A master-slave robot for telemanipulation with haptic feedback

Paulo Fernando Ferreira Rosa
Military Institute of Engineering,System Engineering Department, Pça Gen Tibúrcio 80 - Urca - Rio de Janeiro/RJ, Brazil
rpaulo@de9.ime.eb.br

Fábio Suim Chagas
Military Institute of Engineering,System Engineering Department, Pça Gen Tibúrcio 80 - Urca - Rio de Janeiro/RJ, Brazil
suim@de9.ime.eb.br

Antônio Fernando Rocha Júnior
Military Institute of Engineering,System Engineering Department, Pça Gen Tibúrcio 80 - Urca - Rio de Janeiro/RJ, Brazil
fernandorocha@de9.ime.eb.br

Abstract. *The main objective of this paper is to develop a master-slave type system, that would be able to detect a collision in an unknown environment and transmit it by web. The project development it consisted in: (1) to determine the type of control to be utilized, (2) to elaborate a kinematic project of the robotic manipulator, (3) to develop an implementation via software to validate the system (master manipulator, slave manipulator and communication between them). The software implementation was done using the java language, VRML (Virtual Reality Modeling Language) and EAI (External Authoring Interface). In order to validate the system it was tested with a 1 dof (degree of freedom) real manipulator.*

Keywords: *Telemanipulation, haptic feedback, control architecture and hybrid control.*

1. Introduction

In this project a master-slave system was developed, which was defined with two sub-systems, a master sub-system and a slave sub-system, where both possess the same kinematic and degree of freedom, identical dynamics and same dimensions.

For the development of the system, initially the manipulator's kinematic equations were obtained through the Denavit-Hartemberg method. After determining the equations a study of the mechanical model it was made, and starting from the found model, the control of the system was defined. A communication system was developed that could be operate through the web. The communication was implemented using the resources supplied by the TCP/IP architecture layers.

After defining the communication system, a simulator was implemented in 3D, using the JAVA language in combination with VRML, and the interfacing among the two languages was made through an API denominated EAI; the use of these resources can be justified by the fact that they are of public domain and current technology. At last, the system was tested using a real prototype for a 1 dof; the test consisted in connecting the systems through a simulator and to operate them through the web.

2. Literature review

Teleoperation systems as the proper name suggests are related to a set of devices which may be remotely operated or manipulated. *Tele* comes from the Greek and means distance. In general, this type of system is used in oceanographic explorations, military applications, operation of contaminated nuclear plants, medicine, spatial explorations, and so on. There are several types of teleoperation systems that may be mentioned, as remotely operated vehicles or ROVs. As examples one may mention (Conte at al, 1995): mobile robots systems that have military applications to deactivate land mines. Systems like Zeus (Butner and Ghodoussi, 2003) that are used in robotic surgerys. System as these use cameras, with the purpose to supply a visual feedback of the external environment. In this work cameras were not used, and it was limited in supplying the haptic feedback for the user.

Many papers which deal with teleoperation systems only make reference to the perception of force, separately and do not consider other involved parameters as the perception of texture, temperature and, inclusive, the sensation of pain. Thus, the term haptic may be defined as the capacity to evaluate other parameters as roughness, temperature and the strength applied to an object, that is, all the tactile capacity of the human being. This work doesn't include all these information, because it is only working with two parameters, forces and speed, which already constitute a haptic group.

The importance of the haptic perception for teleoperation is the tentative to simulate in the most real possible way the immersion of the human being in an environment where he needs to be without necessarily be present (telepresence). The haptic presence will improve the human being efficiency to remotely perform a task, or even give him more satisfaction when he deals with entertainment.

Many devices that provide tactile perception have been developed and studied; among them, works as Fernandes at al. (2004), Rosa at al. (2004) and Rosa at al. (2004a) may be mentioned, where one finds the development of a telemanipulation device with 1 dof (degree of freedom), that provides haptic feedback. In (Niki and Shimjo, 2000) a simple haptic device is shown working along with a data base which contains information as temperature and texture of the analyzed object.

Telemanipulation systems have been used in several applications that involve high precision degree, as in surgical applications. In (Çavuşoğlu at al., 1999) one worked in the manipulators' development capable of improve a surgeon's performance, when he accomplishes a surgical procedure. The work that is being exposed in this article possesses the capacity to supply a high degree of precision, but it was not developed with the intention of being used in surgical environment. Although it is believed that the system can be developed to that point.

3. Definition of the Control Architecture

Figure 1 shows the mechanic representation of a teleoperation system of 1 dof (degree of freedom). The system behaves in the following way: The human operator applies a force F on the master mass that is represented by m_m, that initially is in inertia; that force causes a displacement X_m in the master. Through k_f and B_f that are the elastic and the viscous friction coefficient, respectively, the displacement is spread up to the slave mass, that is represented by m_m. In that way the displacement X_s is made, Fig. 1. That displacement is limited by the action of the forces generated by k_s and B_s that are the constants of elasticity and the slave viscous friction coefficient, when this is interacting with the environment. The equations that model the system of Fig. 2 are given for (1) and (2). After the systems equations are obtained it is necessary to get the blocks diagram for the system shown in Fig. 2.

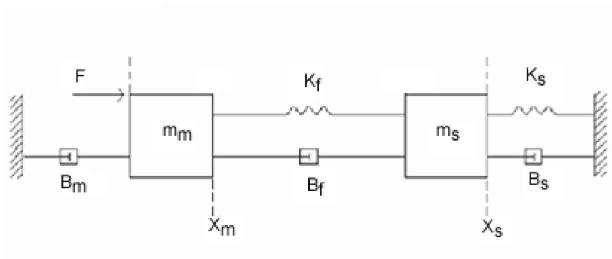

Figure 1. Mechanical model for 1 dof.

The equations that model the Fig. 1 system are given by (1) and (2).

$$m_m \ddot{X_m} = F - B_m \dot{X_m} - K_f(X_m - X_s) - B_e(\dot{X}_m - \dot{X}_s) \tag{1}$$

$$m_e \ddot{X}_s = K_f(X_s - X_m) - B_f(\dot{X}_s - \dot{X}_m) - K_s X_s - B_s \dot{X}_s \tag{2}$$

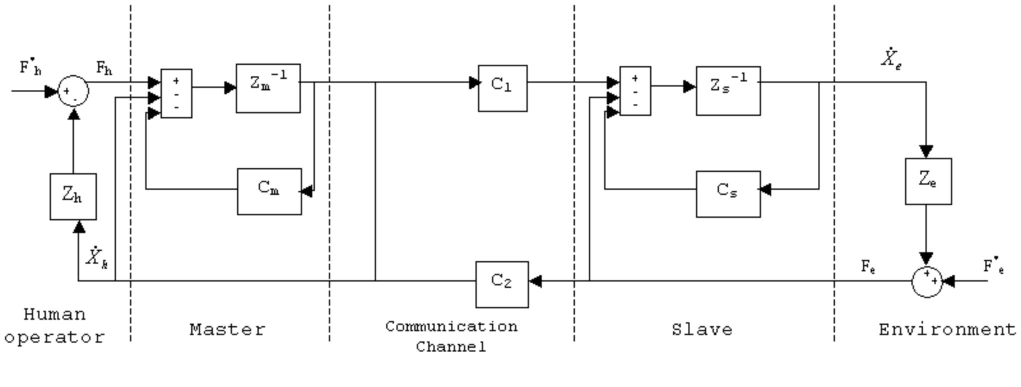

Figure 2. Pseudo blocks diagram of mechanical model.

Along the years, in literature, various types of control architecture have been proposed and among them one may mention (Hannaford, 1989), who proposed the use of a model based in hybrid control, since this control type represents in an intuitive for the performance of an ideal teleoperation system which may be of the other architecture types. This means that the hybrid parameters values may be utilized to compare performance with an ideal system. (Çavuşoǧlu at al., 2001) mention three distinct types of architecture: position error architecture (*PERR*); Kinetics force feedback architecture (*KFF*) and position error architecture with Kinetics force feedback (*P + FF*). This last one is a hybrid formed joining PERR with KFF. The objective of this comparison was to choose an architecture type able to perceive little variations when interacting with a non rigid object.

Figure 2 shows the block diagram of the control architecture that is being proposed. This architecture is an adapted model of (Lawrence, 1992). ${F_h}^*$ and ${F_e}^*$ are the exterior forces of the human operator and of the slave interacting with the ambient, respectively; Z_m, Z_s and Z_e are the impedances of master, slave and ambient; C_1 and C_2 represent the communication channel between master and slave. All the functions, inclusive C_m and C_s will be specified a posteriori.

For this work, hybrid control is being used since it permits to the designer to work with two information types, in this case, force and position. The Justification for utilization of force control is the intensity of the applied torque ; the position entrance allows the increase or the decrease of the speed of the movement execution.

For the explained reasons, it is obvious that the utilization of a control, hybrid type, is perfectly appropriate for the solution of the problem which is to verify the forces interaction of the slave manipulator in a remote ambient.

The diagram names of Fig. 2 are: $Z_m = m_m s$, $Z_s = m_s s$, $C_m = B_m s$, $C_s = C_1 = B_s + (\frac{K_s}{s})$ and $C_2 = K_f$. Their values come from the mechanical model shown in Fig. 1 and by the addition of other gains as Z_h and Z_e that are the entrance and exit impedances in the system.

The teleoperation system may be modeled as a four terminals net or a two ports model. This type of device is based in Norton-Thevenin theorem (Rosa at al., 2004a). Figure 3 shows the mechanical aspect of the system. In (3) the system description in matricial form is shown.

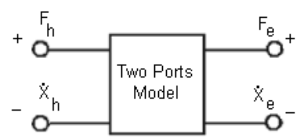

Figure 3. Teleoperation bilateral system as a model of two ports.

$$\begin{bmatrix} F_h \\ \dot{X}_h \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \cdot \begin{bmatrix} \dot{X}_e \\ -F_e \end{bmatrix} \quad (3)$$

The equations 4, 5, 6 and 7 twelve show the coefficients of the calculated hybrid parameters.

$$h_{11} = \frac{(Z_s + C_s)(Z_m + C_m)}{(Z_m + C_m) + C_1} \quad (4)$$

$$h_{12} = \frac{(1 - C_2)(Z_m + C_m)}{C_1 + Z_m + C_m} - C_2 \quad (5)$$

$$h_{21} = \frac{(Z_s + C_s)}{(Z_m + C_m) + C_1} \quad (6)$$

$$h_{22} = \frac{1 - C_2}{C_1 + C_m + Z_m} \quad (7)$$

4. Robotic Manipulator Project

Robotic manipulators are, in their majority, constituted by a set of rigid links united in series through rotational and/or prismatic joints. The number of a manipulator joints informs its freedom degree and the disposition of the joints informs the workspace that it describes. In business, the majority of manipulators has six degrees of freedom (dof) since with this configuration it is possible to position and orient the final effectuator and any point of the space. In this work the project of a 3 dof manipulator will be elaborate; this manipulator does not follow the existent commercial standards but it will be designed to detect collisions in an unknown environment and transmit them to another manipulator, thus giving the information of haptic feedback to whom would be operating the system.

Figure 4 shows the manipulator scheme where the cylinders represent the rotational joints and the cube represents the prismatical joint; also in Fig 4 it is observed that the orientation axles were marked; they serve as an aid to obtain the variables that are used in the manipulator project.

4.1 Manipulator Kinematics

The obtainment of kinematic equations of the proposed manipulator will be done through the Denavit-Hartemberg method (Fu at al., 1987) which leads to the ${}^{i-1}A_i$ matrices, with $i = 1, ..., n$, where n is the manipulator freedom degree. The objective is to obtain a matrix T which is obtained by the multiplication of A matrices or homogenous transformation matrices as one can see in equation 8. Where C_i is the cosine of θ_i and S_i is sine of θ_i. The vector $[\ dx\ dy\ dz\ 1]^T$ is a origin position vector referencing, that was modeled such as system origin reference.

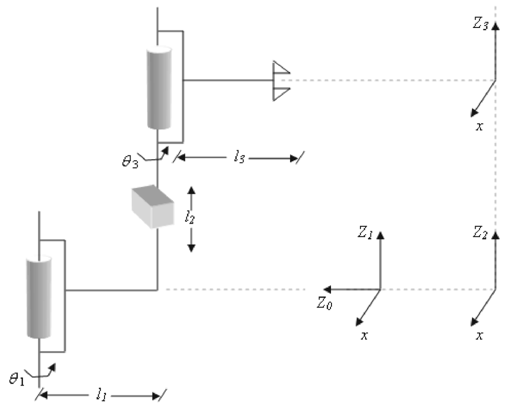

Figure 4. Scheme of a 3 dof manipulator.

$$T_3 = \begin{bmatrix} C_1C_2C_3 - C_1S_2S_3 & S_1C_2C_3 - S_1S_2S_3 & -S_2C_3 - C_2S_3 & 0 \\ -C_1C_2S_3 - C_1S_2C_3 & -S_1C_2S_3 - S_1S_2C_3 & S_2S_3 - C_2C_3 & 0 \\ -S_1 & C_1 & 0 & 0 \\ C_1C_2l_2C_3 - C_1S_2l_2S_3 - S_1l_2 & S_1C_2l_2C_3 - S_1S_2l_2S_3 + C_1l_2 & -S_2l_2C_3 - C_2l_2S_3 & 1 \end{bmatrix}, \tag{8}$$

The values of θ_1, l_2 and θ_2 are done by (9), (10) e (11).

$$\theta_1 = ArcTan\left(\frac{d_y}{d_x}\right) - ArcTan\left(\frac{(l_2)}{\pm\sqrt{r^2 - (l_2)^2}}\right), \tag{9}$$

$$l_2 = -S_1d_x + C_1d_y \tag{10}$$

$$\theta_3 = ArcTan\left(\frac{(C_1C_2)d_x + (S_1C_2)d_y - (S_2)d_z}{-(C_1S_2)d_x - (S_1S_2)d_y - (C_2)d_z}\right), \tag{11}$$

5. Software Simulation

In this session a simulation of the system implemented by software will be exposed. At first a brief explanation on the adopted technology will be given, then the communication between the systems will be shown and to finalize the obtained results will be presented.

For this work java programming language was adopted. This choice may be explained by the following factors:

- High portability: It is independent from the platform.
- Web programmed: It is a language proper for web.
- Free access: It is a public language with open code.

VRML (*Virtual Reality Modeling Language*) is a language that allows the user to create a scene or a scenery in 3D. The scene is formed by various objects (or VRML which is able to allow the user to rotate then, translate them and alter their structure Besides), VRML archives may be combined with *HTML* or *JavaScript* making them easy to be used by a browser.

Knowing the advantages of java language and the VRML easiness it is necessary integrate the two technologies. To this end an API developed for java language called EAI (*External Authoring Interface*) was chosen.

5.1 Graphic simulation

The proposed manipulator was implemented using the combination of java with VRML languages. As the main objective of this work is to transmit the haptic sensation via web, a simulation utilizing the communication system described in session 6was done. In Fig. 5 (A) and (B) one can observe the rotation move to the left and to the right of the superior arm, and in Fig. 5 (C) and (D) one can observe the translation move. It is worth to remember that identical moves are executed by the slave manipulator.

In spite of the unquestionable graphic quality of VRML, that can be demonstrated by the manipulator's (Fig. 5), the technology VRML has be seen as restricted to some old owned technologies. First, all of the current plugins for exhibition of VRML in the Windows platform only allow the use of EAI with the virtual machine of Microsoft (MSJVM). However, Microsoft no more offers support and/or development tools for this virtual machine. The creation of a server in the application form, with the customer and the visualization of the server in applet form found problems regarding the safety, what motivated the need of signature of these applets, process with which we had countless difficulties due to the current disuse of this tool.

Due to these problems, one looked for a plugin for LINUX, what would make possible the use of the virtual machine of SUN and of the second generation of Java (1.2.x, 1.3.x, 1.4.x, 1.5.x). The plugins for Linux still are in initial development stage, being most of them developed by the internet community, in open projects installed in CVS(Concurrent Versions System) serves, as for instance, SourceForge. This is the case of FreeWRL(http://freewrl.sourceforge.net/) that was the chosen option for the implementation test.

As EAI of FreeWRL still was not completely implemented, the communication JAVA/VRML is very slow, even when implemented in a robust machine like a Pentium IV. Implementations that make use of graphic plates 3D still don't exist, what also worsens the tax of exhibition of the three-dimensional models.

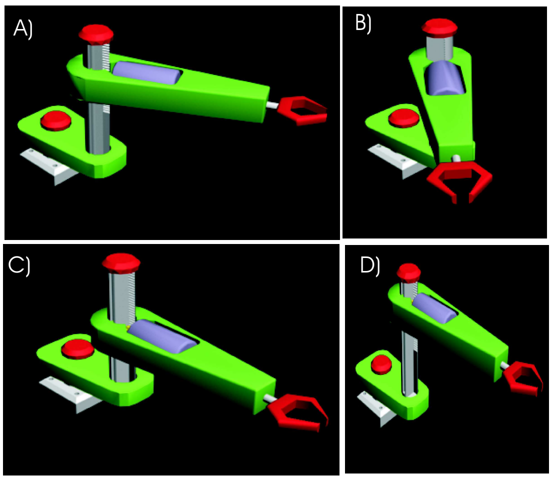

Figure 5. (A)Superior arm rotating to the right and (B) to the left hand side. (C) and (D) Translation movement

6. Communication between Master and Slave

The communication system between master and slave will be done at a level application layer and will use the protocol and resource of subjacent layers provided by *TCP/IP*. The protocol to be developed shall be designed in a way that two robotic manipulators of n-dof communicate from long distances. Some premises are desirable for this. They are: Assurance in relation to the transmission rate; Ininterruptibility of the communication process; Assurance to deliver the information; and transmission in real time.

Analyzing the established requirements for protocol implementation, one verifies that TCP (*Transmission Control Protocol*) is less desirable only in relation to real time communication item. So, TCP was chosen for the system implementation. In principle, the real time communication may be compensated with a communication channel working a high bandwidth.

Observing Fig. 6 one verifies that the system is composed by two robotic manipulators, master and slave. Master generates an analogical signal coming from the execution of a movement by an operator which is transmitted to a station (computer); from there on the signal is converted in digital. A program resident in this station, called *master program*, captures the signal and send it to another station, through a TCP connection. In this other station there is a program called *slave program* which stays in constat alert waiting for a command coming from the master program. The slave program captures the masters signal, convert it from digital to analogical and them transmit it to the slave manipulator. The slave manipulator executes identical move as the one executed by the master and retransmit it to the master program and this later retransmit it to the master manipulator, thus giving the sensation that the human operator is acting in the slave manipulator proper.

The systems work in similar way as a Client-Server system, where the client may be represented by the master program and the server, by the slave system, since this last one shall be always waiting for a requisition. So, the communication between the systems was implemented using this technology. Figure 7 shows the pseudocode of master program and slave program.

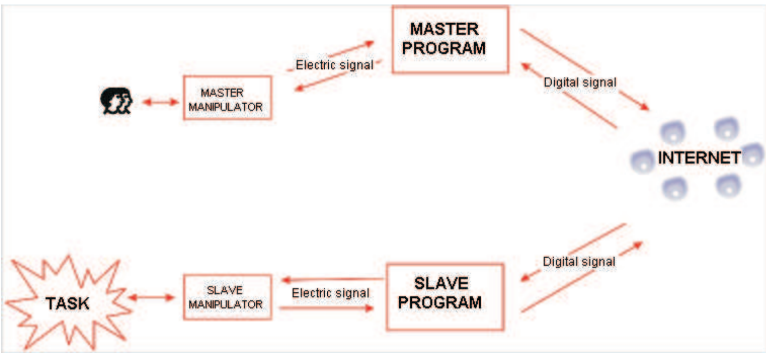

Figure 6. General view of communication system.

7. The system prototype

In order to validate the system, hereafter proposed, it was done using one degree of freedom system described in (Fernandes at al., 2004) and (Rosa at al., 2004b). The system have similar designs for the master and the slave. A sketch of the mechanical concept can be seen in Fig. 8. In order to neglect gravity effects, the arm was placed in horizontal plane. To assist the validation of this system, a simulation was done replacing the gains described in table 1, inside the block diagram shown in Fig. 2.

Table 1. The values used to validate a system for a one degree of freedom

Function	value
m_m	$837.218e^{-6}Kg.m^2$
m_e	$2.584e^{-6}Kg.m^2$
B_m	$60.9408e^{-6}N.m/rad$
B_e	$60.9408e^{-6}N.m/rad$
K_e	$3.5N.m/rad$
K_f	1.0

The values of Z_h and Z_e were approximate in order to give stability to the system, due to the fact of the complexity that is to model the human interaction and of the environment in the system. The equations 12 and 13 show the functions found for Z_h and Z_e.

$$Z_h = 0.5s + 20.0 + \frac{285.72}{s}, \quad (12)$$

$$Z_e = 100.0s + 10000.0 + \frac{10000.0}{s}, \quad (13)$$

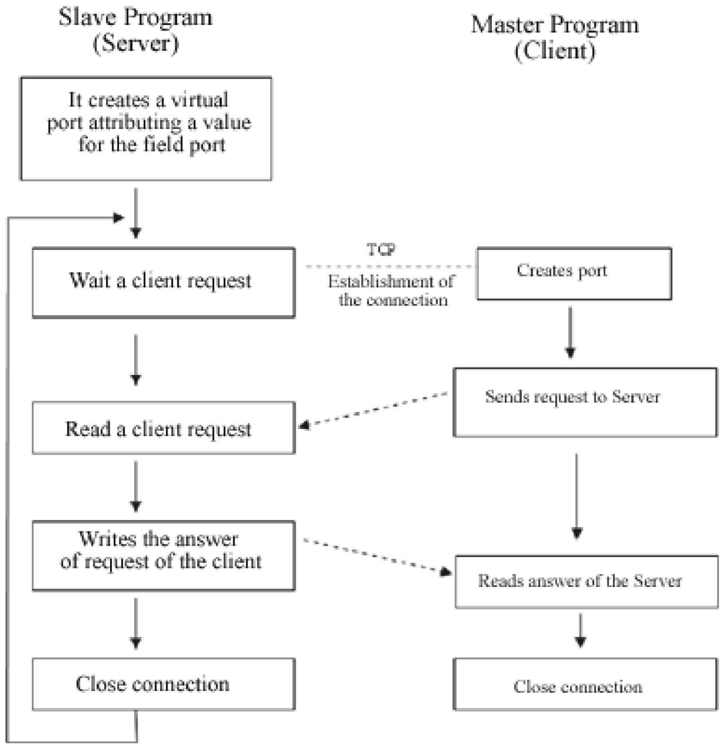

Figure 7. Pseudocode of master program and slave program.

To interconnect the prototype through web, it was projected and built a signal and writing capture device that communicates through the parallel port of the computer.

The manipulator operates with an interval of tension of $\pm 10V$. When a human operator applies a force in the robotic arm; this generates an electric signal. This signal is captured by the data capture device that converts it for digital and writes it in the parallel port of the computer.

The developed simulator captures the signal and transmits it through web, to another computer that accommodates the slave program and this writes the signal sent in the parallel port of the computer; then the signal is read by the signal and writing capture device, that converts the signal for analogical and gives it to the slave manipulator that executes the desired movement. Then the feedback, the signal is captured by the slave and give it to the program master that gives to the master. This process was described in full detail in session 6.The real prototype can be seen in Fig. 9.

8. Conclusions and Future Works

In this work a type of the telemanipulation master-slave system was developed. The system was projected so that the master as well as the slave were identical. In that way both possess same degree of freedom, kinematics, dynamics and dimensions.

Several stages of the system execution were accomplished, as: (1) design of the 3 dof manipulator; (2) definition of the control architecture; (3) graphic manipulator implementation; (4) definition and implementation of the communication system and at the last, the system was tested using a real prototype for a 1 dof. The test consisted in connecting the systems to the simulator and to operate them through the web.

As future work, initially one intends implement collision algorithms to completely evaluate the feedback haptic problem. Them one intends to test the system using the "RedeGiga", tying IME (Military Institute of Engineering) to the National LNCC(National Laboratory of Scientific Computation).

9. References

Butner, Steven E. and Ghodoussi, M., 2003, "Transforming a Surgical Robot for Human Telesurgery", IEEE Transactions on Robotics and Automation, October, Vol.19, no. 5, pp.818-824.

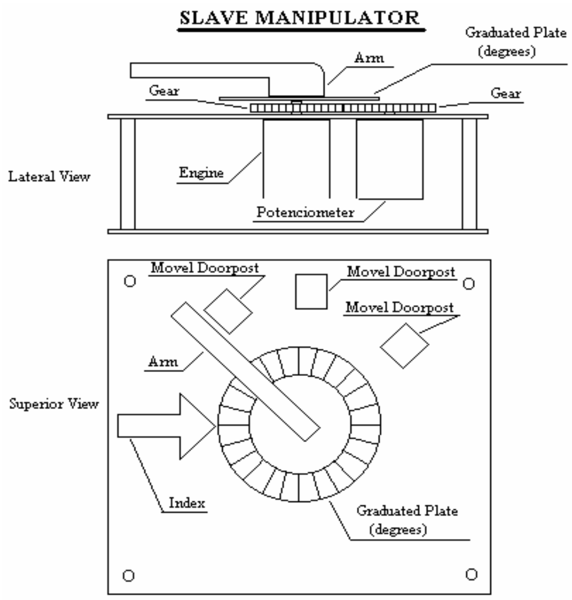

Figure 8. The slave manipulator mechanical sketch. The master has a similar physical design.

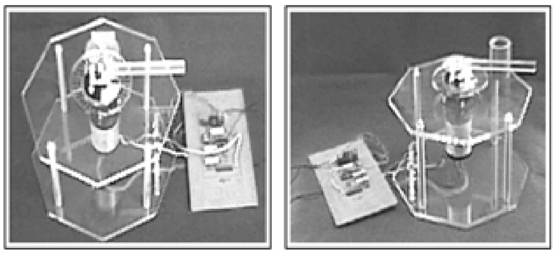

Figure 9. System real model developed for a 1 dof

Çavuşoğlu, M. C., Tendick, F., Cohn, M. and Sastry S., 1999, "A Laparoscopic Telesurgical Workstation", IEEE Transactions on Robotics and Automation, August, Vol. 15, no. 4, pp.728-739.

Çavuşoğlu, M. C.; Sherman, A. and Tendick, F., 2001, "Bilateral controller design for telemanipulation in soft environments", In Proceedings of the IEEE International Conference on Robotics and Automation, Seoul, Korea, May.

Conte, G. and Perdon, A. M. and Zanoli, S.,1995, "A navigation and inspection systems for ROVs", OCEANS 95. MTS/IEEE. 'Challenges of Our Changing Global Environment'. Conference Proceedings., Oct, vol.1, pp.354-359.

Fernandes, J. A. S., Rosa, P. F. F. and Bruno N., 2004, "Teleoperated Manipulator: The Remote Haptic Perception", WCETE World Congress on Engineering and Tecnology Education, São Paulo, Brazil, March, pp.375-379.

Fu, K. S. and Gonzalez, R. C. and Lee, C. S. G., 1987, "ROBOTICS: Control, Sensing, Vision and Intelligence", McGraw-Hill Book Companies.

Hannaford, B.,1989, "A design framework for teleoperators with kinesthetic feedback", IEEE Transactions on Robotics and Automation, August, Vol.5, no. 4, pp. 426-434.

Lawrence, D. A., 1992, "Designing Teleoperator Architectures for Tranparency", in Proceedings of the IEEE International Conference on Robotics and Automation, (Nice, France), May, pp.1406-1411.

Niki, T. and Shimjo, M., 2000, "A development of simple haptic display", IEEE Transactions on Systems, Man, and Cybernetics, pp.1001-1006.

Rosa, Paulo F. F.; Chagas, F. S.; Correia, F.A.C., 2004, "CMSE-3GDL: O Desenvolvimento de um Sistema Bilateral de Telemanipulação Robótica.", In: SBC/IEnRi - I Encontro de Robótica Inteligente SBC2004, Vol.1, Salvador-BA, Brasil, pp.1727-1736.

Rosa, P. F. F.; Chagas, F. S.; Correia, F. A. C., 2004a, "CMSE-3GDL: Development of a robotic telemanipulator bilateral system.",In VI IEEE/Induscon, 2004, Joinville-SC. VI Conferência Internacional de Aplicações Industriais, pp.1415-1420.

Rosa, Paulo F. F. ; Chagas, F. S., Fernandes, J. A. S., Bruno, N., 2004b, "Development of a bilateral device for telemanipulation with tactile feedback.", In: VI IEEE/Induscon, 2004, Joinville-SC. VI Conferência Internacional de Aplicações Industriais, pp.1399-1403.