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Robot Teleoperation with Force Reflection and Impedance Control: A Hand Controller Device

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Abstract

This work presents the development and experimentation of a three degree of freedom hand controller (two d.o.f. for force and one d.o.f. for torque), with force reflection in two of its axes and torque in the third one. This hand controller was developed, intended for both robot manipulator and for mobile robot teleoperation systems. Experiments have been performed using a robotic hand as a remote manipulator, showing good performance of the designed hand controller. Also, an impedance control has been implemented in the remote system allowing the human operator to carry out interaction tasks with the environment (such as polishing, object insertion, grinding, etc.) where it is necessary to control and to "accommodate" the interaction forces and torques, taking care of not damaging the remote robot nor the object it is interacting with. Finally, the tests carried out shown an adequate hand controller adjustment to the specified tolerances for the mentioned tasks.

Keywords: Robot Teleoperation, Hand Controller, Impedance Control, Man-Machine Interface, Force-Position Control.

1 Introduction

In the last two decades, the research involving robot manipulator teleoperation systems has experienced a considerable growth. The main reason for this tendency is the need to increase the human operator integrity and, at the same time, lower overall costs of industrial automatic processes. Some tasks, where robotic teleoperation principles can be applied, include a wide spectrum, ranging from: nuclear reactors repairing, spaceships devices maintenance controlled from earth, handling of radioactive materials, manipulation of explosive devices, submarine searches, remote fire extinction, mining tasks in dangerous underground tunnels, teleoperated repair of high and mid-voltage overhead electrical lines, applications in agriculture, telesurgery, telemedicine, etc. (Kuleshov, V.S., et. al., 1988; Fiorini, P. and Oboe, R., 1997; Castro et al., 2000).

Teleoperation systems generally consist of two robotic manipulator stations (one local and the other remote), a communication channel, and an environment with which both the remote robot and the human operator interact. The manipulators are partially controlled by the human operator and by their own local control algorithms, in a shared control structure (Das, et al., 1992¸Guo, C., et al, 1995; J. Postigo, et al., 1998).

In object telemanipulation, the human operator needs to have control or at least an effective "presence" in the remote site. For this reason, teleoperation systems must allow the "transportation" to the remote site of his/her capacities and skills, as well as his/her intelligence. When performing teleoperation tasks, the operator uses mainly two of his/her senses: vision and kinesthetic perception of the interaction forces. One of the main objectives of the telemanipulation (or remote operation) is the total transparency of the interface being used; that is, the actuators of the robot manipulator execute their commands, the sensors feedback the measured signals and the operator feels like as if he/she was really operating on the device at the remote site (Sheridan, T.B., 1992).

This paper presents the design and development of a 3 d.o.f. local hand controller, two of force (x and y axes) and one of torque (z axis), with force reflection in two of them and with torque reflection in the third, and its application in a robot teleoperation control system (or its possible use to teleoperate mobile robots). A Pentium PC computer (IBM-fully compatible) is used as the interface between the local manipulator and the remote device of the teleoperation system. The computer handles the communications (a full-duplex link), and is in charge of supplying information to the operator of what happens at both ends of the teleoperation system. The developed system allows modifying different parameters of the manipulator control system, such as the control loop gains, the transmission baud rate between both stations, etc. Communication is performed in a bi-directional way ("full duplex"), managed by a resident program in the PC implemented in C++ language (Pappas, C.H., et al., 1993).

In the proposed control structure, the local manipulator *reflects* the forces and torques produced by the interaction of the remote robot with its environment. The control strategy allows the commutation between position control algorithms or force control algorithms in each axis (with independent motions), depending on the free or on the constrained motion of the remote robot. The remote manipulator operates in position control, receiving as a reference command the sensed position in the local manipulator. Each axis of the hand controller operates with the mentioned configuration, independently from other ones.

The paper is organized as follows: section 2 describes the operation features and the general configuration of the developed hand controller. Section 3 covers the proposed control structure, while section 4 shows the experiments made using the hand controller in a laboratory teleoperation system. Finally, section 5 summarizes the conclusions and future work.

2 Hand Controller for Robotic Teleoperation

The developed hand controller for teleoperating robot manipulators (or mobile robots) will be described in detail next.

2.1 Hand Controller Operation

In order to control the hand controller, fulfilling the initial proposals of: versatility, device friendly to the user and electronic circuit optimization, the following general operation scheme is proposed, as indicated in figure 1.

The following functional blocks can be distinguished in this figure:

- ***Supervisory PC:*** It is the graphic interface with the user and manages the communication between the hand controller (local manipulator) and the remote manipulator or device.
- ***Communication system:*** It is in charge of the digital signal transmission of information at the speed specified by the user. The protocol used between the system and the PC is the RS-232C protocol (BlackBox, 2001).

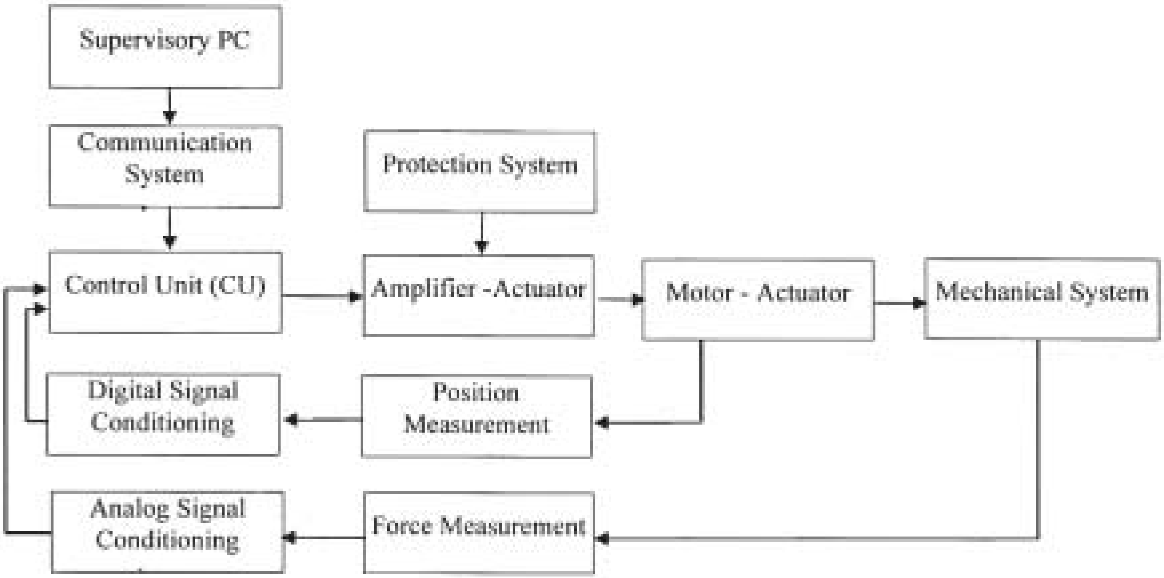


Figure 1: General scheme of the hand controller configuration

- ***Control Unit (CU):*** It conforms the main element to operate the hand controller and it is a part of the 80C196KC microcontroller. Its main task consists of executing the algorithms in Assembler language. These algorithms conform the position and force control structure of the local hand controller. The CU generates the electrical signals of the Pulse Width Modulation (PWM), gyrating sense (the control actions that command the actuator through the amplifier block), etc. In this block, control algorithms for each one of the variables to be controlled have been programmed. It operates with feedback signals from different blocks of the measurement electronic circuits and signals from the supervisory PC, as well.

- ***Amplifier-Actuator:*** It carries out the adaptation of the control action signals generated in the control block, to apply them properly to the motor-actuator block. This system generates the signal to drive the motors of the actuators, based on the information coming out from the control block.

- ***Protection system:*** It protects the motors of the three axes of the hand controller during its operation, not allowing them to exceed the nominal current of the motors.

- ***Motor-Actuator:*** It consists of a driving D.C. motor that supports the torques and the opposition forces that are applied on the hand controller's end effector and the D.C. motor is in charge of transmitting the motions to the mechanical system, reflecting this way the force from the remote site.

- ***Mechanical System:*** It is constituted by the structure of motion transmission to the end effector and by the iron supporting shell.

- ***Force Measurement Block:*** The devices in charge of obtaining signals coming from the Wheatstone bridges constitute it.

- ***Analog Signal Conditioning:*** It is the responsible of giving the appropriate electric format to the measured force signals.

- ***Position Measurement:*** It performs the position measurement of each one of the three axes of the hand controller.

- ***Digital Signal Conditioning:*** After obtaining the signals of the position measurement block, they are processed in the block of digital signal conditioning, giving them an appropriate format for their interpretation in the control unit. This block generates signals of gyrating sense and frequency signals of each motor.

The linking of all these functional groups allows one to carry out the hand controller's control, fulfilling the desired outlined requirements of functionality.

2.2 Configurations of the Hand Controller

Several connection configurations of the developed hand controller were tested during the experimental phase. These configurations are:

- Hand Controller – Simulated Environment: the hand controller may be connected to a PC in which runs a program that simulates a remote virtual environment. The limitation of this scheme is that the program must administrate the communication with the hand controller, respecting the protocol that was defined for the developed applications. This scheme can be appreciated in figure 2.

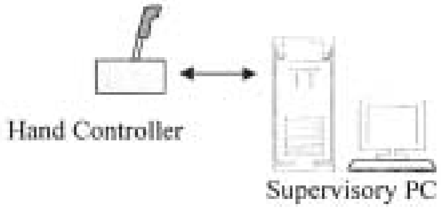


Figure 2: Hand controller and the simulated environment configuration

- Hand Controller-PC – PC-Remote Device: In this mode, the hand controller is connected to the PC performing as a supervisor, from which the information flows to another remote PC which is handling another device (either a robot manipulator or a mobile robot). This scheme (figure 3) does not have any limitations for the local system since the C++ programs developed for the PC, may be adapted to this supervisory function. It should be foreseen that the PC that manages the remote device would perform the communication protocol that was described in 2.1.

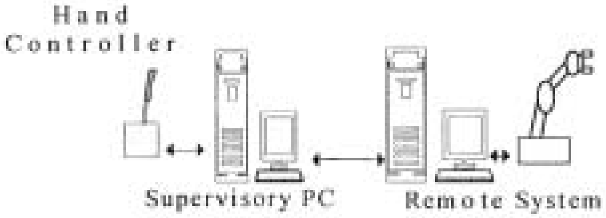


Figure 3: Configuration: Hand Controller-PC – PC-Remote Device

- Hand Controller-PC – Remote System: In this case, both the hand controller and the remote device are connected to the same PC. The PC administers the communication between the hand controller and the remote robot, performing as well as an user interface

(Figure 4). This scheme has been used for the development and experimentation with the hand controller. It should be noticed that the remote system uses the communication protocol that the hand controller uses as well.

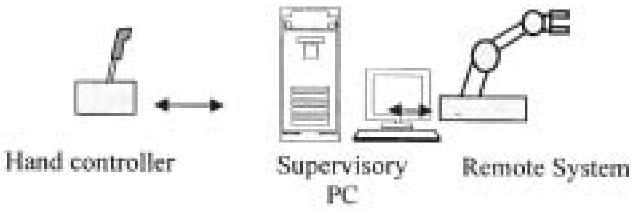


Figure 4: Hand Controller-PC – Remote System configuration

- Hand Controller – Remote Manipulator: In this configuration, the hand controller is connected directly to the remote manipulator without intervention of the supervisory PC. In this case, we cannot visualize the information (on the PC monitor), something possible to be done when having a supervisory PC (as in previous schemes). The remote manipulator will manage the communication to and from the hand controller, according to its defined protocol. This scheme is shown in figure 5.

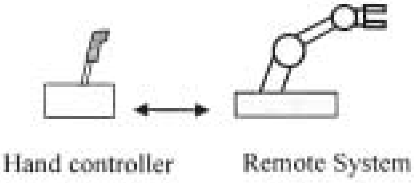


Figure 5: Hand controller – remote manipulator configuration

2.3 Electronic and Mechanical Characteristics of the Hand Controller

The structure of the hand-controller consists of a steel frame to which all the mechanical components are fixed. This device allows, according to these mechanical components, motions on the three axes (x,y,z) in a 3D space, thus leading to a three-degree-of-freedom hand controller. In the picture (figure 6), the mechanical and electrical components of the hand controller can be observed.

The mechanical coupling/articulation of the hilt beam, for motion on x and y axes, is through a pair of crescent-shaped, steel guides with a pair of holes in their ends, for connecting them to the D.C. motor axes (Figure 6). Each steel guide can move within a limited angle (± 30°) and is also connected to a D.C. motor that generates the reflection force (opposite compensation force) on each x and y axis, respectively. The hilt beam is also directly joined to a third D.C. motor which reflects the z-axis torque (having a limited ± 53° angular motion) on the human operator's hand.

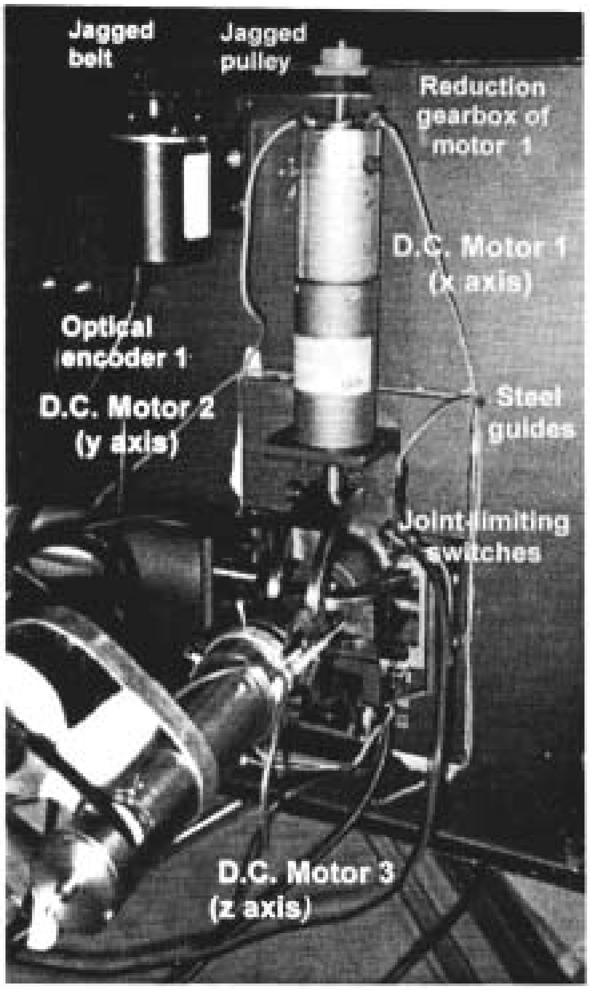


Figure 6: Upper view of the mechanical structure of the developed hand controller

The steel guides differ in size for both axes (x and y), which allows them to be placed one below another concentrically, though separated at orientation angle of 90°. Each D.C. motor has a high-ratio reduction gearbox (314:1 for the x- and y-axis motors and 2500:1 for the z-axis motor). Optical encoders placed on the supports of the frame sense the hand controller's position. These supports are placed in such a way to have the axes of each motor and its corresponding optical encoder in parallel. Mechanical transmission between these axes is through a jagged belt-and-pulley set. Each hand controller axis has supports to mount the joint-limiting switches that will operate in case the motor comes close to an extreme position. The joint-limiting switches will serve as protection for the motor, as well as to limit the motion of each one of the hand controller axis.

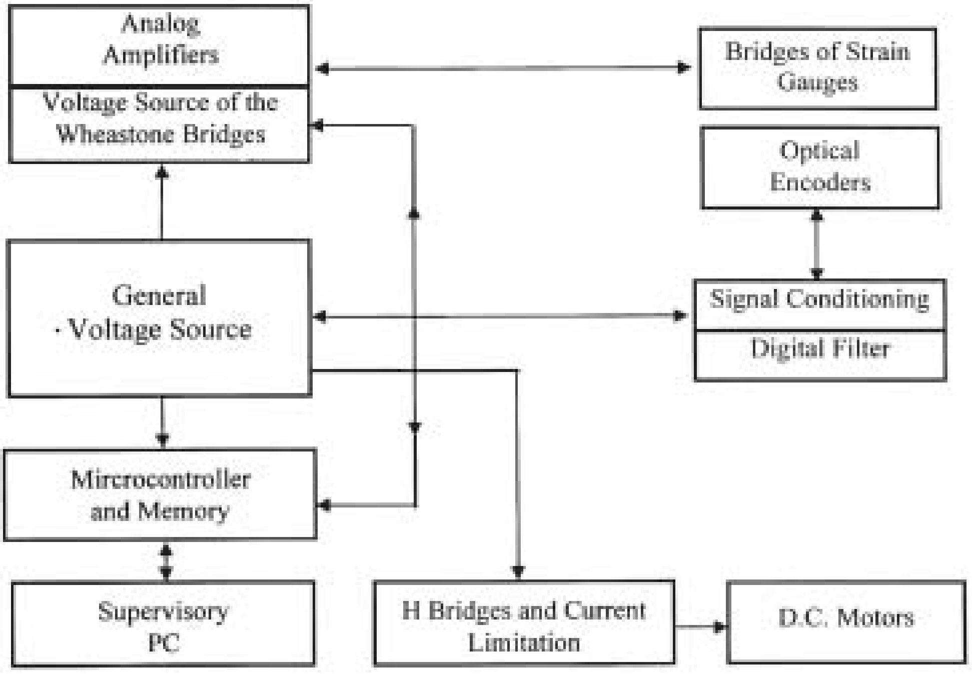


Figure 7: Functional diagram of the hand controller

The reflection, of the force sensed in the remote site, to the hand controller grip, is made through the modification of the force references to the motor control of each axis *(x,y,z)*. This modification is proportional (through a force gain block) to the sensed magnitude of the force in the remote hand. Also, it is possible to generate force references, from the local hand-controller to the remote hand, when the human operator exerts a force over the grip. This force is sensed by the strain gauges placed on the load cell and is transmitted as position/force references to the control system of the remote hand.

Figure 7 shows a general operation diagram of the mechanical, electrical and electronic components of the hand controller.

2.4 End Effector

The end effector of the developed hand controller consists of a load cell and a haptics-hilt mounted on it. The load cell is of cantilever beam type made of aluminum with thermal stress cracking. The dimensions and geometry of the beam are shown in figure 8.

Three main areas of the beam can be distinguished in Figure 8:

- The zone at left: it is used to fix the load cell to the axis that generates the hand controller's motions. This zone has a hole with a screw, which allows a better clamping to the aluminum beam.
- The central zone: in this area, the cross-section dimensions have been reduced, in order to concentrate and increase the surface strains produced on the beam when forces or torques are applied to it. At the same time, there are two new subsections in this zone: a square-section zone, where the strain gauges (that sense the deformation on the *x* and *y* axes) are glued to; and a cylindrical portion destined to measure the torsion or torques (in the z axis) applied to the load cell (in this portion of the load cell, the strain gauges are placed at a 45° angle from the main axis). It can be demonstrated that such strain gauges placement is adequate to measure torsion in circular sections. Besides, with this geometrical arrangement, the load cell allows to sense forces in two axes (*x* and *y*) and torque in the third one (*z-axis*).

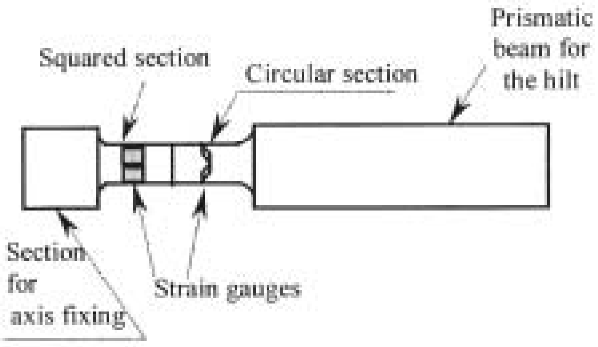


Figure 8: Hand-controller's load cell

- The right zone: This is the longest area of the three; where the hilt is placed on. The hilt determines the grasping area of the end-effector in a way that the human operator may manipulate the hand-controller.

In order to sense the forces and torques on the three axes, a set of strain gauges are mounted on the faces of the central section, which are electrically connected as a Wheatstone bridge configuration. The bridge, with the strain gauges placed in the opposite faces in the square-section zone, permits a better sensibility of the sensed deformations along the *x* and *y* axes.

For the circular section, strain gauges especially designed for this type of applications have been used. These commercial strain gauges, constituting a half-Wheatstone bridge, are placed at 45° angle with respect to the beam's axis, but with a 90° difference in orientation between both bands of the half bridge.

Figure 9 shows a general scheme of the force and torque sensing method of the hand-controller (for only one axis) and a zoomed view of the mechanical coupling between each D.C. motor and its corresponding optical encoder.

3 Control Structure

This section will briefly describe the proposed structure for the hand controller operation in robot teleoperation tasks. The supervisory computer is in charge of defining in what mode the hand controller will operate. Initially, the system begins in a position control mode until establishing the connection of both systems (remote system and local system via the communication channel). Once the position references, sensed and backfed by the remote system, are given, the local system executes them to position the hand controller. At the same time, the supervisory computer verifies that the positions of both systems be closely enough. In case that the positions of the local and remote robot are close to each other, the supervisory computer enables the human operator to commute the hand controller to the force control mode. The hand controller will remain in this last mode until the human operator indicates the supervisory computer to commute the hand controller again to the position control.

Figure 10 shows the control scheme proposed for the hand controller, which is basically a position control with the possibility of a commutation to force control.

The proposed scheme consists of two control loops connected to the actuator, according to a logic circuit contained in a block denominated ***supervision module***. The supervision module is a real time application that displays the hand controller operation on the computer monitor. The developed program allows the modification of the controller gains, the system transmission rate, the reference axes located in the remote system and the proportionality relation between the displacements (positions) in the local system as well as in the remote system. This program drives the data transmission between the hand controller and the remote system (robotic manipulator or mobile robot) through an RS-232C communication protocol (BlackBox, 2001).

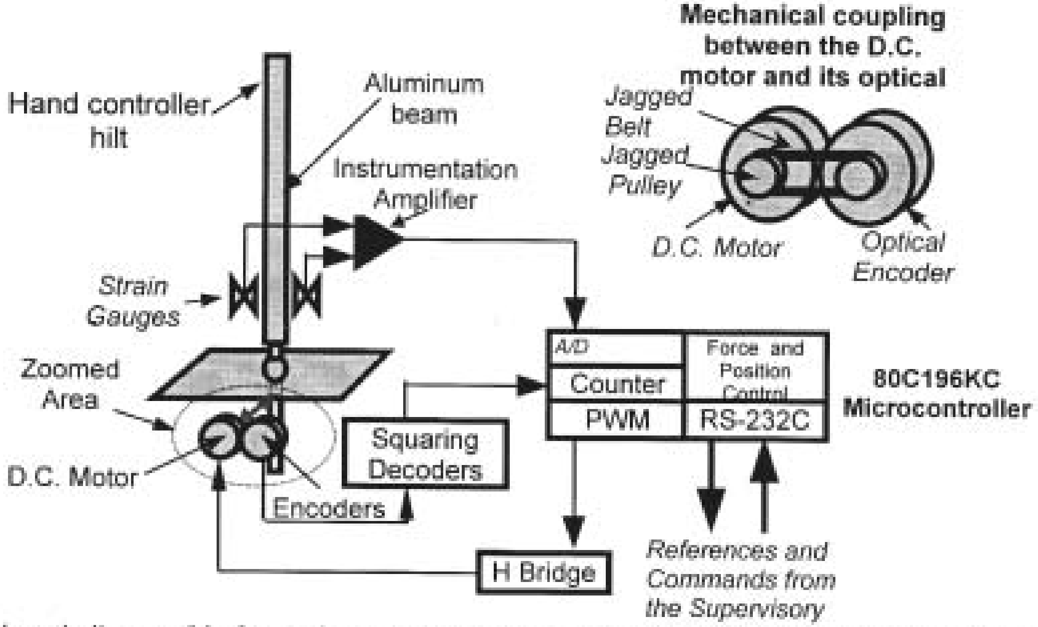


Figure 9: Schematic diagram of the force and torque sensing structure, mechanical motor coupling and communication with the supervisory computer

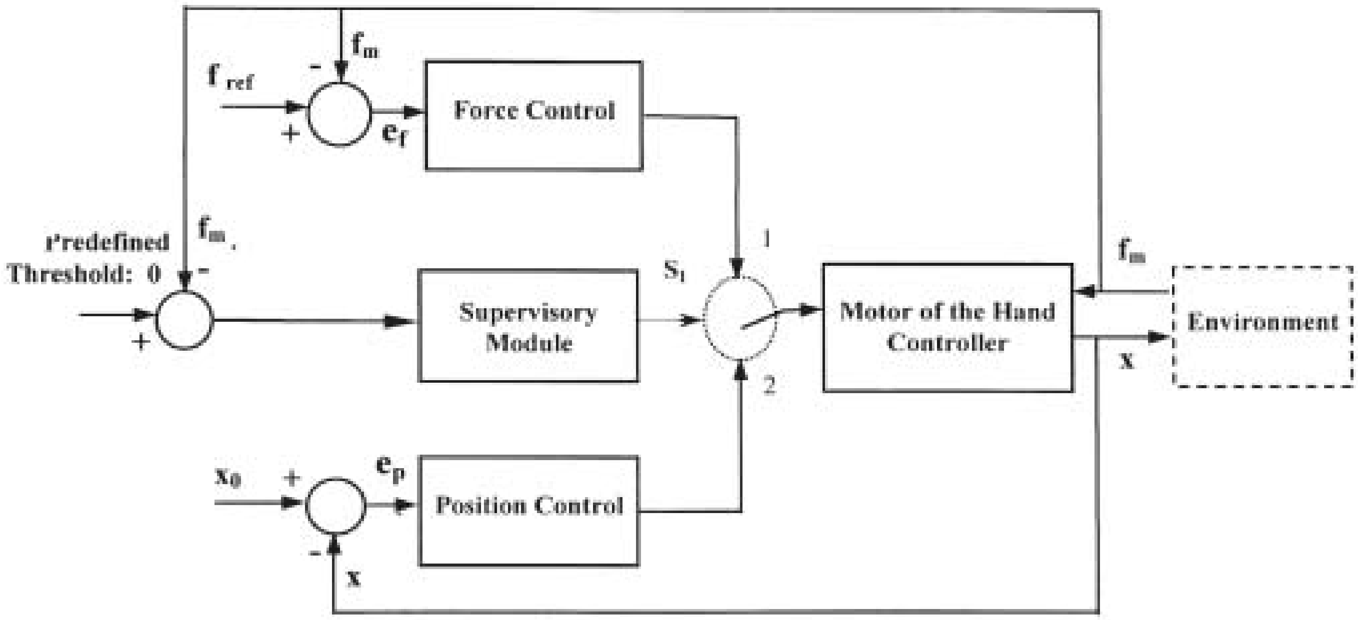


Figure 10: Block diagram of the proposed motion control that commutes to force control

The physical connection between the local station (hand controller) and the remote station of the teleoperation system is made via a shielded coaxial wire. The supervision module works as follows: while the interaction force with the environment f_m is lower than a predetermined threshold then the supervision module holds the S_1 key at position 2, yielding in a position controller behavior of the teleoperation system; but if at any time f_m equals or is higher than the threshold value, the supervision module commutes the S_1 key to position 1, so that the system behaves as a force controller. If at any time, the force becomes lower than the threshold, and holds this value for a while, then the supervision module will again place the S_1 key in position 2, returning the system to a position control behavior. In the hand controller, a control structure as the described, is used for each axis (x, y or z). The control loops operate simultaneously, in a completely independent way one from each other.

3.1 Control Algorithms

The control algorithms for the robotic teleoperation hand controller, used to generate control actions in each loop, are of PI conventional type. Such algorithms were developed in Assembler language in order to manage the 80C196KC microcontroller (Lage, A., 1994). A C++ language algorithm was developed to be an interface between the user and the rest of the robotic teleoperation system. In the PC one may visualize the state of the variables that are being controlled, as position and forces of the remote manipulator. Also, the control loop gain constants can be modified, as well as the data transmission rate in a bidirectional mode between the local and the remote stations. The developed algorithms are described in the following.

3.2 Assembler Installation

The developed program basically consists of a main program and of several subroutines that carry out specific tasks, which are mentioned in the following sections.

3.2.1 The Main Program

The main program is in charge of processing the algorithms of the three independent control loops implanted in each axis of the hand controller. In this program, the positions of the three motors that drive the hand controller are updated. The commutation of position control to force control, or viceversa, can be done with this program as well. Therefore, the operation sequence of each implanted algorithm is controlled.

3.2.2 Control Loop Communication Method

Since the main algorithm should process the three control loops implanted in the teleoperation system, it is necessary to control the program evolution, in such a way that the mentioned loops are executed in a sequential and periodic mode, independently from the operation mode of the hand controller. To perform this function, a variable denominated "*axis*" is provided to the program. This variable acts as an indicator, to know which is the axis that works next (according to hexadecimal values, previously established). When the program finishes processing a control loop corresponding to any axis, and before entering the next control loop, the program verifies the "axis" value, jumping to the control loop subroutine that this variable indicates. Once it has entered the loop and it has been processed, before leaving the loop, it puts in the variable "*axis*" the value that corresponds to the following axis of the sequence. In this way, the program process each control algorithm in a sequential and periodic mode.

3.2.3 Method to Commute between Position Control and Force Control

The method that is used to commute from position control to force control (and vice versa) in the hand controller is based on the use of a variable denominated "*mode*". This variable indicates, according to a predetermined hexadecimal value, to the main program, if it should process a position control algorithm or a force control algorithm for the axis in question. Initially, the program begins controlling position, because the hand controller should be positioned until the communication with the remote system has been established. The commutation from one control mode to the other will depend on the supervisory computer.

The hand controller also has a protection against communication unexpected interruptions. This protection is activated if the communication is interrupted by any reason, between the local station and the remote station. In that case, the hand controller will be permanently controlling position, according to the last position that it received as a reference position.

3.3 C++ Installation

The communications handling between the local system and the remote station of the robotic bilateral teleoperation system is done through a computer. This PC is the responsible for the control of the communications, the error handling, the supervision of the change of variables and also some other specific tasks. This program was developed in C++ language due to the power of this language to generate functions such as the handling of computer interruptions, the processing of mathematical equations, the readiness to low level programming and the possibility of developing information visualization functions in a simple way.

Figure 11 shows a simple operation scheme of the algorithms designed for the hand controller.

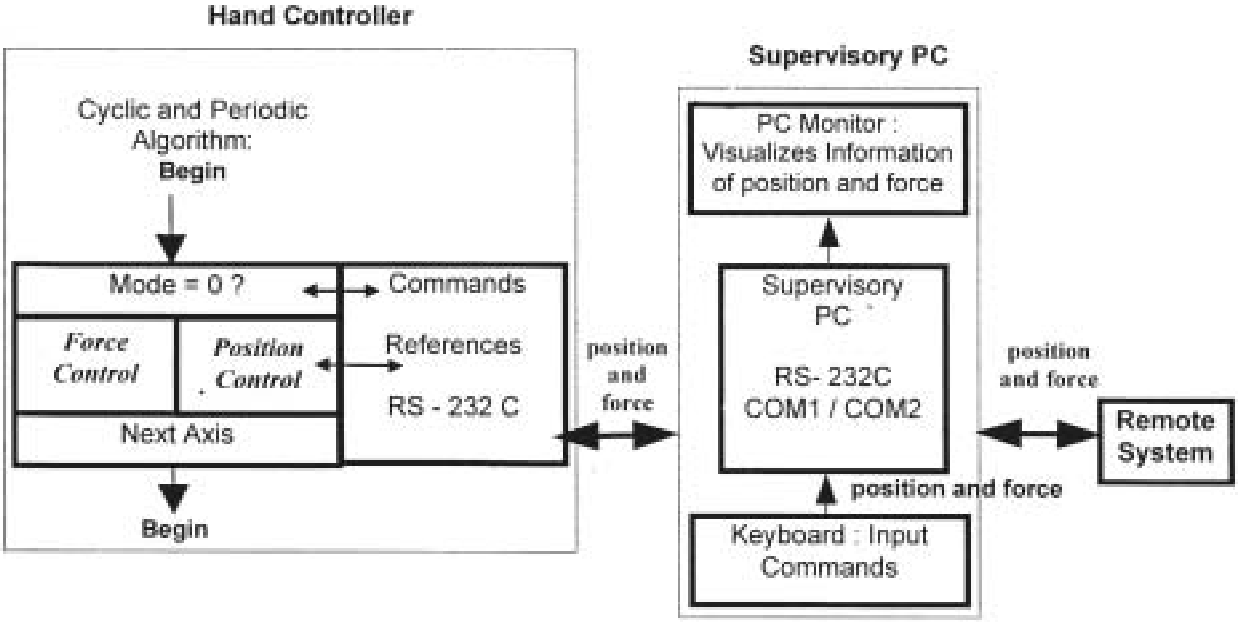


Figure 11: Scheme of the motion control algorithm that commutes to force

The program running in the computer uses the PC serial port 1 (COM1) to communicate with the hand controller, because the 80C196KC microprocessor communicates using a serial protocol that has been adapted to the RS-232C protocol. It has also been selected the COM2 port to link the local system with the remote station. This should be changed for some other adapter to carry out the communication task (such as a net communication board, the parallel port of the computer, etc.).

The program developed in C++ uses the interruptions of reception of the serial parallel PC adapter to administer the whole communication scheme of the robotic teleoperation system. The program periodically executes the sequence of events that are detailed in the following: The first event that takes place is the determination of a pressed key of the PC keyboard; as a second step, the program runs one of the different types of possible communications. Finally, it proceeds to visualize the data transferred between both stations (local and remote).

4 Experimentation

In the experimental phase, the performance of the developed hand controller was tested connecting it to an intelligent two-fingered robotic hand developed at the Automatics Institute (INAUT), considering it as a remote device (remote robot). This structure allows to teleoperate a remote robotic hand with the local hand controller, then constituting a robot teleoperation system with force reflection. The constructive characteristics and associated electronic of the robotic hand are described in detail in Tramontin's work (1997). The hand was used to run a new control algorithm, which works in a similar way to the one implanted in the hand controller. The algorithm also handles the commutation between the position control and the force control structures, or vice versa, if such function is enabled modifying its control program. In addition, the communication system used for the remote intelligent hand was the same developed for the local hand controller, based on interruptions and "full duplex" data transmission. This was done to obtain a better data transfer rate between the hand controller and the remote robotic hand.

The robotic bilateral teleoperation system works as follows: the server PC receives the data from the hand controller through the serial port COM 1 and from the remote robotic hand through the COM2 serial port. The position and force signals backfed from the remote hand are sent towards the hand controller as sensed signals; and then the signals coming from the hand controller are sent to the remote robotic hand as reference commands. Thus, each one of the signals is used as a reference signal for each one of the implanted control loops (local and remote). It should be noticed that the proposed teleoperation system has certain limitations; one of the most important ones is that the communication time delay between the local site and the remote site is not considered here. This simplification is due to that both sites are connected to the supervisory PC through a multi-wired shielded cable using the RS-232C protocol; in spite of this, its application possibilities may vary. For example, this teleoperation scheme can be used in applications where dangerous substances are manipulated in a room (remote site) and the local site (with the hand controller and the human operator) is placed at a few meters distance (up to 15 m). In this case, the time delay is not significative because of the proximity of both sites and the results obtained are still valid.

4.1 Experimental Results

The robotic bilateral teleoperation system was tested at several communication speeds between the local and the remote stations. Also, the elasticity values of the impedance control implanted in the remote hand were varied during the experiments. Figure 12 shows a picture of the developed system.

Some of the experiments that were carried out with the teleoperation setup are discussed in the following section.

4.1.1 Different Data Transmission Speeds

In this experiment, the 3-axes hand controller was used as the local robot and, as the remote robot, the INAUT's intelligent robotic two-fingered hand was implanted. It should be emphasized that though the hand controller has 3 degrees of freedom, the remote grip can only be controlled in one space direction (since it only has one degree of freedom). For this reason the y direction of the hand controller was chosen to control the force and the position in it. Besides, it was also proven that, with a greater proportional constant in the force control loop, the teleoperation system answered to a smaller force applied by the human operator in the free motions. If the proportional constant was too high, in the moment of a crash with the surrounding environment, the system tends to be unstable. To improve this situation, as well as the teleoperation system response and to give certain autonomy to the remote station, an impedance control loop was included (Hogan, N., 1985), only considering the elastic constant of the impedance term in the remote system (intelligent robotic hand). Some important concepts and definitions on impedance control will be mentioned briefly in the following.

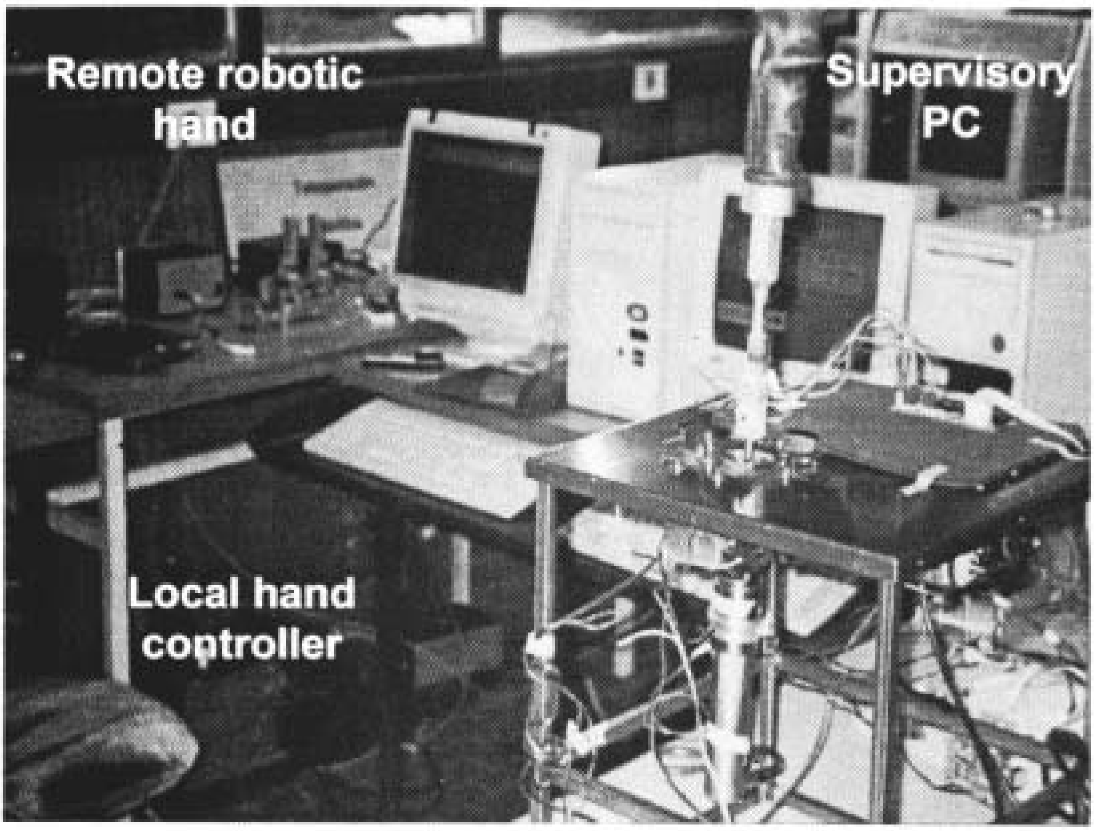


Figure 12: Experimental robotic teleoperation setup

The impedance of a mechanical system is defined as the dynamic relationship between the applied force and the displacement velocity,

$$\mathrm{f}(t) = Z(p)v(t) \qquad (1)$$

where $\mathrm{f}(t)$, $v(t)$ and $Z(p)$ represent the force, the velocity and the impedance of the mechanical system, respectively; and $p=d/dt$ is the derivative operator. In terms of the actual position of the robot's end effector $\mathbf{x}(t)$, Eq. (1) can be re-written as:

$$\mathrm{f}(t) = Z(p)\, p\mathbf{x}(t) \qquad (2)$$

In this case, a desired motion trajectory $\mathbf{x}_d(t)$ is specified for the remote robot manipulator and the robot impedance is defined by:

$$\mathrm{f}(t) = Z(p)\, p\mathbf{x}(t) \qquad (3)$$

where: $\mathrm{f}(t)$ is the force applied by the remote robot end effector against the environment, and $\mathbf{x}(t) = \mathbf{x}_d(t) - \mathbf{x}(t)$ is the robot motion error.

A *desired impedance* should be specified to establish the robot's behavior in an impedance control structure. It is natural, for its simplicity, to define an impedance linear relationship. Also, since the dynamic behavior (linear model) of the robot manipulator is of second order, it is logical to specify a second order desired impedance:

$$\mathrm{f}(t) = (\mathbf{M}p^2 + \mathbf{D}p + \mathbf{K})\, \mathbf{x}(t) \qquad (4)$$

where, $\mathbf{f}$ represents the *applied force* by the remote robot against the environment. The matrix **M** is called inertia matrix, **D** is the damping matrix and **K** is the elasticity matrix. Matrices **M**, **D** and **K** are design matrices, and are specified according to the dynamic behavior of the robot.

In the proposed impedance loop (see section 4.1.2), only the elasticity matrix **K** term of Eq. (4) was considered in the remote system (intelligent robotic hand). Figure 13 shows the results for a transmission rate of 57600 bauds (between the local and remote stations) in a) position and b) force control in *y space direction*. In figure 14, the same experiment is shown, without varying the controller parameters neither the remote impedance, but for a transmission speed of 300 bauds.

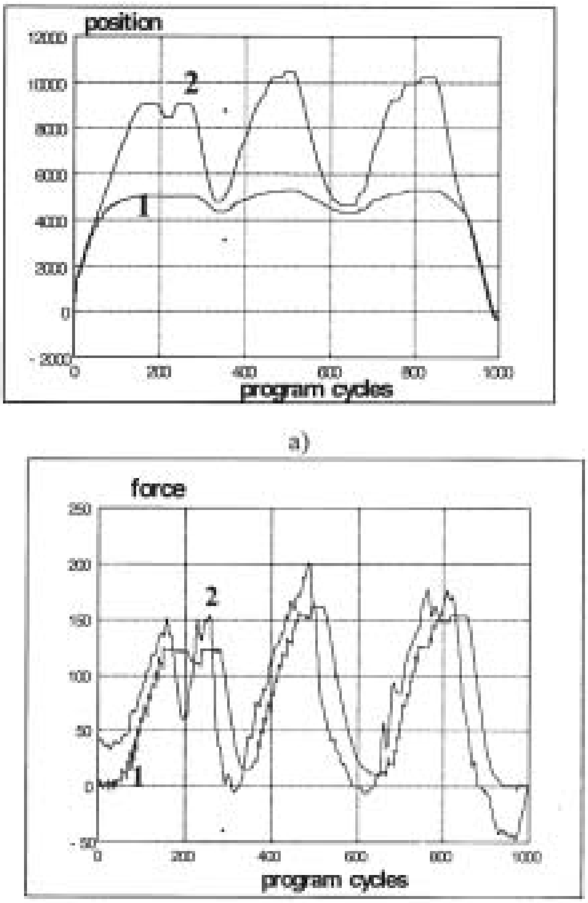
It is important to notice, for a correct understanding of the time scale of all the figures (from figure 13 to figure 18), that it is given in program cycles. The equivalence is the following:

*1 program cycle = 0.506 seconds, for a transmission speed of 300 bauds;

*1 program cycle = 15.8 mseconds, for a transmission speed of 9600 bauds;

*1 program cycle = 2.63 mseconds, for a transmission speed of 57600 bauds.

It should also be noticed that in position figures (e.g. Fig. 13) a), 10000 pulses of the optical encoder are equivalent to 22.92° of change in the position of the hand controller (or 0.4 radians). These conversions should be also kept in mind for the comparison of all the above mentioned figures. For example, the time scale of Figs. 13a) and b) represents a total period of 6 seconds.



a)

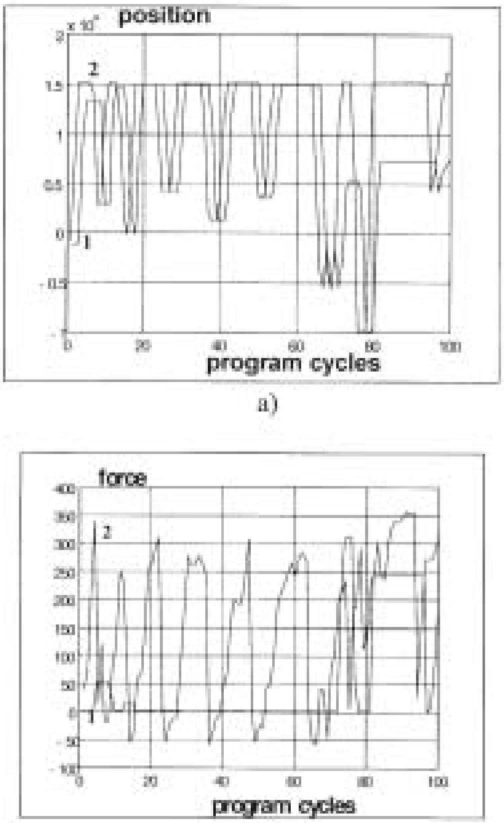
b)

Figure 13: a) 1: Remote robotic hand position, 2: Local hand controller position (axis *y* only). b) 1: Sensed force in the fingers of the remote robotic hand, 2: Sensed force in the local hand controller (axis *y* only). Elastic constant of the remote hand impedance: ***K***=32, proportional constant of the force controller K_{Pf}=40; transmission speed: 57600 bauds

If these last two figures are analyzed (figures 13a, 13b, and 14a and 14b), it can be observed that for a lower transmission speed (300 bauds), as it was expected, the system responds in an uninterrupted way due to the higher sampling time generated in the communication. When increasing the communication speeds, the system stability was increased, and therefore, to obtain a bigger fluency during free motions reflected in the teleoperation system. As for the constrained motions (remote system contact with an object or an environment), it was proven that the teleoperation system was unstable at low transmission speeds. This problem was solved when increasing the communication speed to 57600 bauds.

4.1.2 Different Remote Impedance Values

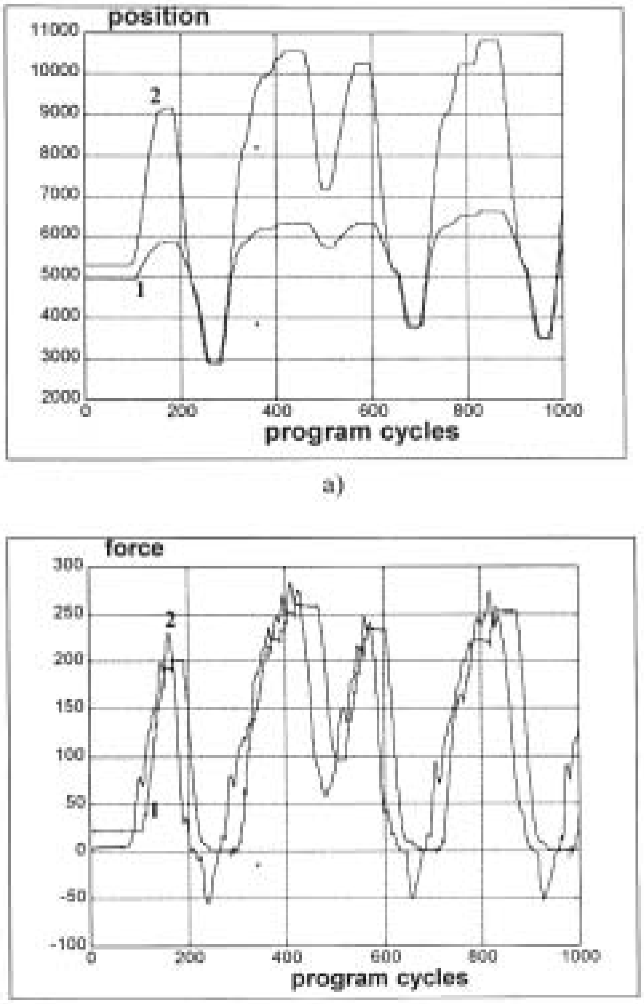
The experimental conditions were the same ones considered for Section 4.1.1, but it was changed, for the same transmission speed between the local and the remote stations (57600 bauds), the elasticity term of the fictitious impedance implanted in the remote robotic hand. Figures 15a), 15b), 16a) and 16b) show the results of these experiments.



a)

b)

Figure 14: a) position and b) force, with the same parameters of the experiment in Fig. 13a) and b). Elastic constant of the remote hand impedance: ***K***=32, K_{Pf}=40; transmission speed: 300 bauds

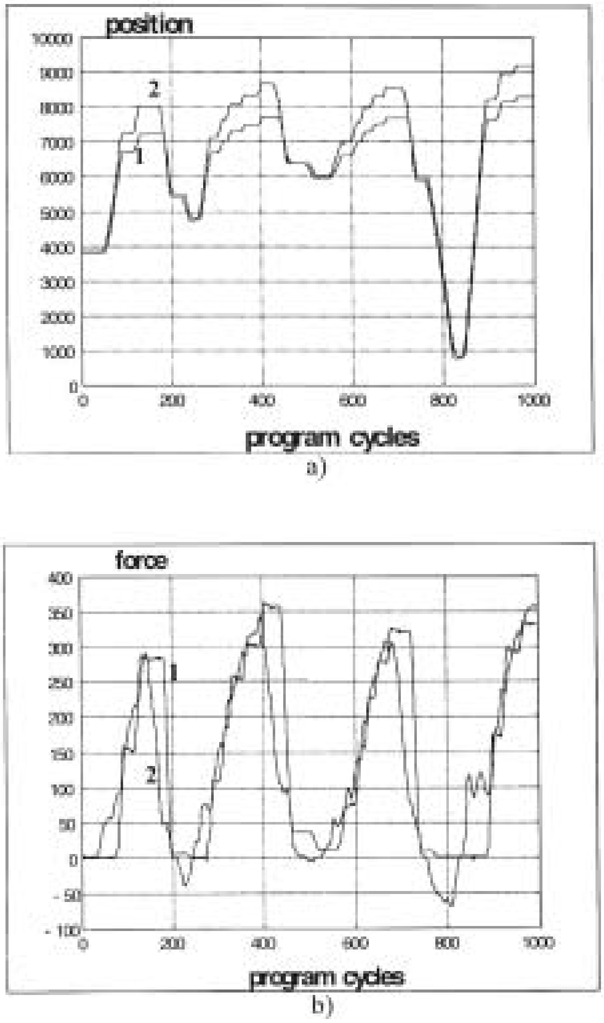


a)

b)

Figure 15: a) **1**: Remote robotic hand position, **2**: Local hand controller position (axis y only). b) **1**: Measured force in the fingers of the remote robotic hand, **2**: Measured force in the local hand controller (axis y only). Transmission speed: 57600 bauds, elastic constant of the remote hand impedance: K=16; K_{pf}=40

Experimentally, it was proven that the events that take place in a crash situation of the remote system with some objects (or with the environment) were improved, regarding the system's response, allowing a better manipulation of them. The bigger the K constant values, the more stable response of the teleoperation system (as it is shown in figures 15 and 16).

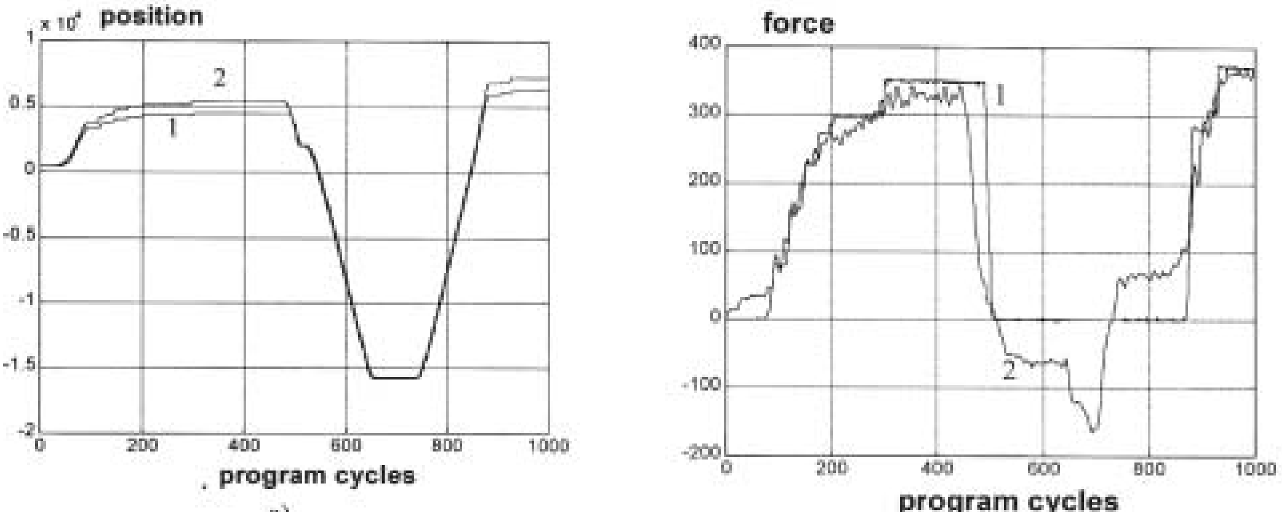


a)

b)

Figure 16: a) **1**: Remote robotic hand position, **2**: Local hand controller position (axis y only). b) **1**: Measured force in the fingers of the remote robotic hand, **2**: Sensed force in the local hand controller (axis y only). Transmission rate: 57600 bauds, elastic constant of the remote hand impedance: K=2; K_{pf}=40

Finally, figures 17 and 18 depict the experimental results (for the same elasticity value) of the developed hand controller. It can be clearly seen that the behavior and performance of the hand controller worsens when the proportional constant (K_{pf}) of the force PID controller is decreased (with an integrative force constant K_{if} = 0 in both cases).



a)

b)

Figure 17: a) **1**: Remote robotic hand position, **2**: Local hand controller position (axis *y* only). b): **1**: Sensed force in the fingers of the remote robotic hand, **2**: Sensed force in the local hand controller (axis *y* only). Transmission speed: 57600 bauds, elastic constant of the remote hand impedance: $K=2$; proportional constant of the force PID controller $K_{pf}=80$

a)

b)

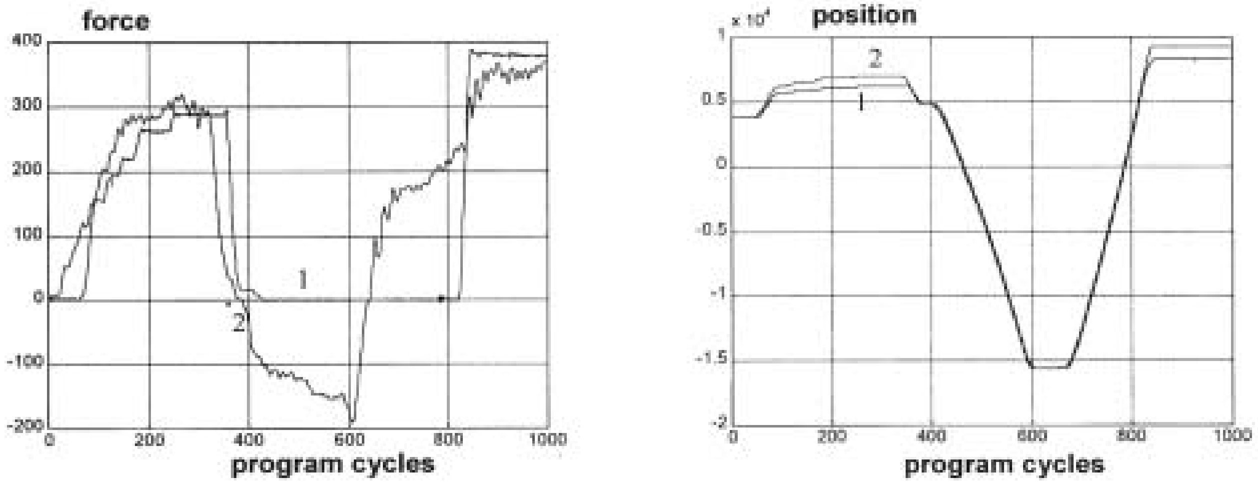


Figure 18: a) **1**: Remote robotic hand position, **2**: Local hand controller position (axis *y* only). b) **1**: Force sensed in the fingers of the remote robotic hand, **2**: Force sensed in the local hand controller (axis *y* only). Transmission speed: 57600 bauds, elastic constant of the impedance of the remote hand: $K=2$;

5 Conclusions

In this paper, the design, development and experimentation of a three degree of freedom hand controller (forces in *x-y* axes and torque in the z-axis) for bilateral teleoperation of robotic manipulators has been presented.

The control system for the bilateral teleoperation structure was designed in such a way that the human operator, acting on the hand controller, sends position and force commands to the remote system through a communication channel,and at the same time receives the position and force signals that the remote system reflects when it senses its interaction with the remote environment (bidirectional information in the communication channel) in constrained motion tasks.

The control algorithms, for each of the three motors of the hand controller, were designed and programmed in the Assembler language of the MC80196KC microcontroller. The software necessary to visualize the graphic environment of interface between the user, the developed hand controller and the remote environment where the teleoperation task is performed was developed as well. The graphic information to the human operator (added to the control loop as a visual feedback of both force and position of the remote robot), allows to set accurately the desired values of the interaction force with the environment.

Finally, an experimental bilateral teleoperation setup was mounted, using as an intelligent robotic hand as the remote system (developed at the INAUT). This setup allowed one to exhaustively test the teleoperation system in order to show the force and torque reflection properties of the local station hand controller. These test shown a stable behavior and a good performance of the whole telerobotic system. Besides, good results were obtained as far as the hand controller performance, in force as well as in position when executing interaction tasks, specifically when manipulating objects with the hand, positioning them and exerting a determinate force against them.

In relation with the possible applications of the hand controller, after the tests it was concluded that, the greater the transmission speed between the local and the remote stations the better the hand controller performance. This is because the controller is more stable and shows a bigger fluency when performing interaction tasks (constrained motion). This fact is very interesting in the cases where communication time delays should be considered.

The proposed laboratory teleoperation system (which includes the developed hand controller) allows the analysis and design of advanced control schemes for robot manipulators as well as for mobile robots. In addition, the hand controller can be used to human operators trainee, in tasks involving constrained motions of the remote robot (for example, in tasks for robot manipulators such as polishing pieces, insertion of objects, soldering, etc.; and for mobile robots in the case of motion in partially structured environments, detection of obstacles, etc.).

As future works, the replacement of the one-degree-of-freedom remote robotic hand for an industrial robot: the 4 degree-of-freedom Bosch SR 800 (Dölling, E., O. Márquez, 1996), is one of the tasks to cope with. The main idea, to be developed, is to teleoperate this industrial robot with the developed hand controller, while performing interaction tasks, applying advanced control structures. Furthermore, it is also a future challenge the teleoperation of a mobile robot using an available Intranet at the INAUT. Later, advanced control schemes will be tested for teleoperation through the Internet, to consider the communication time delay effects in the performance and in the stability of the complete teleoperation system.

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