Pode DESIGN AND CONSTRUCTION OF A LOW COST FORCE FEEDBACK MANIPULATOR

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Abstract. *The use of Virtual Reality for training purposes is already very common in some areas (like training of aircraft pilots), but it remains as a proof of concept in other areas. Medical training is one of these areas where Virtual Reality has a huge potential but it is not widely spread yet. The main reason for this is the difficulty in building a device able to provide the user a haptic feedback similar to real surgey. This fact can be observed in the high cost of force feedback manipulator commonly sold in the market.*
Due to this scenario, this work aims to design and analyze a low cost force feedback device to be applied in ophthalmologic surgical simulator using Virtual Reality.
At last, a prototype has been built based on the numerical simulations of the mathematical model of the designed force feedback device.

Keywords: Trainning Simulator, Force Feedback, Mechatronical Manipulator, Sensing Device

1. Introduction

A surgical simulator using Virtual Reality can be described as the device that is able to provide visual and force feedback in such a way that its user feels inside a real environment. In general, a surgical simulator is composed by the followings elements (see Meier, Rawn, Krummel and Thomas, 2001):

1. Force feedback device. It is a mechanism that provides haptic cues.
2. Virtual Reality glasses. Using these special glasses, the user can be in touch with images generated by the system. A regular PC monitor can be used either, but the Virtual Reality glasses are able to provide each eye with a different image producing a 3D image for the user
3. Position and Orientation sensors. It is a system of sensors that moves together with, for example, the head of the user, transmitting position and attitude for the simulation system. This feature allows the images generated by the system to be consistent with the user's point of view.
4. Simulation Software. This software must control all the system and must store the information related the virtual environment.

The objective of this work is to build a force feedback device able to provide haptic cues compatible to real surgeries. Hardly a device like this would be applicable to all kind of surgical simulation. As a result, cataract surgery has been chosen as a target of this work. The reason for this option comes from the fact that cataract surgery is very common and demands fine motor skills.

The central mechanism of the manipulator is based on the Delta mechanism, invented by Clavel (Parallenic,2004). Inspired in parallelograms, this mechanism has three legs that are linked by spherical joints to a platform that has its orientation constant along the movement. The next figure shows the Delta mechanism.

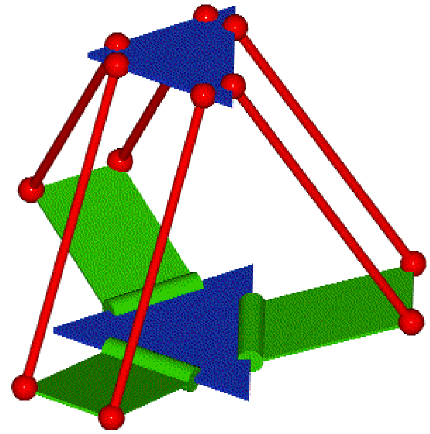

Figure 1 – Delta Mechanism.

Delta is a parallel mechanism, though it has the advantages and disadvantages natural to this kind of mechanism. Compared to serial mechanisms, Delta, as a parallel one, is more accurate and rigid, but it has a smaller workspace and more frequent internal singular points.

2. Modeling

The first step in this study is to determine the direct and inverse kinematics of the Delta mechanism. Next picture shows the main dimensions of Delta (L_B , L_P , a_1 and a_2) , and the generalized coordinates that define the position of the mechanism (θ_{11} , θ_{21} and θ_{31}).

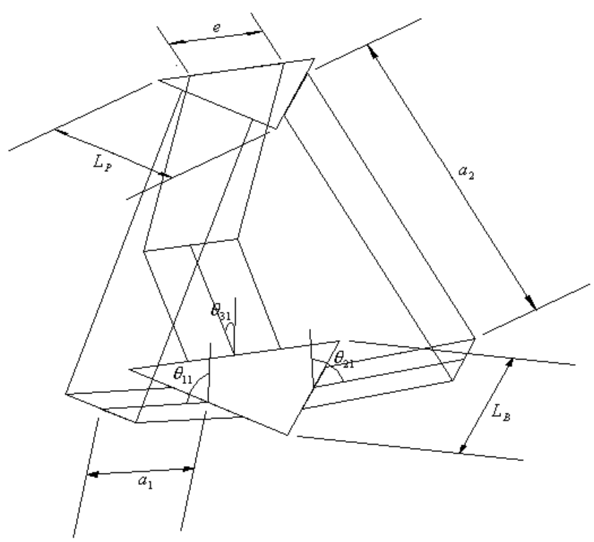

Figure 2 – Delta mechanism dimensions.

The direct kinematics defines the position of the platform given the angles θ_{11} , θ_{21} and θ_{31}. Inverse kinematics produces the angles θ_{11} , θ_{21} and θ_{31} given the position of the platform.

The kinematics of Delta mechanism comes from the following relationship:

$$\left| O_{i2} - P_i \right| = a_2 \qquad i = 1,2,3 \tag{1}$$

where, O_{i2} is the point located in the extreme position of the lower link of the i-th leg, and P_i is the point located at the mid point of the edge of the platform linked with the i-th leg. The relation above (Eq. (1)) states that distance between these two points is constant and equal to a_2.

Once the kinematics of Delta is constructed, the next step is to determine the dynamic equations that govern the mechanism movement when forces and torques are applied to it. Delta dynamic equations are determined dividing it in four parts: three legs and the platform (as in figure 3). Dynamic equations for each of these parts can be written as functions of the interaction forces among these parts (Andersson, 2005).

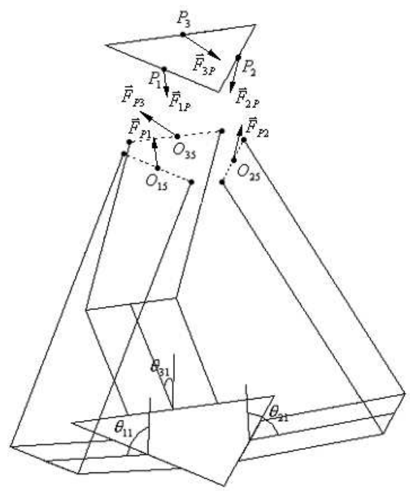

Figure 3 – Interaction forces in the Delta mechanism.

Accelerations are considered to be known in the direct dynamics. Using the equations found for the legs and platform, torques can be determined. Once direct dynamics is achieved , inverse dynamics can be derived from the direct model.

The dynamic model of the haptic device comes from the dynamic equations of the Delta mechanism interacting with DC motors (mechanism actuators) and a force sensor mounted on the platform. This sensor is related to the control strategies (explained in the following section) and is modeled as a mass-spring-damper system. The dynamic model chosen for the DC motor is based on the electric circuit shown in the next figure (Spong, 1989).

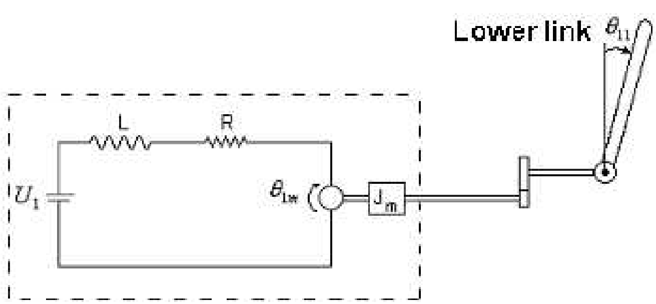

Figure 4

$$\frac{L}{R}\frac{di_1}{dt} + i_1 + \frac{K_v}{R}\dot{\theta}_{1m} = \frac{U_1}{R} \tag{1}$$

L and R are respectively the electric inductance and resistance of the motor armature. K_v is constant, i_1 is the armature current and U_1 is the voltage applied.

The final equations of the mathematical model of the Delta manipulator are shown below (Andersson, 2005):

$$(M + M_m)\cdot \ddot{q} + C + G = \Gamma_{atrito} + \alpha U - \beta\dot{q} + J^T F_S \tag{3}$$

$$M_S \ddot{q}_S = F_S + F^{ext} \tag{4}$$

Where:

M - Mass matrix of the Delta mechanism (3×3)

M_m - actuators inertia diagonal matrix (3×3)

q - generalized coordinates of Delta mechanism (3×1)

C - Delta manipulator gyroscopic matrix (3×1)

G – matrix of gravitational load applied to the Delta mechanism (3×1)

Γ_{atrito} - matrix of friction torque applied to the actuators (3×1)

α - diagonal matrix whose no null elements are equal to nK_T/R (3×3)

β - diagonal matrix whose no null elements are equal to $bn + n^2 K_T K_v/R$ (3×3)

n - gear ratio of the actuators

K_T - torque constant of the d.c. motor

K_V - velocity constant of the d.c.motor

J^T - transposed Jacobian matrix of Delta mechanism (3×3)

F_S - matrix of interaction force between Delta mechanism and force sensor

M_S - mass matrix of force sensor

q_S - generalized coordinates of the force sensor

F^{ext} - external forces applied in the force sensor by the user

3.Manipulator Control

Using the terminology based on the analogies between mechanical and electrical systems, a force-feedback should behave as an Admittance or as an Impedance. In the first case, the manipulator measures forces and displays positions. In the second case, manipulator measures positions (velocity or acceleration, depending on the situation) and displays forces. WYSIWYF (Yokokohji, 1996) is a example o manipulator that displays admittance and Phantom (Massie and Salisbury, 1994) is an example of manipulator that behaves as an impedance . Sampaio (2002) designs and tests an active sidestick that is implemented for both strategies. Pictures bellow show a implementation for the admittance control and for impedance control (for an one degree of freedom manipulator).

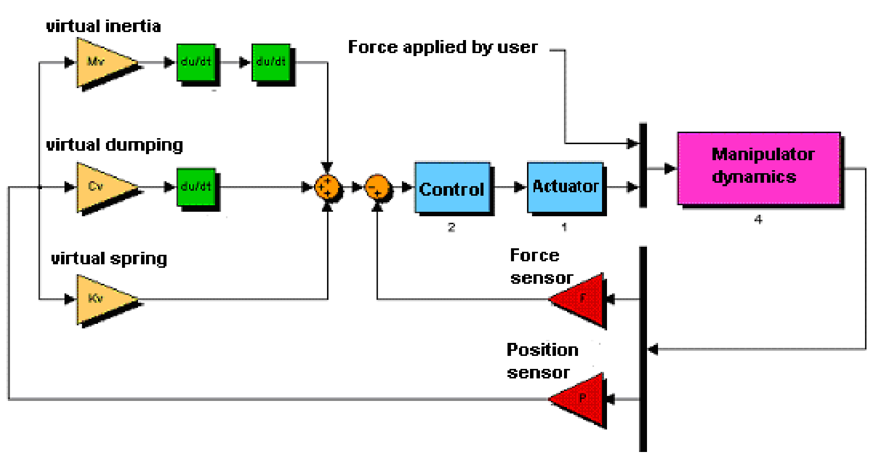

Figure 5 – Block Diagram for the manipulator as an impedance output.

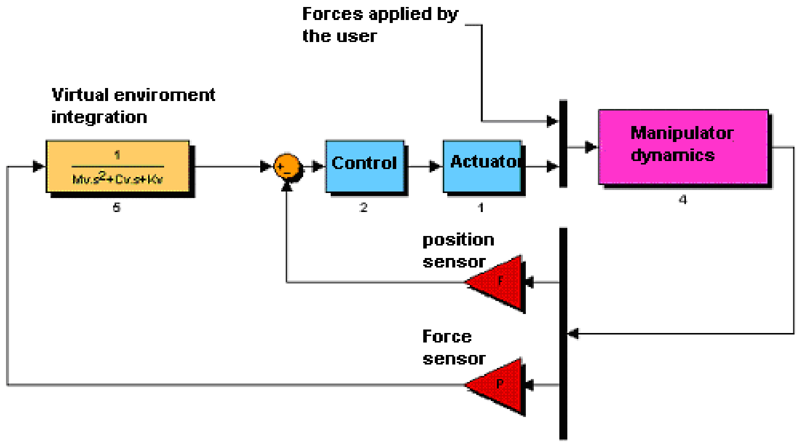

Figure 6 - Block Diagram for the manipulator as an admittance output.

In the impedance control scheme proposed in Figure 5, an inner loop controls the force, and the outer loop establishes the set point for the control in the inner loop. In the Admittance control scheme (Figure 6), the inner loop controls position, and the outer loop establishes the position set point.

In this work, a similar approach is used for the three-degree-of-freedom Delta manipulator. For each Cartesian direction, a SISO control is used. The manipulator transposed Jacobian matrix, updated for each time interval, is used to write the control signal in terms of actuators signal. Next pictures show the block diagrams for Delta manipulator using Admittance and impedance control.

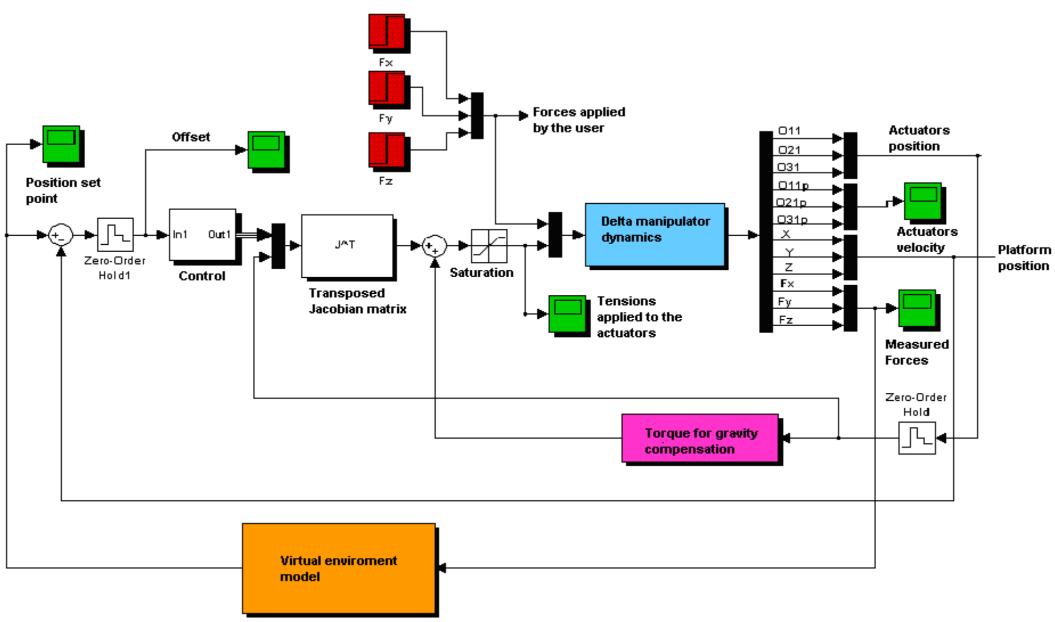

Figure 7- Admittance - Position control.

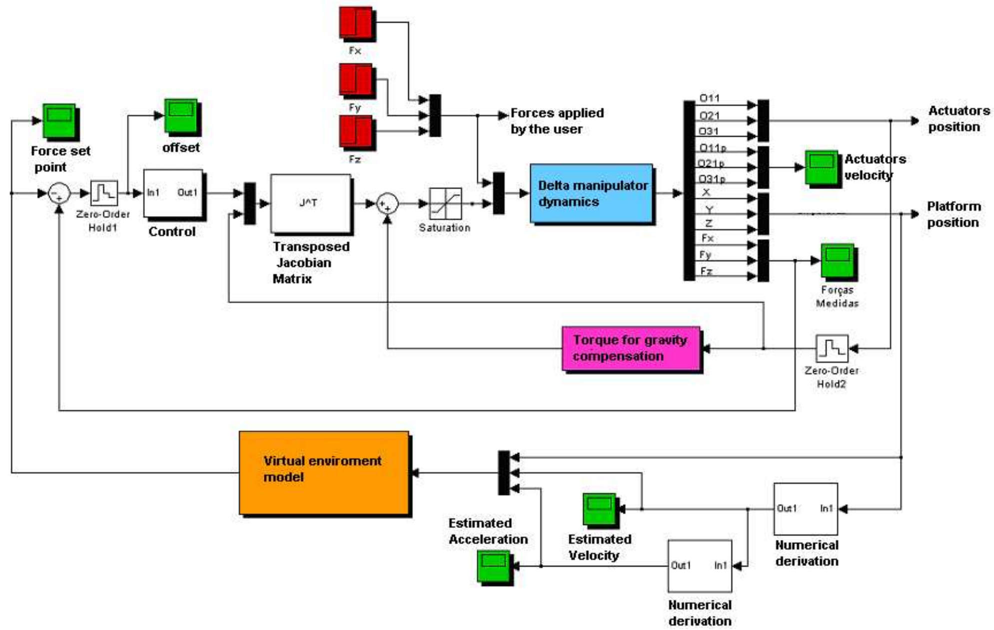

Figure 8 - Impedance - Force control.

4.Prototype

Based on the simulation results (not shown here), a prototype was built with the intention to verify the real behavior of Delta manipulator using the control strategies explained above. In a first approach, the force sensor measures force only in Z direction (up and down movement). Next figure shows the prototype.

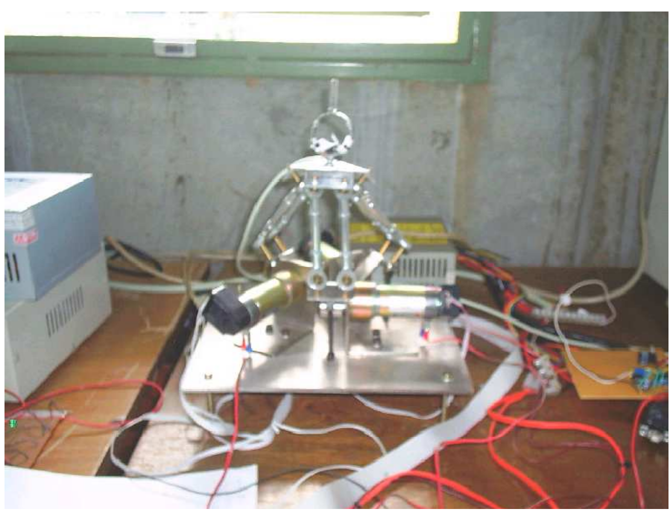

Figure 9 – Delta manipulator prototype.

A standard PC computer with a digital I/O board controls the manipulator. A power interface has been built to transform the computer digital output to a PWM signal with power enough to activate the DC motors. This power interface is shown in the next figure.

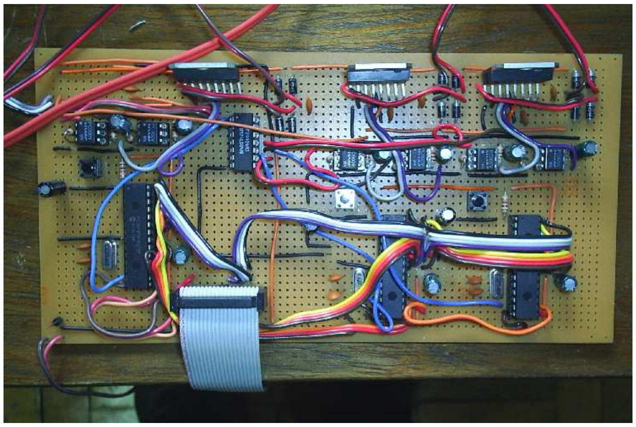

Figure 10 – Power interface.

The position of the actuators are measured by incremental encoders. An interface board has been built to count the pulses coming from the encoders and to send the position of the actuators to the PC. The PC reads the encoders position using its I/O board digital input. This interface board is shown in the next figure.

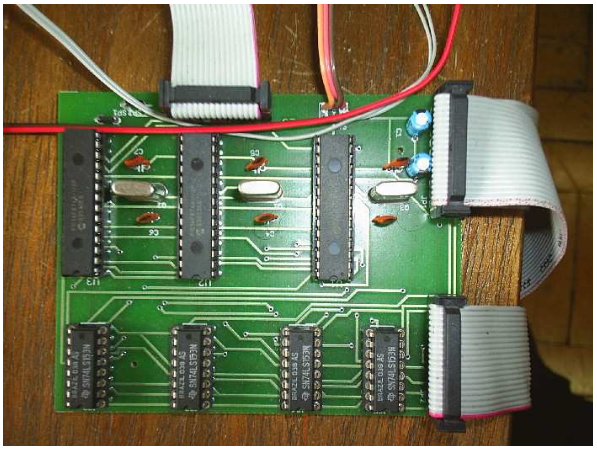

Figure 11 - Encoders interface board.

Figure 12 - Force sensor (strain gages attached in a metallic ring linked in Wheatstone bridge).

The virtual environment for both numerical simulation and physical prototype is a virtual wall perpendicular to the Z axis (XY plane). When the manipulator touches the wall, parameters of flexibility, damping and inertia are assigned for the contact with this virtual obstacle.

This virtual environment was implemented graphically either. The picture bellow shows this implementation. The virtual plane is located almost in the top of the eye. The red sphere represents the position of the Delta platform.

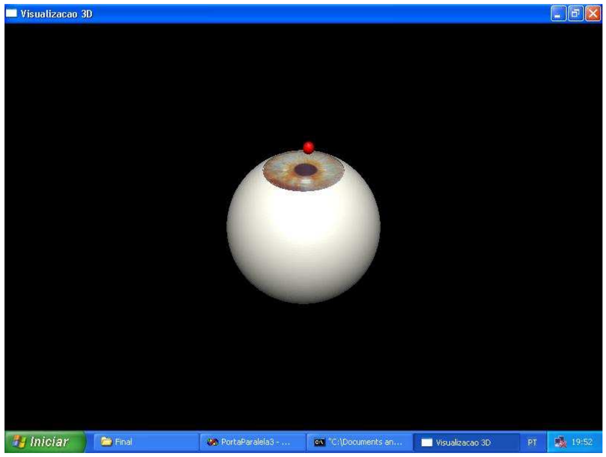

Figure 13 - Virtual environment graphically implemented.

5.Experimental Results for Position Control (Admittance)

Graphics bellow show the data collected for the implementation with position control.

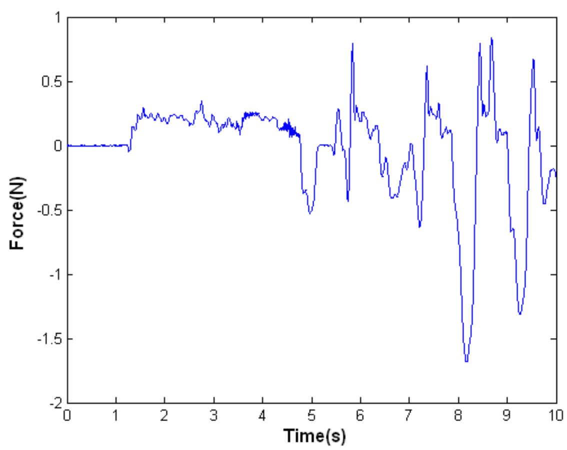

Figure 14 – Force applied by user (Z direction).

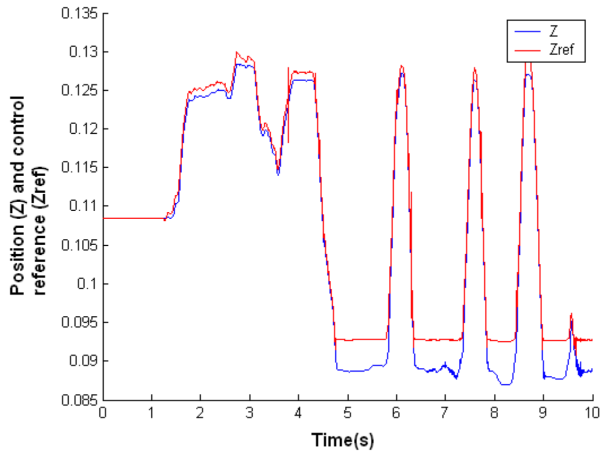

Figure 15 – Comparison between platform positions and references (Z direction).

When user touches virtual walls the position graphic becomes flat (as can be seen above).

6.Experimental results for Force Control (Impedance)

Graphics bellow show the data collected for the implementation with force control.

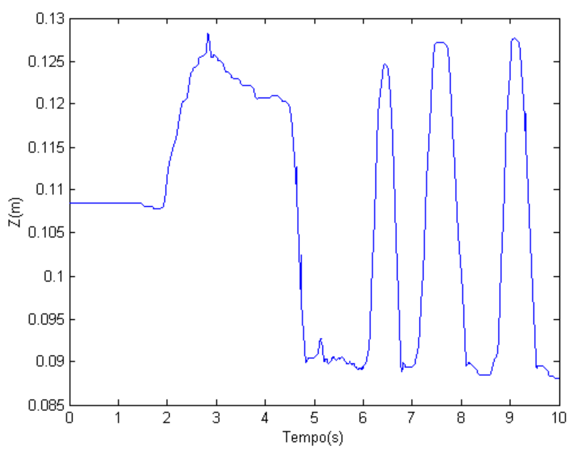

Figure 16 - Platform position (Z direction) .

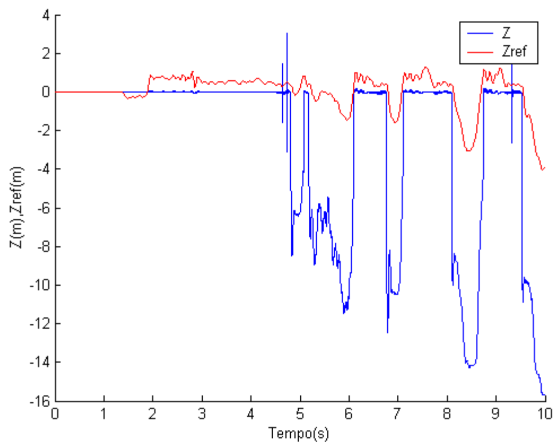

Figure 17 - Force applied by user and corresponding reference values.

Again, when user touches virtual walls the position graphic becomes flat.

7.Conclusions

The prototype works well both for position and force control. After some improvements (force sensor in three directions, and faster control loop, for example) this manipulator can be fully used for practical purposes. This particular manipulator version performance is limited mainly by some control instabilities (larger gains in control bring better performance, but after a threshold, if the gains are increased, instabilities are introduced in the controlled system) and by actuator saturations. Another important point is related to the control tuning. It was observed that if the control is tuned for a good performance in free movement (not touching virtual wall), probably this tuning will have a bad performance for a virtual wall, and vice-versa. It can be concluded that, in general, a good control tuning depends on the parameters that define the virtual environment, and that a good tuning for a given situation doesn't mean that this will be good for very different scenarios.

8.References

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9.Responsibility Notice

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