with a handle or a glove fixed to its last link. The kinematics of the first 5 DOF of the system is shown in Figure 2. The exoskeleton is equipped with optical encoders at each joint and three force sensors, based on a strain gauge architecture that can measure the torque on the last three joints of the system.

Figure 1: *The arm force feedback exoskeleton*

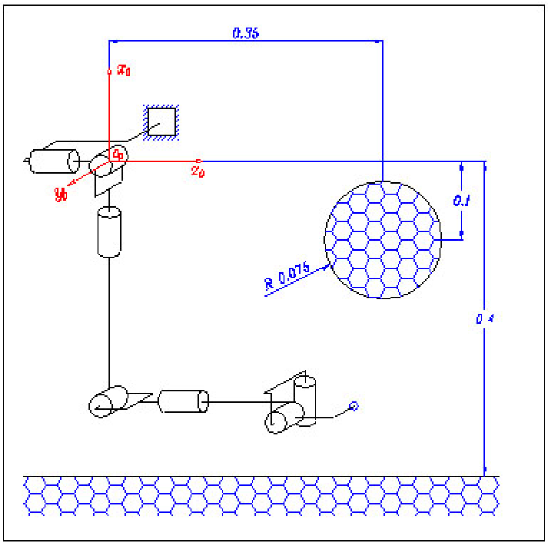


Figure 2: *The virtual environment and the Arm-Exoskeleton worn by the operator in the 5DOF set-up*

In the following the results of some haptic experiments that have been conducted on the arm exoskeleton are presented. In the Virtual Environment a full-body avatar of the operator is represented as it is shown in Figure 3, while the contact forces are displayed as solid arrows. The operator can observe the movements of his arm on a wide screen, on which all the computer generated Virtual Environment is projected. Several objects with different geometrical shapes have been represented, such as a sphere, a wall, a cube and polyhedral objects, according to the scheme illustrated in

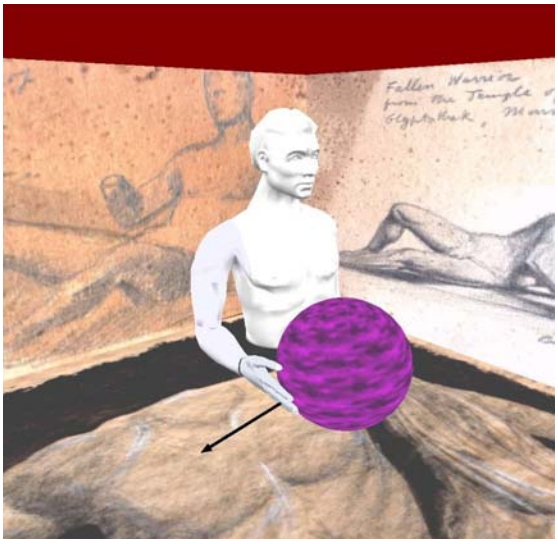


Figure 3: *Representation of the contact in the Virtual Environment*

Figure 2. The operator can move freely his arm in the space, without feeling the weight of the exoskeleton, since gravity and friction forces are compensated by the action of motors. A measure of forces and displacements of the contact point during the simulation allows to assess the performance of the system, i.e. the capability of providing the correct perception of the contact to the user. When the hand enters in contact with an object, forces are generated against the operator's hand in order to impede it to penetrate in the object.

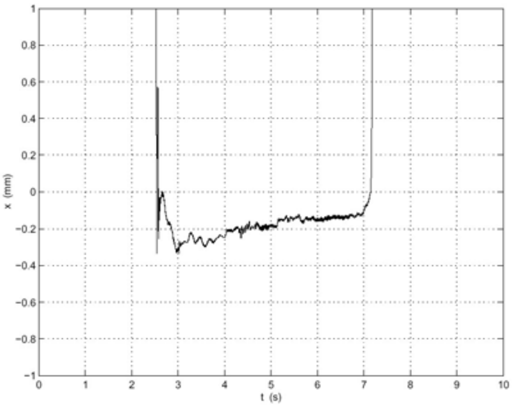


Figure 4: *Plot of position vs. time during the simulation of the contact with a virtual wall at x=-0.2 mm*

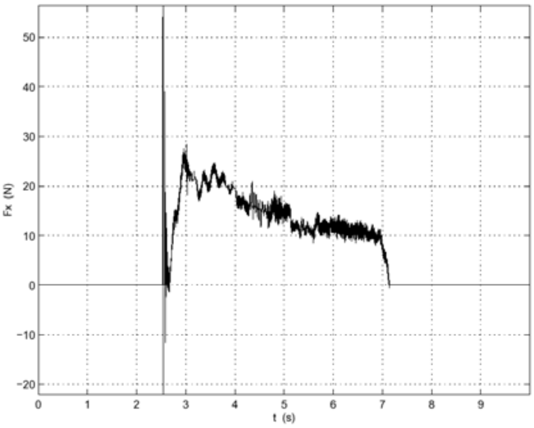


Figure 5: *Plot of force vs. time during the simulation of the contact with a virtual wall at x=-0.2 mm*

Figure 4 and Figure 5 respectively show experimentally measured position and force during the contact between the operator's hand and a virtual wall. The haptic cues are displayed to the operator by simulating virtual mechanical impedance at the contact point. The calibration studies of the controller have permitted to set up the optimum value of the impedance, in order to avoid the onset of vibrations or the sensation of a very soft surface. As it can be observed in the plots, after a transient peak due to the collision with the surface, the reaction force reaches a stable value of about 15 N. The optimum parameters of the simulated mechanical impedance that determine the best performance during the contact have been estimated as a mechanical stiffness of 80 N/mm and a viscous damping of 0.3 N/(sŒmm). Anthropomorphic force-feedback exoskeletons can be suitably employed in Virtual Prototyping applications, where a full immersion of the operator can be realized by wearing such devices in a natural and comfortable way. In order to extend the capability of PERCRO arm exoskeleton system, a portable device for the hand has been recently designed at PERCRO for the force-feedback on user's fingertips during grasping. Such a device will be worn by user's forearm and integrated with the arm exoskeleton on its terminal link that will support its weight. While the micro-system will allow enhancing the stiffness and the perceived inertia of the systems where a manipulation task is performed with the fingers, the macro system will allow reaching a greater workspace with the hand.

Such a system will allow the simulation of grasping and moving objects in the space, with the correct feeling of interaction forces/torques generated by the contact with other objects.

4. The Desktop Haptic Interface system

Another paradigm of interaction with a virtual environment can be realized with desktop HIs. HIs with reduced number of degree of freedom can be employed for the three-dimensional exploration and navigation in the Virtual Environment enriched with the sensation of contact with the vir-

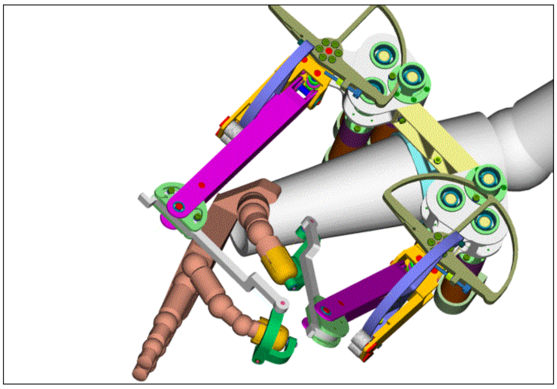


Figure 6: *The pinching haptic interface*

tual objects. Low DOF HIs represent an alternative choice, when it is not requested to sense the posture of the entire human arm and the nature of the performed task can be carried out with a single contact point. An example of such a device is the desktop two Haptic Interface system realized at PERCRO, shown in Figure 7. Such a 2 DOF HI [5] is actuated by a novel transmission system, which allows increasing the isotropic behavior of the system force response. The HI can exert forces up to 10 N in its plane. Although the system possesses a plane geometry, it can be used for rendering 3-dimensional shapes too, by exploiting vector fields of lateral forces: a force resistant to the motion of the operator's hand and lying in the plane of motion is perceived as a positive slope, while a force pushing along the motion direction as a negative slope. This effect has been exploited in numerous investigations [11] to display virtual features, such as holes or bumps. The main advantage of a desktop device is the reduced cost with respect to higher DOF HIs.

Figure 7: *The desktop 2 DOF HI*

The system is controlled in real-time through a control system based on two main treads running with different clocks, according to the architecture shown in Figure 8. Two different nodes manage the execution of the two threads. The Haptic Module is executed on a DSpace Control Board, while the Graphics Module is executed on a Pentium III 1GHz equipped with a NVidia GetForce3 Graphics Board.

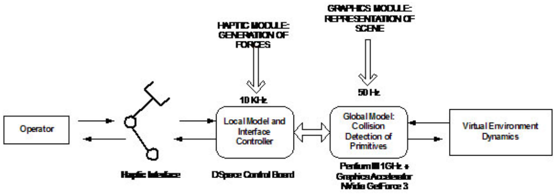


Figure 8: *Block representation of system architecture*

The thread that manages the graphic representation of the overall virtual environment is executed at each 30 msec and, detects primitives that are in contact each other in the Virtual Environments by means of a collision detection algorithm. In the case of the planar kinematics, it has been adopted a collision detection algorithm based on the generation of Voronoi diagrams and distance fields of colliding primitives using graphics hardware. Such an algorithm, developed for Computer Graphics purpose only [8], has been integrated with a hierarchical collision detection algorithm and adapted in order to fulfill the requirements of force feedback generation. Figure 9 shows the concept underlying the collision detection algorithm in a simple case of contact between a point and a circle, represented by means of polygonal representation. When the point is closed to the circle, Voronoi diagrams are computed in a square area surrounding the point. Such an area is divided in sub-areas with different colors, each different color identifying the polygon edge that is closest to the point.

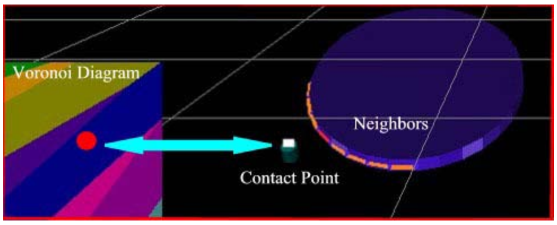


Figure 9: *Example of Voronoi Diagram associated to the contact of point with a circle*

On the basis of the contact primitives, a local model of the virtual environment is extracted by selecting neighbors of the primitives that are in proximity of the contact point. Such local model is then sent to the Haptic Module, which generates the force feedback at a refresh rate of 10 KHz. The Haptic Module is based on a Fast Collision Algorithms incorporating a God-Object for the computation of forces, according to [9]. Figures 10,11,12 show a sequence of different frames of a virtual simulation of insertion of peg in the hole. When the peg is pushed against a boundary of the yellow housing, a reaction force is computed in real time, which avoids the penetration of the two bodies. The peg in the hole represents a paradigm of assembling operations. In such a case the contact forces allow to feel whether the correct relative position of the two bodies has been addressed for the insertion task.

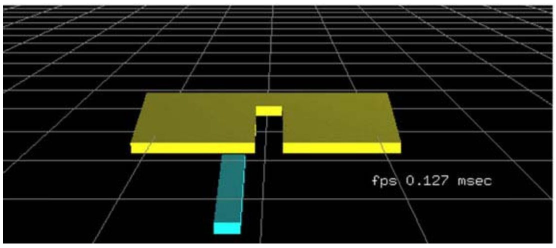


Figure 10: *Peg in the Hole task: non colliding objects*

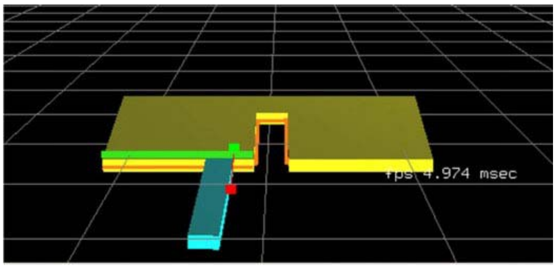


Figure 11: *Peg in the Hole Task: The peg is colliding with an edge of the yellow housing*

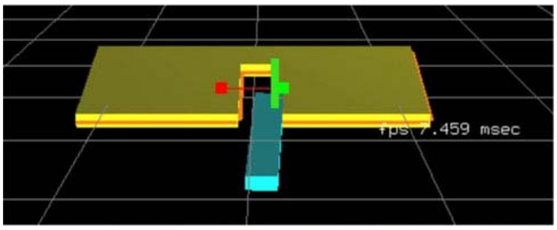


Figure 12: *eg in the Hole task: The peg is colliding with an edge inside the hole*

5. Conclusions

Haptic Interface systems present a great potential for applications in virtual prototyping. Although multi-degree of freedom systems are preferable for complexity of tasks that can be simulated, low degree of freedom haptic interfaces could constitute a valid alternative, in term of cost and encumbrance of device.

6. References

[1] Niesen MR, Luecke GR, *Virtual Dynamic Prototyping for Operator Interface Design*, Proc of IEEE RO-MAN99, Pisa-Italy.

[2] Yoshikawa T, Yoshimoto K, *Haptic Simulation of assembly operation in Virtual Environment*, Proc. of ASME IMECE 2000, Symposium on Haptic Interfaces and Teleoperation, Orlando FL-US.

[3] Lu SC-Y, Shpitalni M, Gadh Rajit, *Virtual and Augmented Reality Technologies for Product Realization*, Annals of the CIRP Vol. 48/2/1999.

[4] Frisoli A, Avizzano CA, Bergamasco M, Data S, Santi C, *Dynamic modeling of primary commands for a car simulator*, IEEE 2001 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM '01) 8-12 July 2001 Como, Italy.

[5] G.M.Prisco, A.Frisoli, F.Salsedo, M.Bergamasco,*A novel tendon driven 5-bar linkage with large isotropic workspace*, Proc. of ASME (American Society of Mechanical Engineers) IMECE99, International Mechanical Engineering Congress and Exposition (http://www.eng2.uconn.edu/alarm/imece99), Nashville (TN-USA).

[6] D Ferrazzin, F Salsedo, A Frisoli, M Bergamasco, *Strategy Manager Implementation in a Motion Based Two-Wheeled Vehicle Simulator*, 32nd ISATA, International Synposium of Automative Technology and Automation, Vienna-Austria.

[7] Bergamasco M, *Force replication to the Human Operator: The Development of Arm and Hand exoskeletons as Haptic Interfaces*, Proc. of 7th International Symposium of Robotic Research 1995, Springer Verlag.

[8] Hoff KE, Culver T, Keyser J, Lin M, Manosha D, *Fast Computation of Generalized Voronoi Diagrams Using graphics hardware*, SIGGRAPH '99

[9] Craig Zilles and Ken Salisbury, *A Constraint-based God-object Method For Haptic Display*, IROS '95.

[10] G Jansson, *Basis Issues concerning visually impaired people's use of haptic displays*, Proceedings 2000 Intl COnf Disability, Virtual Reality & Assoc. Tech.

[11] J. M. Weisenberger, M. J. Krier, M. A. Rinker, *Judging the Orientation of Sinusoidal and Square-Wave Virtual Gratings Presented via 2-DOF and 3-DOF Haptic Interfaces*, Vol. 1, No. 4, March, 28, 2000

Haptic Displays Used for Exploration of Works of Art at Museums

Antonio Frisoli, Gunnar Jansson, Massimo Bergamasco, Celine Loscos

---

Abstract

The Museum of Pure Form is a virtual reality system where visitors can interact with digital models of sculptures through the sense of touch. The paper presents the results from the evaluations of the Pure Form system conducted during 2003 and 2004 at several exhibitions held in European museums.

---

1. Introduction

Haptic perception represents the most immediate and intimate way of interacting with sculptures and other art objects, allowing the observer to perceive the concept of space the artist has impressed on the art forms during their formation. For reasons of security and preservation, visitors to traditional museums are allowed only to see the objects, and, since touching them is not permitted, this experience falls short of a full appreciation of the artistic value and intrinsic beauty of the collections. Moreover, the appreciation of visual art is often denied entirely to blind and visually impaired visitors. Through the conjunction of virtual reality (VR) and haptic technologies, the Museum of Pure Form aims at offering an alternative by giving the haptic perception of artistic forms an approximation of the same essential role it had for the artists during their creation. Various examples exist of systems where haptic interfaces are used to interact with art forms. Most of such examples are based on using haptic devices as synthesis tools (see for instance [17][18]). Less often haptic devices have been used as tools for better analyzing art pieces. The only existing example of this, to the authors' knowledge, is the work of McLaughlin and her group at USC [15].

Project development was carried out by a consortium of partners coordinated by PERCRO. Several museums were involved in the project. The Galician Centre for Contemporary Arts (CGAC), Santiago de Compostela (Spain), the Museo dell'Opera del Duomo (OPAE), Pisa (Italy), and the Nationalmuseum (NM) of Fine Arts, Stockholm (Sweden) actively participated in the project by hosting and organizing public temporary exhibitions. Other associate museums that have contributed to enrich the digital collection of works of arts were the Conservation Centre at National Museums Liverpool (UK) and the Petrie Museum of Egyptian Archaeology, London (UK).

Figure 1: *The museum installation at CGAC site*

The Museum of Pure Form has had a number of deployments in cultural heritage institutions across Europe. In September 2003 a new multimedia room was opened at OPAE, while formal evaluation of the project in a CAVE-like environment [10] took place at University College London in November 2003. This has continued at CGAC and at the NM during the first three months of 2004.

At CGAC the Pure Form systems were exhibited throughout the month of February. More than 400 users explored the potential of haptic interfaces for engagement with artworks. In Figure 1 it is shown the complete set-up of the

Pure Form system, as it was installed in CGAC during the exhibition held in the museum. The exhibition at NM was arranged in cooperation with the museum staff (especially Hans Öjmyr) and the staff of the Interactive Institute, Stockholm (especially Halina Gottlieb), in March and April 2004 in connection with a larger exhibition "False and Genuin" featuring genuine works of art and different kinds of copies, authorized as well as forged. The virtual works of art to be explored haptically were here considered as a special kind of copy. This paper presents the results of the evaluations that were conducted at the different exhibition sites during 2003 -2004.

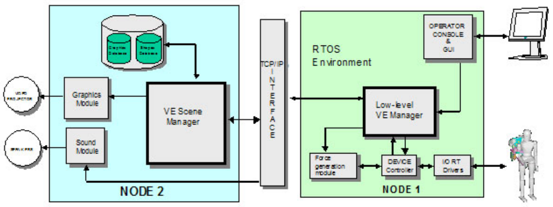


Figure 2: *General architecture of the Museum of Pure Form.*

2. Overview

The complete Museum of Pure Form system is composed of the following components:

1. the haptic interface system
2. the database of the 3D models of sculptures
3. the stereoscopic visualization system
4. the software API (Application Program Interface) libraries for the haptic and graphics rendering.

The overall system architecture is schematized in Figure 2. The simulation and control of the Haptic Interface system are deployed over 2 computing nodes, which have been implemented on a low-cost platform composed of two PCs.

2.1. General description of the system

The need of a more realistic haptic interaction in VE has encouraged the development of devices that make use of multiple points of contact [12], when the interaction is not tool-based. In the Pure Form system two haptic devices have been specifically devised in order to provide the user forces on two contact points on the hand. They are an exoskeleton device and a desktop device.

The anthropomorphic exoskeleton device can be worn on the operator arm, as shown in Figure 3, and can globally exert forces of arbitrary direction and amplitude on the index and thumb fingertips, along all over the whole workspace covered by the arm. The Pure Form desktop device is composed of two distinct robotic arms placed on two support columns placed in front of the visualization screen (Figure 4). They reach the fingertips of the operator's hand with thimbles that can be worn on two fingers either of the same hand or of two different hands.

Figure 3: *The Pure Form exoskeleton system.*

In the museum exhibitions the simulation of the virtual environment was displayed through a stereoscopic visualization screen with back projection and passive polarization. The dimensions of the screen were 2m width by 1.5m height. The projection screen was fixed through a frame and the haptic interface was placed in front of the screen.

Seventeen sculptures belonging to different historical periods were digitized though laser scanning and post-processed to produce accurate polygonal meshes. The count of polygons of meshes was then reduced in order to reduce the complexity of the models and improve the performance of both haptic and graphic rendering algorithms (Figure 5).

The characteristics of digital models generated by a 3D laser scanning process, constituted as they are by a large number of polygons and moreover very densely distributed over the surface, make these models very hard to be haptically rendered in real time with conventional algorithms. The generation of the force information was realized through a constraint-based algorithm, based on the god-object concept introduce by Zilles and Salisbury [13]. A detailed real-time haptic rendering of surface of the model was achieved by running the force generation module on a local model of the contact area, while the collision detection was conducted in a separate thread on the whole model.

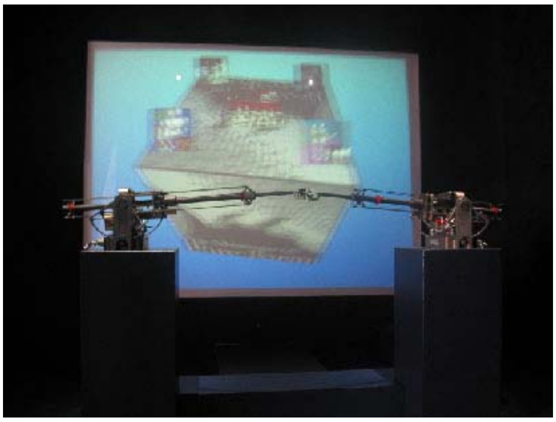


Figure 4: *The Haptic Desktop system being in use at OPAE.*

3. Problem

The aim was to evaluate the PURE-FORM haptic displays used by museum visitors manually exploring virtual copies of statues and at the same time obtaining a stereo visual copy. The results from evaluations at three museums, OPAE, CGAC and NM and from experiment conducted at the ReaCTor facility of UCL are reported.

4. General method

The PURE-FORM desktop device was used at OPAE museum, while the PURE-FORM exoskeleton haptic display was used at all remaining locations.

Questionnaires were used at all museums. The questions were partly common in the different contexts, but they were also partly different depending on local conditions. The general content of the questionnaires was a result of cooperation between representatives for the partners of PURE-FORM and the museums involved in the evaluation. It consisted of questions about the experience of specific parts of the statues, ratings of general aspects of the usability of the device and the personal background of the participants. In the present report a summary of the evaluations is given with references to original preliminary texts.

5. Evaluation within a multimedia exhibition at OPAE

The PURE-FORM display at OPAE was part of a larger multimedia exhibition providing a virtual visit to the area, the Miracle Square, including as well the Dome and the Leaning Tower. The evaluation was performed in cooperation with the staff of OPAE. Details of the questionnaire, as well as the results are given in [2].

Figure 5: *Real vs. digitized copy of the Salomé by A. Pisano (1300).*

The available virtual statues were five sculptures of the Italian gothic period by Giovanni and Andrea Pisano. The questionnaire, available in Italian and English and given to about 150 museum visitors, consisted of 20 questions, most of them with answers in multiple choice form.

5.1. Results

The time spent with the PURE-FORM desktop haptic display was estimated to be more than five minutes by about half of the number of visitors and a majority (93 %) touched the virtual statues. Most of them found the experience amusing (73 %) and/or instructive (61 %).

6. Evaluation within a CAVE-like environment

A CAVE-like room (CAVE Automatic Virtual Environment [10]), i.e. a room with floor and 3-4 walls back-projected with a stereoscopic visualization of a virtual computer-generated scenario, was used for the experiments. The tests were conducted within the ReaCToR at the Department of Computer Science, University College London. The PURE-FORM exoskeleton haptic display was installed. Visitors could navigate through a virtual museum, select a virtual works of art from the Petrie Museum or OPAE and interact with it (Figure 6). In total 2 statues were chosen to be made available during the tests.

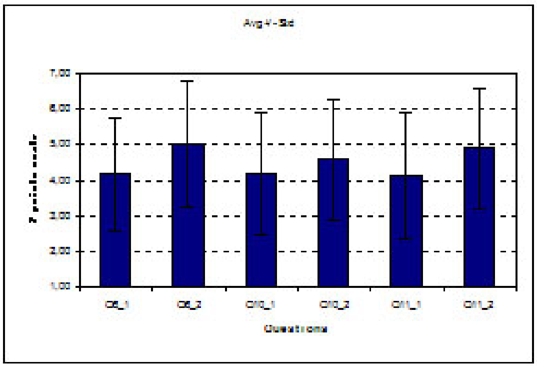


Figure 6: *The interaction with statues during the simulation in the CAVE-like environment.*

6.1. Methods

A main part of the evaluation concerned co-location of stereo graphics and haptic display information. A group of 6 computer-literate adults (50% male, 50% female) were invited to take part to the experiment. A simple task was set, the users being asked to explore the shape of two statues wearing the exoskeleton haptic device respectively with force feedback enabled and disabled. Each task took lasted five minutes and statues were presented in different orders. After the completion of the exploration, the users were asked to complete a questionnaire with 30 questions, of which 7 dealt with the sense of touch and 9 with the sense of presence. Two other additional questions dealt with the user's observation of the environment.

The answers were given on the basis of a 1 to 7 (Likert) scale.

6.2. Results and discussion

The analysis of results, even if based on a limited sample, evidenced a significant difference between the means of answers related to the sense of touch for the condition with and without haptic feedback (Mann-Whitney U test, $p<0.001$).

All the scores in the touch-related set of questions were above the midpoint of the scale for the haptics on condition. For instance Question 8 ("Did you feel you were touching the statue") scored a mean of 4.4 with SD = 1,12 vs. 1 with SD = 0, while Question 11 ("To what extent could you feel the different curves and shapes of the facial features?") reaches a mean of 5 with SD = 1.1 vs. 1 with SD = 0, respectively for the two conditions of haptics on and haptics off.

No significant differences were observed in the set of questions related either to the observation of the environment and to overall sense of presence, even if higher scores where obtained in questions related to presence and a higher number of errors were committed in the description of the environment in the condition with haptics on.

Informal observations [2] indicated that co-location was very important to enhance the experience, but it was also found that some participants had problems to visualize a 3D stereo object and focused on the front wall instead of the 3D position of the stereo model. This led to a discrepancy between visual and haptic information and loss of the stereo effect. A planned solution was to place the haptic interaction as close as possible to the projection wall.

6.3. The exhibition at CGAC

The PURE-FORM exhibitions in Santiago de Compostela and Stockholm had much in common both in the general arrangements and in the questionnaires presented. However, there were also differences and the evaluations are partly presented separately. A more detailed report of both evaluations was given in [2].

Methods The participants had to choose two statues for exploration among seven available ones. The questionnaire was presented, in Spanish, Galician and English versions, and collected from 127 visitors, 69 women and 58 men with a mean age of 28 and 31 years, respectively, in both cases SD = 9 years. A majority (56 All statistical evaluation was carried out using non-parametric tests. Correlation factors were computed using the Spearman rank test, while comparison of means was made through Mann-Whitney U statistics.

6.4. The exhibition at NM

Methods Two statues were used in the evaluation, Saint John by Andrea Pisano. and the "The thorn extractor" by an unknown artist (marble copy of a Roman bronze sculpture), and all visitors explored both, with the order of presentation varied between them. The exploration time was between 3 and 28 min (M = 8 min, SD = 3 min). The questionnaires (presented in Swedish and English versions) were given after the explorationand filled in individually by the visitors in their own pace outside the exhibition area.

Usable questionnaires were obtained from 115 sighted visitors (Mean age = 33 years, Range = 13 - 71, SD = 14 years). About two thirds were men, and nearly the same proportion had a university degree. Only a minority (13 %) had earlier experience of virtual reality or similar installations.

Two-thirds reported never or rarely playing computer games, while the self-reported experience of computers had a mean of 5.5 on a 7-degree scale.

The questionnaires from six blind visitors will be analyzed, as well as those from 13 visitors who took part when only one of the two fingers of the display was functioning.

6.5. Results

6.5.1. Haptic experience of specific parts of the statues.

The questions on this subject were typically of the following form: "To what extent could you feel the shape of X" with the answer given on a 7-point scale. The specific parts concerned at NM hair, beard, face, breast, back and clothes and the means varied between 3.8 and 5.3 with SDs between 1.5 and 2.0. At CGAC the features were pressure and volume, curves and shapes of the facial features, and the shape of the dress and body features with means between 4.1 and 5.1 and SDs between 1.6 and 1.8.

In sum, all the means except one were above the middle point (4) of the scale. The exception was the back of a sculpture that apparently was more difficult than the other features; the visitor had to explore from behind.

6.5.2. The feeling of touching a statue.

A general question at both museums about the exploration with the haptic display was "Did you feel that you were touching the statue?" with an answer on a 7-point scale. The means of the answers for the four statues at the two museums varied between 4.2 and 5.0 and the SDs between 1.7 and 1.9, thus again over the middle point of the scale.

6.5.3. Factor analysis of questionnaire answers at CGAC.

A factor analysis of a selection of answers at CGAC was undertaken in order to identify some main factors underlying the visitor experience and determining the final judgment of the overall exhibition (Table 1, Table 2; for details, see [2]). The questions can be grouped in several sets and reduced in number according to the results from the factor analysis that was conducted through a Principal Component Analysis (Varimax with Kaiser Normalization).

This division in sets led to the identification of six factors that were able to account for the 75% of the variability observed among subjects' answers. The expression of the 6 factors is reported in the tables below, together with the relationship of each factor with the items that compose it.

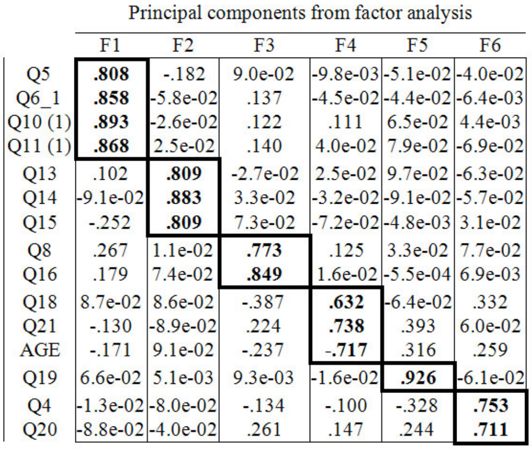
The above 6 factors allows to carry out the analysis of results on a reduced set of variables and to better highlight the relationships among them.

The most important factors found were related to Haptic experience (F1), Device usability (F2) and Added value of haptic experience (F3) as detailed in Table 1.

Factor F1 mainly refers to the ability of persons in getting a realistic feeling of touch in the VE, while F2 represents the usability and satisfaction of usage of the device, and F3 the added value that visitors perceived from the experience in the VR. Factors F4, F5 and F6 are instead related to the visitors profile.

F1: Haptic experience
Q5 Were you able to feel the volume? Q6 Did you feel you were touching the sculpture? Q10 To what extent could you feel the shape of X? Q11 To what extent were you able to perceive the specific parts of the statue X, i.e. facial features?
F2: Device usability and satisfaction
Q13 It was easy to learn to use the device Q14 I felt comfortable using the device Q15 Overall, I am satisfied with the device
F3: Added value of haptic experience
Q8 Does the feeling of touch improve your experience? Q16 How much do you improve your knowledge about arts?
F4: Visitor's age related profile
Q18 How would you describe you visit to the museum of pure form? Q21 Do you play videogame? AGE Age of the visitor
F5: Previous VR Experience
Q19 Have you had previous experience of virtual reality?
F6: Familiarity with pc
Q4 Did you need to ask more information? Q20 Please rate your degree of familiarity with computers

Table 1: *List of the principal components identified from the factor analysis*



Principal components from factor analysis

	F1	F2	F3	F4	F5	F6
Q5	**.808**	-.182	9.0e-02	-9.8e-03	-5.1e-02	-4.0e-02
Q6_1	**.858**	-5.8e-02	.137	-4.5e-02	-4.4e-02	-6.4e-03
Q10 (1)	**.893**	-2.6e-02	.122	.111	6.5e-02	4.4e-03
Q11 (1)	**.868**	2.5e-02	.140	4.0e-02	7.9e-02	-6.9e-02
Q13	.102	**.809**	-2.7e-02	2.5e-02	9.7e-02	-6.3e-02
Q14	-9.1e-02	**.883**	3.3e-02	-3.2e-02	-9.1e-02	-5.7e-02
Q15	-.252	**.809**	7.3e-02	-7.2e-02	-4.8e-03	3.1e-02
Q8	.267	1.1e-02	**.773**	.125	3.3e-02	7.7e-02
Q16	.179	7.4e-02	**.849**	1.6e-02	-5.5e-04	6.9e-03
Q18	8.7e-02	8.6e-02	-.387	**.632**	-6.4e-02	.332
Q21	-.130	-8.9e-02	.224	**.738**	.393	6.0e-02
AGE	-.171	9.1e-02	-.237	**-.717**	.316	.259
Q19	6.6e-02	5.1e-03	9.3e-03	-1.6e-02	**.926**	-6.1e-02
Q4	-1.3e-02	-8.0e-02	-.134	-.100	-.328	**.753**
Q20	-8.8e-02	-4.0e-02	.261	.147	.244	**.711**

Table 2: *Composition of principal components as derived from factor analysis*

	Q22			Age		
	R	p	N	R	p	N
Q22	1.000	--	127	**-.276**	**.003****	**113**
Age	**-.276**	**.003****	**113**	1.000	--	127
F1	**.306**	**.010****	**70**	-.009	.939	71
F2	-.142	.242	70	.060	.619	71
F3	**.373**	**.001****	**70**	-.133	.268	71
F4	.191	.114	70	**-.758**	**.000****	**71**
F5	.052	.668	70	**.324**	**.006****	**71**
F6	.027	.824	70	**.276**	**.020****	**71**

** Correlation is significant at the .01 level (2-tailed).
* Correlation is significant at the .05 level (2-tailed).

Table 3: *Correlation between principal factors, age and Q22 (Spearman rank test)*

6.5.4. General Judgement.

their general opinion on the system (Q22: "Write your general opinion about the Museum of Pure Form"). In CGAC answers, the general opinion Q22 that persons have expressed was positively correlated with F1 and F3, but with F2, and negatively correlated with age (Table 3). The evaluation results provided a strong indication that the final judgment of the system was expressed on the basis of the quality and added value of the haptic experience; moreover younger people expressed in general more positive comments. Questions related to the usability of the device (F2) did not provide any significant influence on Q22.

6.5.5. Importance of haptic, in addition to visual, experience.

At NM for both statues the visitors were asked to judge if touching the statue added anything to the visual experience. The Ms of the answers were 4.8 and 4.9, respectively, on the 7-degree scale with SDs of 1.8.

The analysis of Q16 ("How much do you improve your knowledge about arts?") in CGAC answers highlighted the elements that almost provided an additional value to the experience in VR with respect to a traditional one. A significant correlation was found with answers to Q5, Q6, Q8, Q10 and Q11 that are all related to the haptic experience (F1). This indicates that the haptic experience by itself was considered as an added value.

6.5.6. The usability of the haptic display.

Three questions at both museums concerned general aspects on the usefulness of the display:

1. It was easy to learn to use the device (Q13).
2. I felt comfortable using the device (Q14).
3. Overall, I am satisfied with the device (Q15).

The answers were given on a 7-point scale from "strongly disagree" (1) to "strongly agree" (7). The result is given in Table 4.

	CGAC			NM		
	N	M	SD	N	M	SD
Easy to learn	126	3.2	2.1	114	5.1	1.5
Comfortable	128	3.3	2.0	115	4.6	1.5
Satisfied	124	3.4	1.9	114	4.9	1.6

Table 4: *Results of usability questions at the two museums)*

From the analysis of answers of CGAC test, it is found that the answer to Q15 was significantly correlated with those to questions Q5 (R=-0.294, p=0.001), Q6, (R=-0.256, $p<0.004$ (1), R=-0.230, $p<0.02$ (2)) and with Q13 and Q14, too. This means that in general the user's satisfaction was strictly dependent on their haptic experience.

The wish of finding similar installation (Q17: "Would you like to find similar installations?") was found to be strongly dependent on the overall satisfaction with the system (Q15, R=-0.259, p=0.004) and the overall learning from the experience (Q16, R=0.199, p=0.027).

6.5.7. Amusement/ instructiveness of the experience.

At CGAC 70 % of the visitors answered that they found the experience amusing and 39 % that they found it instructive. At NM the answer was given on a 7-point scale with 1 as low judgment and 7 as high judgment. The experience was evaluated on average as amusing (mean score 6.2 with SD 1.0) and instructive (mean score 5.6 with SD 1.2).

6.5.8. Suggestion and wishes from visitors.

At CGAC 96 % of the visitors reported that they wanted similar devices at other museum. At NM the answers were given on a 7-point scale as in the earlier questions. On average visitors expressed their willingness of suggesting the visit to friends (mean score 5.7 with SD 1.5) and wanting similar devices (mean score 5.7 with SD 1.6).

6.5.9. Effect of age.

Age influenced the general opinion expressed on the system, as it was found to negatively correlated with general judgment (Q22) in answers at CGAC.

Moreover the visitor profile (factors F4, F5 and F6) was dependent on age, as it is shown from the correlation factors in Table 2.

The habit of playing video-games was negatively correlated to the age, and this determined also the level of amusement that was derived from the experience (Q18). A positive correlation was observed between the habit of playing videogames Q21 (that was measured on a 7 points scale) and Q8 (R=0.202 N=125 $p<0.025$), meaning that people acquainted with interactive pc games better appreciated the usefulness of the haptic experience.

Familiarity with VR systems and with PCs was instead positively correlated with age. People that were more familiar with PCs needed also to ask additional information on the system.

However there was no significant relationship between the level of familiarity with computers and virtual reality, and the scores reported in the other evaluation categories.

6.5.10. Effect of training.

In the CGAC exhibit two sculptures were randomly

presented to the visitors according to the preferences that they expressed. This allowed us to compare the answers related to the haptic experience of the first and second sculpture, and to estimate the effect of training in the interaction with haptic device. It is evident the effect of training for getting acquainted with the application: if we compare the values of Q6 (1 and 2) and Q11 (1 and 2): there is a significant difference (Mann-Withney test) of the means of Q6 ($p<0.0001$) and Q11 ($p<0.005$) for the first and the second sculpture, but the difference is not significant for Q10. Greater scores were achieved during the exploration of second sculpture, thus indicating an improvement in performing with the device (see Figure 7).

6.5.11. One finger or two fingers used.

In real life more than one finger is used at the same time in most tasks. That number of exploring fingers is important has been shown experimentally concerning identification of objects [3].

The results were much improved already when the number was increased to two. However, the size of the contact area is also important [4][5]. Only increasing the number of contact areas has been demonstrated to be insufficient [6]. This was also shown in a study of the performance of 13 visitors at the exhibition at NM that had information from only one finger available (because of temporary failure of the second finger of the device). There answers were not significantly different from the answers of the visitors with information from two fingers.

6.5.12. Visually impaired visitors.

Visually impaired people, especially those with total loss of vision, have severe problems of accessing information from 2D pictures, even if much effort has been devoted to get them well functioning [7].

One of the main obstacles is the difficulty of haptically getting 3D information from such pictures, and it has been suggested that haptic display may be a partial solution [8][9]. It was planned to include visually impaired visitors in the evaluation at NM, but, unfortunately, it was possible to get only six participants. They are also older than the sighted visitors (M = 47, Range = 29-59). The answers from such a small group may, however, provide indications of a result.

Figure 7: *Effect of training during the interaction with two subsequent sculptures.*

For most of the questions the answers for the visually impaired are roughly the same as those for the sighted, but there are tendencies for lower reported experience of having felt the statues and satisfaction with the display. The importance for the experience of the statue was judged at Nationalmuseum to be somewhat lower for the visually impaired (M = 4.0) than the added value for the sighted (M = 4.9), which is against the expectations of a higher value for the visually impaired.

The suggestions for improvements are about the same as those given by the sighted. However, one additional suggestion was given by the blind: completion with a verbal description.

The last suggestion is probably a most important one for making the haptic display useful for the visually impaired. The display provides a direct access to 3D aspects of the work of art and is thereby an important improvement in comparison with 2D pictures. However, a major problem remains: to get a rapid overview. Verbal information may contribute to a solution of this problem. This information may be given in an introduction including, among other things, suggestions about suitable exploratory procedures. Verbal information may also be given when specific parts of work of art is touched, similar to the information provided at tactile maps on a touch tablet [14].

6.5.13. The importance of training.

It was shown above that already the experience of one statue provided greater values for the next one. More experience can be expected to provide still greater values, as it has been demonstrated experimentally [11] that a considerable improvement can be expected after a few hours of training to use the device. It was not suitable in the present context to arrange with long training sessions and long exploration times with the display, but such arrangements would probably have improved both self-rated and measured performance.

7. Main conclusions.

There was a large spread in the judgments; for many questions the whole 7-point scale was utilized. Thus there were visitors who "not at all agreed" or "strongly disagreed" with the positive statements, as well as visitors who "agreed very much" or "Strongly agreed". It should be noted that the present study was based on self-ratings of performance. Their relations to performance measured with objective methods are uncertain. Such measurements can provide both better and worse results. However, it is quite evident that the visitors in general found the experience of the haptic display amusing. High mean judgments were also obtained for questions about the instructiveness of the experience, and the positive judgments are in majority concerning the questions about "suggesting friends to visit" and "wanting similar devices in other museums". On the other side, the improvements suggested indicate that many visitors wanted to be able to more fully utilize the capacities of the haptic sense, especially to use larger parts of the hands. A haptic display with suitable such possibilities can be expected to be more satisfactory. This conclusion is strengthened by our own and others' research mentioned above indicating the effects of constraints of the information in all present-day haptic displays. Concerning the use of the haptic display for aesthetic experience of objects of art it must be noted that aesthetic aspects have not been covered in this study. The participants' tasks were to judge the experience of physical properties of the objects of art. A study of aesthetic aspects remains to be done.

8. References

[1]. Bergamasco M., *Le Musee del Formes Pures*, 8th IEEE International Workshop on Robot and Human Interaction, RO-MAN 99, September 27-29 1999, Pisa, Italy.

[2]. PURE-FORM. *The MPF in Museums*, Deliverable 14. 2004. PERCRO, Scuola Superiore Sant'Anna, Pisa, Italy.

[3]. G. Jansson & L. Monaci, *Haptic identification of objects with different numbers of fingers*, in S. Ballesteros & M. A. Heller (Eds.), Touch, Blindness and Neuroscience, 2004, pp. 209-219. Madrid: UNED Press.

[4]. G. Jansson & L. Monaci, *Improvement of identification of objects with a haptic display: Increasing the information at each contact point is more efficient than increasing the number of contact areas* Report in progress.

[5]. S.J. Lederman, & R.L. Klatzky, R.L., *Haptic identification of common objects: Effects of constraining the manual exploration process*, Perception & Psychophysics, 2004, Vol. 66, pp. 618-628.

[6]. A. Frisoli, F.Barbagli, S.-L. Wu, E. Ruffaldi, M Bergamasco & K. Salisbury, *Evaluation of multipoint contact interfaces in haptic perception of shapes*, 2004, Symposium of Multipoint Interaction, IEEE ICRA2004, Proc.

[7]. P.K. Edman, *Tactile graphics*, 1992. New York: American Foundation for the Blind.

[8]. G. Jansson, *Can a haptic display rendering virtual 3D objects be useful for people with visual impairment?*, Journal of Visual Impairment and Blindness, 1999, Vol. 93, pp. 426-429.

[9]. G. Jansson, M. Bergamasco, & A. Frisoli, *A new option for the visually impaired to experience 3D art at museums: Manual exploration of virtual copies*, Visual Impairment Research, 2003, Vol. 5, pp. 1-12.

[10]. Cruz-Neira C., Sandin D., Defanti T.:*Surround-screen projection-based virtual reality:The design and implementation of thecave.* ACM Proceedings of SIGGRAPH '93(1993), 135-142.

[11]. G. Jansson & A. Ivås, (2001). *Can the efficiency of a haptic display be increased by short-time practice in exploration?*, in G. Goos, J. Hartmanis & J. van Leeuwen (Series Eds.) & S. Brewster & R. Murray-Smith (Vol. Eds.), Lecture Notes in Computer Science: Vol. 2058. Haptic Human-Computer Interaction, pp. 88-97. Heidelberg, Germany: Springer.

[12]. Frisoli A, Simoncini F, Bergamasco M., *Mechanical Design of a Haptic Interface for the Hand*" ", 2002 ASME International DETC- 27th Biennial Mechanisms and Robotics Conference , Montreal- Canada, September 29 - October 2, 2002

[13]. C.B. Zilles, J.K. Salisbury. *A constraint-based god-object method for haptic display*, in Proceedings of IROS 1995.

[14]. E. Holmes & G. Jansson (1997), *A touch tablet enhanced with synthetic speech as a display for visually impaired people's reading of virtual maps*, in CSUN 12th Annual Conference on Technology for People with Disabilities [3.5 diskette, file Holmes_e.txt]. Northridge, CA: California State University, Northridge.

[15]. McLaughlin, M.L., Sukhatme, G., Shahabi, C. and Jaskowiak, J., *The Haptic Museum*, Proceedings of the EVA 2000 Conference on Electronic Imaging and the Visual Arts, Florence, Italy, March 2000.

[16]. Bergamasco M. , Frisoli A., Barbagli F.,*The Museum of Pure Form*, Proc. of ICAR 2003, Coimbra-Portugal [17]. Buttolo P., Stewart P., Chen Y. "Force-Enabled Sculpting of CAD Models", Ford Research Laboratory, ASME (American Society of Mechanical Engineers) IMECE2000, International Mechanical Engineering Congress and Exposition, Orlando (Florida), November 2000.

[18]. Gregory AD, Ehman SA, Ling MC, *inTouch: Interactive Multiresolution Modeling and 3D Painting with a Haptic Interface*, Proc. IEEE Virtual Reality Conference, 2000.