

Dynamic Modelling and Hardware-in-the-loop Simulation applied to a Mechatronic Project

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Abstract. *In this work, Hardware-in-the-Loop (HIL) techniques are applied in the control designing and development stages of a complex mechatronic project. Complex mechatronic systems usually have several degrees of freedom (DOFs), many sensors and a large number of work conditions possibilities. Such techniques are used with the objective to extend the capability and flexibility of development and designing. The methodology is based on the simulation of part of the system, or a group of them, in a virtual environment provided with real time software and hardware. The simulation works in synchronism with a real system through a virtual-electro-electronic interface. In this paper HIL techniques are used to design and develop a control system for a complex mechatronic project. The project consists on an anthropomorphic hand with several DOFs and it is intended to realize manipulation tasks. In the development stage each real subsystem, i.e. controller, actuators and sensors, is tested working in set with a simulated system. Results show that HIL techniques improves the capacity and flexibility for system development, and additionally allow designing and development of more complex mechatronic systems.*

Keywords: *hardware-in-the-loop, mechatronic systems, control system, robotic hand, dynamic modeling*

1. INTRODUCTION

Mechatronic projects designing and development, since it conceiving up to the final product, involves serial stages. Diverse tools and technologies are employed in such stages and, for some, the construction of previous prototypes is necessary. On the other hand, robotic systems that operate in specific environments, as aerospace and subaquatics robots, need special apparatus to simulate environments and operation conditions in experimental tests.

In a similar way, complex mechatronic systems with several DOFs, that presents diverse sensors, controllers and actuators, need special attention in the design and development stages. For this complex projects the wide group of system configuration possibilities induces the construction of several prototypes for experimental tests, which demands people and resources. After the experimental test with the constructed prototype, the data analyzes and systems comparisons are difficult and time demanding.

For such complex systems, each possible system configuration, either for specific operation conditions, either for system with lots of DOFs, when selected, or projected it is necessary to model and to test it to verify if the system projected attends the project requires. Many times this strategy, that demands time, people and resources, is not enough to test, or verify, all the possible work conditions and system configuration.

In many research areas HIL techniques have been used attempting to reduce demanding project time and costs. Examples of such applications can be found in the automotive industry (Vath,2006)(Park,2005), traffic control (Bullock,2004), controller analyzes (Linjama,2000)(Terwiesch,1999), military industry (Cotic, 1999), aerospace industry, between others. The mechatronic projects have also been improved with HIL techniques on attempt to extend the project capacity and flexibility.

The HIL techniques have the required characteristics to assist complex systems development. The techniques consist on the simulation of a subsystem that works in real time and in synchronism with part of the real system. This way it is possible to test different system configurations on different operation conditions. It is possible to start from a simple model simulation and progressively to add real parts until a complete real system simulation. In many situations it is possible to reduce or even substitute some experimental stages. Thus, each subsystem is tested separately during the designing and development stage without constructing prototypes, which improves the capacity to design and to project complex system.

In this paper HIL techniques are applied to design, develop and test an actuator system for a mechatronic project. The work is divided into two stages, in the first, the offline stage, the subsystems are modelled, the models parameters are preadjusted, and a position controllers is designed. In the second stage, the online stage, HIL techniques are used to analyze the controller's hardware and software, to verify the hand movements and its behavior in manipulation task. The HIL simulations are realized without the construction of a hand prototype.

In the next section, section 2., the system analyzed is described, each system element, or subsystem is modelled through different approaches. In section 3., a controller is designed and its parameters are calculated in section 3.4. The whole system is simulated in real time in section 4, and progressively real subsystems is added to the hybrid environment.

HIL simulation are done to test the system behavior for different working conditions, the system behavior is analyzed for one finger movement in section 4.3.3, and for a manipulation task in section 4.3.4. Finally some conclusions and discussions are considered in the last section 5.

2. SYSTEM DESCRIPTION

The system studied here is an actuator system for an anthropomorphic hand. The hand project (fig.2) is inspired on the human hand. It has four fingers and a simplified thumb, each finger and the thumb has four DOFs, where the fist ones are responsible for aduction and abduction. Each DOF is directly driven by a servo system through a cable transmission, for more details Benante(2007).

Due to the mechanical characteristics, the actuators are placed outside the hand body and direct current motors (DC motors) are selected to movement the joints. A cable transmission system transfers the movements from the DC motors to the hand joints. The controller system is responsible to control its angular position.

The system studied is composed by a DC motor, an encoder for angular displacement measurement, a servo amplifier and a controller (controller's hardware and software). Each system element cited before is from now on treated as a subsystem. The subsystems are offline modelled and tests are realized to obtain and/or to adjust their parameters. The block diagram below summarizes the actuator system and the subsystems. The servo amplifier is a linear voltage amplifier operating on voltage regulator, the actuator is a brushless DC motor with a planetary gear, the motor angular position is obtained by an incremental encoder.

The angular position is controlled by a dedicated hardware and a proportional-integral-derivative (PID) controller is the control technique adopted.



Figure 1. The anthropomorphic hand project.

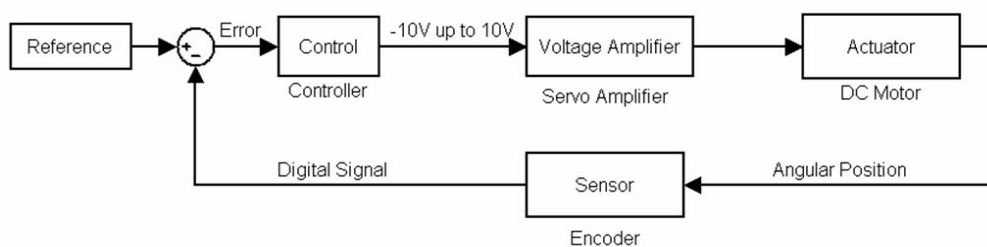


Figure 2. System block diagram.

The motor and the servo amplifier are both supplied by Maxon. The brushless DC motor, with 20watts of output power and 25mm of external diameter, presents a planetary gear with 19:1 transmission ratio. The incremental encoder mounted on the motor shaft has 3 channel (A, B and Index) with a resolution of 500 counts per revolution. The servo amplifier selection depends on the DC motor power, the servo amplifier selected presents a maximum power output of 50 Watts at 30V and it operates as a voltage amplifier with a variable gain G regulated by an potentiometer. To realize the angular motor control a dedicated device was chosen. The hardware, fig.3 , consist on a DSP from Texas instrument. The selected DSP is based on a TMS320F2812 DSP embedded in a eZdsp F2812 board, that have a CAN module. A full description of the DSP and its configuration to control a DC motor can be found in Dias(2006).



Figure 3. System devices, the DSP hardware, the DC motor, and the servo amplifier.

3. OFFLINE MODELLING, TESTING AND CONTROL DESIGNING

In this section the servo actuator system is described in detail. Each subsystem is dynamically modelled and its parameters are adjusted through traditional methods and/or through experimental analysis. The DC motor is modelled through its characteristic equation and its parameters are taken from the manufacturer catalog. Based on the DC motor output power the servo amplifier was select, due to the poor specification supplied by Maxon, it dynamical model and parameters are experimentally obtained through frequency response analysis (FRA). Offline tests are realized to compare the servo amplifier and motor dynamic models with the real devices. Additionally, a PID controller is designed to attend the project requires. Offline experimental tests are done to analyze the controlled system response.

3.1 DC motor modelling

The DC motor selected to drive the joints is dynamically modelled and its parameters are adjusted through experimental analysis. The motor dynamic model is determined through the characteristic equation and its parameters are previously taken from the manufacturer catalog.

Direct current motors is one of the classical actuators used in mechatronic systems. Specially Brushless DC motors were selected because of their special characteristics as the small relation of size/weight per output torque. To obtain the motor model, it is considered the electric circuit (fig.3.) that represents the DC motor electronic. The electric circuit may be simplified as the fig.3. shows.

When a voltage is applied a resulting torque, proportional to the current, is applied on the motor shaft. When the torque is applied there is an angular acceleration as a function of the shaft inertia and of the viscous friction. The DC motor transfer function, relating motor angular output with the voltage applied, is given by:

$$M(s) = \frac{\theta}{V_a}(s) = \frac{K_m}{(L \cdot s + R_a) \cdot (J \cdot s^2 + (B + \frac{K_m \cdot K_b}{L \cdot s + R_a}) \cdot s)} \quad (1)$$

Where: θ is the motor angular displacement; V_a is the applied voltage; K_m is the torque constant; L is the motor inductance; R_a is the armature resistance; J is the motor inertia; B is the viscous friction; and K_b is the back electric and magnetic fields (EMF) constant;

3.2 Servo amplifier modelling

A voltage amplifier is necessary when it is intended to drive a power system, in this case a DC motor, by a signal from a digital microcontroller.

The device selected is a linear servo controller (model LSC30/2) used to control DC motors up to 50 Watts. In this application it operates on voltage regulator mode. At this mode the amplifier applies a voltage " V_{out} " on the motor armature proportional to the input voltage " V_{in} " from the microcontroller as eq. 2 shows.

$$V_{out} = G \cdot V_{in} \quad (2)$$

The linear gain G is regulated by a potentiometer and it varies from 0 up to 2.5.

The linearity between input and output voltage is observed only on stationary regime, however the device presents a dynamical behavior in non-stationary regime (transient regime). All the information available on the manufacturer catalog is insufficient to analytic calculate it dynamic model. When the analytic modelling is difficult or impossible, the modelling must be done experimentally.

Frequency response analysis, see (Chiou,2006), are used to calculated the servo amplifier model. FRA consists on the application of an oscillatory voltage signal with known magnitude and frequency as an input. Then, the measured system output is compared with the input. Both input and output are oscillatory signals with the same frequency but with different magnitude and phase. Through the Bode plot it is possible to calculate the frequency modes by the asymptote method.

An experiment as the described above was done. An oscillatory frequency was applied as input, and it was varied from $\omega = 0.5rad/s$ up to $\omega = 26000rad/s$. The output magnitudes were measured and compared with the input magnitude. Due to the difficult of measurement, the phase between the signals was not considered. With the experimental data the Bode plot was drawn and the frequencies modes were calculated.

The second order systems damping values can not be calculated directly from de Bode plot. These values were adjusted until a satisfactory solution. The model frequency response and the real system frequency response are compared in the Bode plot of fig. 5.

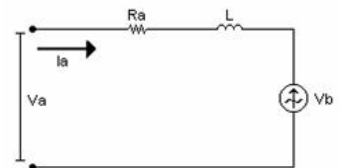


Figure 4. Simplified motor electrical circuit.

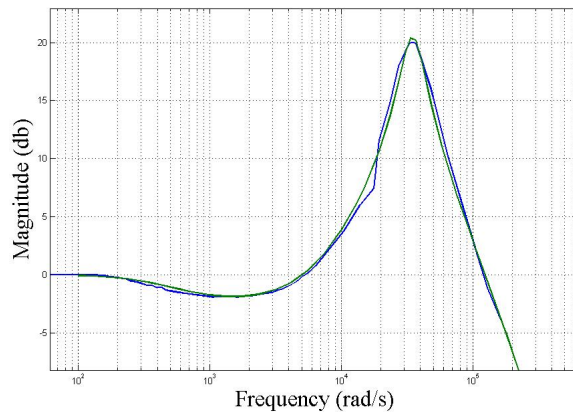


Figure 5. Frequency response comparison between the model (green line) and the real device (blue line).

The final model transfer function calculated through the frequency response modelling method is given by:

$$H(s) = \frac{1}{\frac{1}{490} \cdot s + 1} \cdot \frac{\frac{1}{2000^2} \cdot s^2 + \frac{2 \cdot 1.7}{2000} \cdot s + 1}{\frac{1}{35000^2} \cdot s^2 + \frac{2 \cdot 0.2}{35000} \cdot s + 1} \cdot \frac{1}{\frac{1}{150000} \cdot s + 1} \cdot G \quad (3)$$

Expanding the eq. 4:

$$H(s) = \frac{2.50 \times 10^{-7} \cdot s^2 + 1.70 \times 10^{-3} \cdot s + 1}{1.10 \times 10^{-17} \cdot s^4 + 1.82 \times 10^{-12} \cdot s^3 + 2.50 \times 10^{-8} \cdot s^2 + 2.05 \times 10^{-3} \cdot s + 1} \cdot G \quad (4)$$

The controller runs with a period of $T = 0.005 \text{ms}$, so the high frequency terms of eq.4 can be simplified. The final servo amplifier transfers function is given by:

$$H(s) = \frac{2.50 \times 10^{-7} \cdot s^2 + 1.70 \times 10^{-3} \cdot s + 1}{1.67 \times 10^{-12} \cdot s^3 + 2.41 \times 10^{-8} \cdot s^2 + 2.05 \times 10^{-3} \cdot s + 1} \cdot G \quad (5)$$

Additionally it was studied the influence of the gain G value on the system response. It was observed that the behavior do not depends on the gain values. For more details about the DC motor modelling and servo amplifier modelling see Pedro(2005).

3.3 Offline DC motor and servo amplifier models validation

Each DC motor transfer function parameter can be determined directly through experimental testing. However, the experimental determination of each parameter may be not practical or efficient in many situations. Due to this difficult the motor parameters are taken from the manufacturer specification. Preliminaries tests showed that these values are close from the real values, however to design an effective controller it is necessary to obtain precise parameters.

The parameters are adjusted from the values previously selected through experimental tests. The adjusted transfer function is given by the equation:

$$M(s) = \frac{\theta}{V_a}(s) = \frac{3.3 \times 10^{-2}}{(5.50 \times 10^{-3} \cdot s + 5.10) \cdot (2.10 \times 10^{-6} \cdot s^2 + 2.50 \times 10^{-4} \cdot s)} \quad (6)$$

It was observed that the main uncertain parameters is the damping constant B , whose value was adjusted to fix with the real parameter.

An experiment was done to compare the adjusted model with the real system. In this experiment a simple proportional controller was implemented. The comparison between the virtual model response and the real system response are presented for different Kp values, $Kp = 1$, $Kp = 2$, $Kp = 3$ and $Kp = 4$. An unitary step was applied as input and the motor angular position, as well as the servo amplifier output voltage were measured. After the experiments, simulations with the virtual model were done with the same operation condition.

Figure 6 shows the comparison between the data acquired and the simulation results.

Through results comparison it can be observed that the adjusted model response is close to the real system (real devices) response.

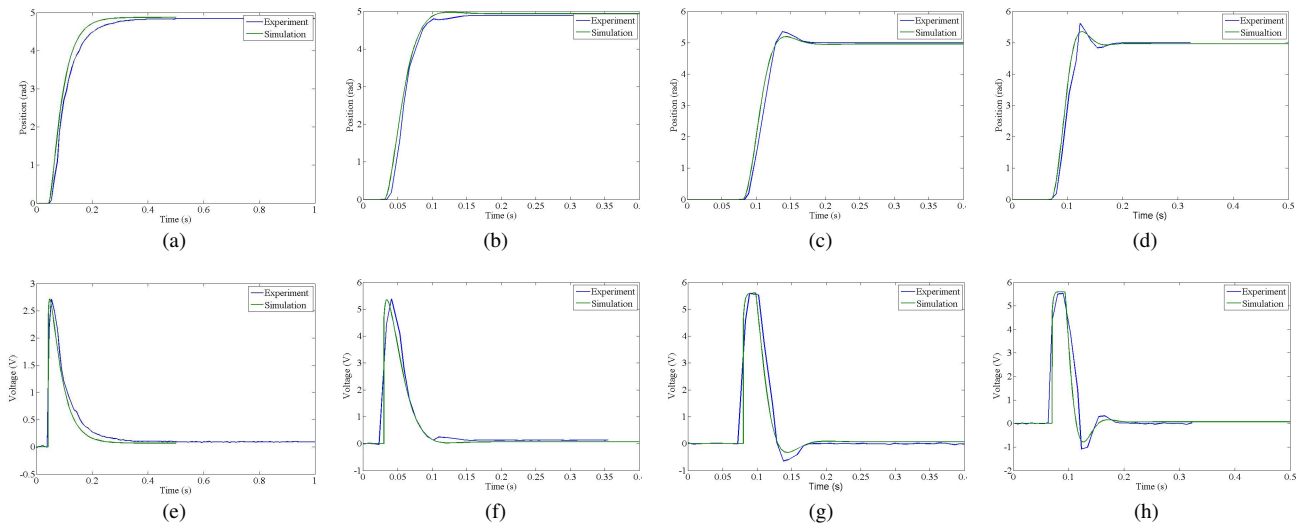


Figure 6. Offline comparison between the model and the real system for different values of Kp . The columns from left to right present the response from $Kp = 1$ up to $Kp = 4$. The top graphics show the position response comparison and the bottom graphics show the voltage applied comparison. The blue line shows the experiments results, and the green line shows the simulations results.

3.4 Control design

When a system is developed, some characteristics are desired as time response and maximum overshoot. In this case, the requirement is the angular positioning control with 0.2sec of time response and a maximum of 20 percent of overshoot. Once a model close to the real system was obtained the controller can be designed. A PID control is designed.

The PID controller has a good response since the system's plant is well known. In other words, the system needs to be linear and invariant in time and its model parameters need to be well known. Once the calculated model is close to the real system, we are able to design a PID control. The PID controller gains are previously calculated from computational simulation using Ziegler-Nichols (1942) and after refined through the root locus analysis (Ang,2005).

The PID controller equation is given by:

$$C(s) = \frac{Voltage}{error}(s) = Kp + \frac{Ki}{s} + Kd \cdot s \quad (7)$$

Where p is the proportional gain, Kd is the derivative gain and Ki is the integrative gain. The calculated values are: $Kp = 3.7$, $Kd = 0.043$ and $Ki = 0.0756$. A complete description of the PID parameters determination can be found in Pedro (2005).

4. ONLINE TESTS AND HIL SIMULATIONS

In this section , HIL simulation starts from a complete system simulation and each real subsystem element described and modeled on section 3., is progressively added to the simulation. In the target, a computer provided with real time software and hardware, the simulated system runs in real time. The simulated models work in synchronism with real devices, the interface between simulation and the devices is done by I/O boards. The HIL simulation is monitored in an ordinary PC (host) provided with Interface Development Environment (IDE) tools.

4.1 Hardware-in-the-loop techniques

HIL techniques has been used to assist the development step of complex projects. Used in traffic engineering (Bullock,2004), automotive cell fuel (Vath,2006), steering system (Park,2005) HIL is concerned with the development of a computational and an experimental environment that runs simultaneously in real time.

The computational environment consists on a robust platform (target) provided with a real time system operation and real time tools. In the computational environment the system models run in real time. The experimental environment consists on the real devices and system measurement. The models simulated on the computational environment run in synchronism with the real devices of the experimental environment. As a consequence, many subsystems may run virtually and simultaneously while a reduced number of real subsystems are implemented.

In mechatronic projects, where a large number of subsystems and DOFs are found, HIL techniques can also be used. By means of the HIL simulation the design and development of mechatronic system can be significantly accelerated.

In the online stage of this work, the experimental setup consists on the devices described in section 2 and modelled in section 3. The computational environment consists on the target capable to run the subsystem models in real time. The

interface between experimental and computational environments is done by I/O board.

With such apparatus is intended to test the controllers designed, analyze the subsystem models and test the devices (DC motor and servo amplifier) selected. This technique is also used to verify the hand's behavior in a manipulation task. In these manipulation task analyze one real actuator system works with two virtual actuator systems and, simultaneously, the hand's plant is also simulated.

4.2 HIL environment description

The target is composed by a robust platform called Versa Module Eurocards (VME). The VME is a parallel and asynchronous bus that allows many microprocessor working together and data transfer ratio of 8, 16 and 32 bites, with a maximum ratio transfer of 320MB/s. The MVME162 station is ideal to support real time application. The model used in the project is a MVME162 provided with a 32MHz MC68040 microprocessor, 8MB DRAM, Ethernet interface and 512kB SRAM.

It also allows installation up to four interfaces modules. Each module is denominate industry pack (IP), see fig.7 . The IPs, or peripheral devices of interface, are directly connected to the VME bus. The Acromag IP220 is an analog output with 16 channels with output from -10V up to 10V and 12bits of resolution. The Acromag IP320 is an analog input whit 16 channels each one presenting -10V up to 10V input and 12 bit of resolution. The MVIP341 is an digital input/output with 40 TTL channels. The IP Quadrature presents 4 channels for incremental encoder input. More details about the HIL environment description can be found in Pedro(2005).

The target environment, where the real time simulations run, is provided with a real time system operation denominated VxWorks from WindRiver. The VxWorks is an real time operational system of 32 bits with support of asynchronous multitasks, it uses POSIX support that is a standard library for operational systems, based on Unix, created by IEEE. The VxWorks together with some software tools (such as publisher, compiler and depurator) forms the integrated programming environment called Tornado. Tornado is an IDE for embedded systems.

The host station (an ordinary PC) is provided with Simulink and Matlab development environment. Such environment offers a powerful tool called Real Time Workshop (RTW) that provides fast prototyping and automatic code compiling from block diagrams for a great variety of platforms. RTW is able to compile application to the VME platform provided with VxWorks as system operation. Figure 7 shows the HIL environment.

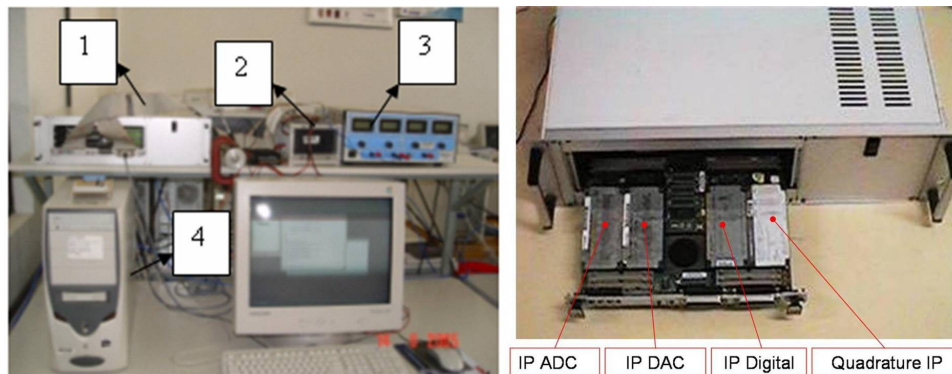


Figure 7. a) The HIL environment 1)The target (MVME162), 2)The servo amplifier, 3)Power supply, 4)The host(PC). b) MVME162 station and the Industry Packs.

4.3 HIL simulations

The HIL environment described above is now used to validate the model calculated, to verify the controller behavior, verify one finger movements, and also to analyze a manipulation task.

First of all, the whole system is simulated in the target environment. The controller and the models parameters can be modified and sent from the host to the target through an Ethernet connection. The system response for an applied input is sent back to the host and both input and output can be visualized in real time. This experiment was done to test the capacity of parameters modification and response monitoring.

4.3.1 HIL simulation for controller's hardware analysis

Before adding the real servo amplifier and the real DC motor to the HIL simulation, its intended to analyze the controller's hardware and software behavior.

The controller's hardware selected for this application was a DSP microcontroller, and to verify if it attends the project

requirements an HIL simulation was done. At these the controller's software designed was embedded at the DSP to control up to 4 motors. Four motor models ran in real time in the target, and through the analog IP the DSP controlled the virtual motors. It was verified that the DSP is able to control up to four motors, in other words an entire hand finger. For more information about the DSP hardware description and its selection for the application see Dias(2005).

4.3.2 Online DC motor and servo amplifier models validation

The HIL environment is now used to validate the models calculated and also to verify the controller behavior. These HIL simulation was done to verify if the models can represent the real actuator system.

Firstly the DSP hardware was tested through a serial of experiments. At this experiments the DSP was responsible to control a simulated model that was running in the target (Dias,2006). The results found by Dias(2006) shows that the hardware attends the project requirements. The controller designed on section 3.4 was embedded in the DSP microcontroller to drive the motor, and the real motor response was measured through the IP quadrature.

At these HIL simulation, the same input was applied to both systems (real and virtual). This input consist on a real trajectory that represents opening and closing of a finger's joint. Both response could be observed at the host, and fig.8 presents a range of the experiment results. Analyzing the difference between them it is clearly that the model can represent the real system. Also concerning the possible inputs and trajectories which could represent hand's movements and manipulation tasks, it could be concluded that the controller can be applied for such application.

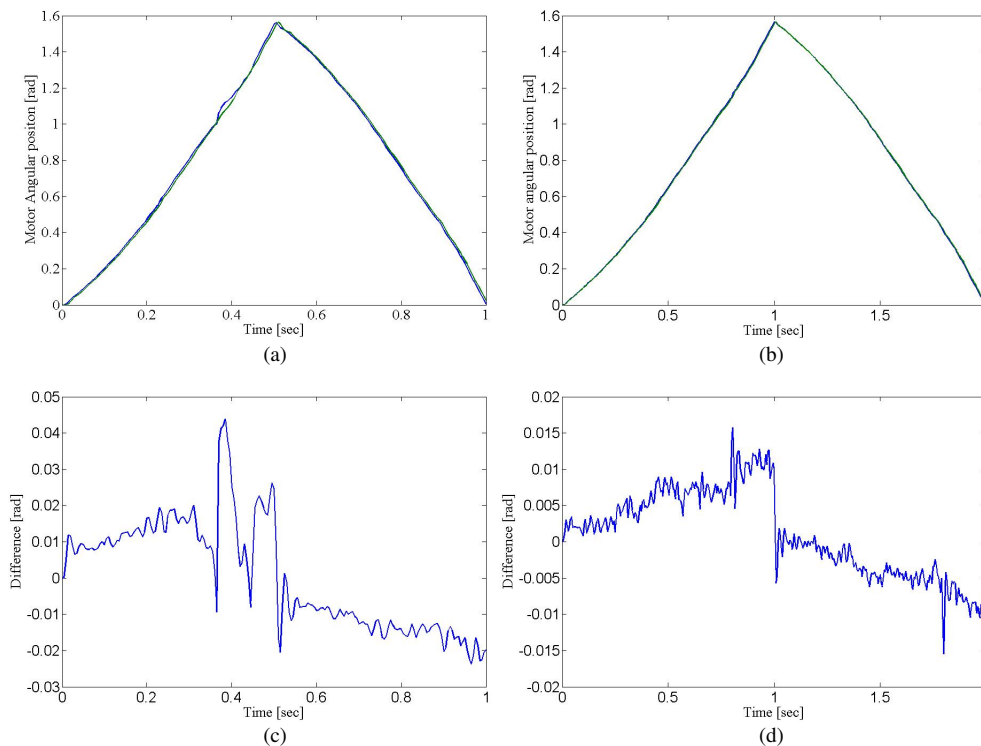


Figure 8. Movements of closing and opening one joint for $T=1\text{sec}$ (a) and $T=2\text{sec}$ (b) and its respective differences ((c) and (d)) between real controlled motor (blue line in (a) and (b)) and simulated controlled motor (green line in (a) and (b)).

The difference observed between the model response and the real system response is represented on graphics of fig.8(c) and fig.8(d) (for $T=1\text{sec}$ and $T=2\text{sec}$ respectively). Such differences are small than the errors presented when the motor follows a specific trajectory. The model validated is up from now used to analyze the hand kinematics on a manipulation task.

4.3.3 HIL simulation for finger movements

The models validated were used to verify the behavior of the hand's movements. For such verification, three simulated motors ran in synchronism with one real motor. The inputs were a trajectory of closing one finger obtained through direct kinematics.

At the simulation, the real motor drove the second joint and the virtual motors drove the third and fourth joints, the first responsible for adduction/abduction was kept fixed. Because of the relation between the motor dynamics and the hand dynamics (about 1/40) and also due to the gear transmission ratio (19:1), the hand's dynamic was not considered at these

experiment.

Figure 9(a) illustrates the trajectory of closing one finger as well the considered coordinate system. The graphics of fig. 9(b) presents the error between the output and input. The same procedure was applied for different movement times. The errors observed prove that the controller implemented is able to execute the desired movements, such as the human hand movements.

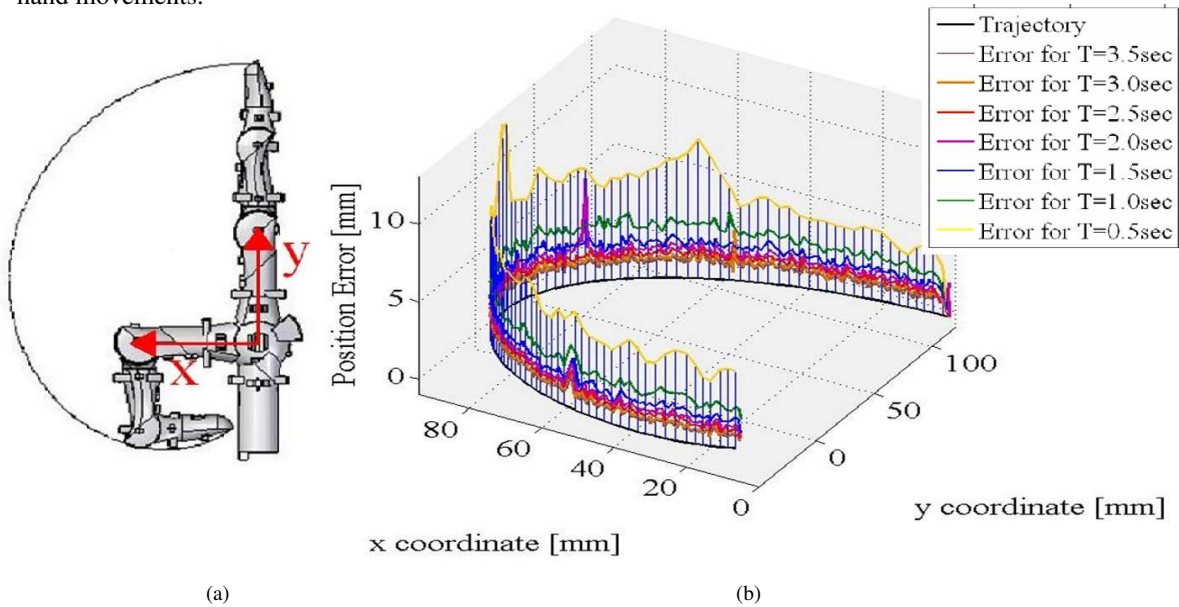


Figure 9. (a) Trajectory of the finger closing (desired trajectory). (b) Positioning error between the desired trajectory and the trajectory obtained in the HIL simulation.

4.3.4 HIL simulation for a manipulation task

Once the controller was designed implemented, and also offline and online validated. It is intended to verify its behavior in a manipulation task, and if it is able to execute that.

Caurin(2004) proposed a strategy to manipulate a pencil. The trajectory to manipulate the pencil generated through the strategy adopted is here used to verify if the control designed is able to realize the manipulation task.

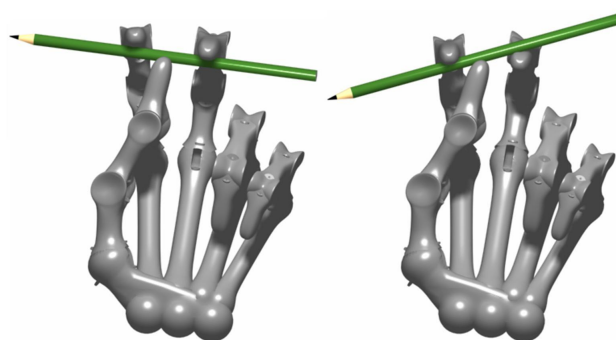


Figure 10. Manipulation task, initial and final position. Figure modified from Caurin(2004).

Figure 10 illustrates the initial and final position for a pencil manipulation. The motors' trajectories previously obtained for the fourth finger (see Caurin(2004) for detail of the nomenclature) was used as the controller reference.

At this HIL simulation four motor are responsible to movement the finger. The real one represents the movements of the first virtual joint, the second, third and fourth virtual finger's joints were driven by three virtual motors. The finger position was calculated through direct kinematics and compared with the desired manipulation trajectory. The desired manipulation trajectory was executed in a period of $T = 1sec$. Figure 11 shows the desired trajectory for x, y and z coordinates and finger positioning error. The total positioning error obtained was $Error_{max} = 6.9519mm$ and the mean positioning error was $Error_{mean} = 1.8216mm$.

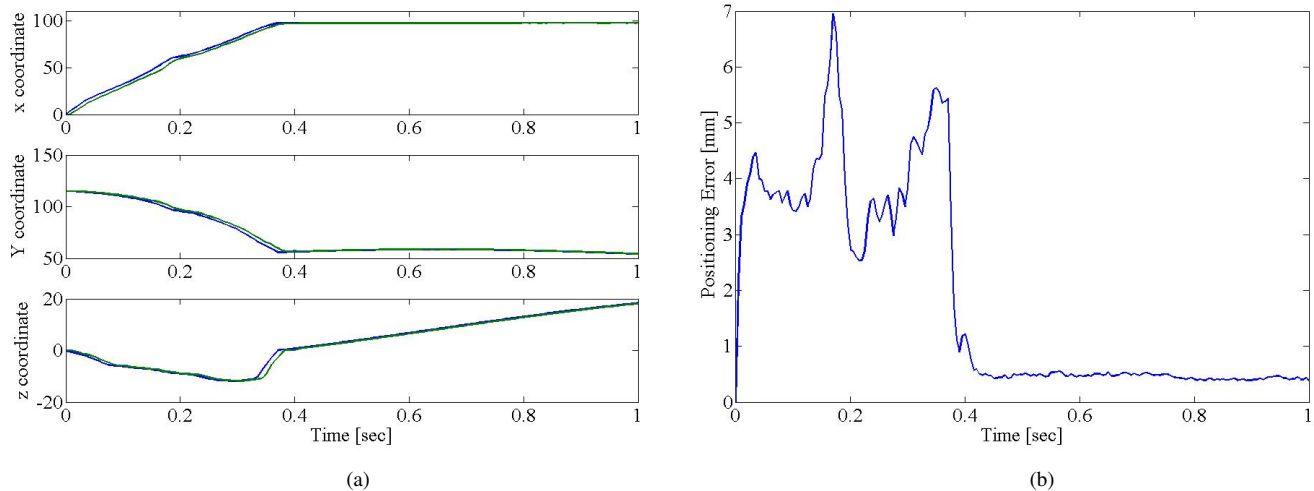


Figure 11. (a) Differences between the desired trajectory and the obtained response for x,y and z coordinates. (b) Total positioning error.

5. CONCLUSION AND DISCUSSION

Hardware-in-the-loop techniques have been used in this work to design and develop a control system for a complex mechatronic project. The dynamical model for each actuator subsystem was modelled offline. The models calculated were simulated and each subsystem was tested, the results showed that the models' response are close to the real system response. Still concerning the offline stage, there are some regards. About the linear servo amplifier the frequency response method proved to be able to find the dynamical model experimentally. On the other hand, the parameters supplied by the manufacture about the DC motor are close from the given values, however, one parameter, the viscous friction B , needed to be adjusted. The value was adjusted through a serial of offline tests. The offline experiments showed that the system model response is close to the real system.

After the modelling a PID controller were designed with the precise system's model. The controller's parameters were obtained through simulations using Zigler-Nichols method. The controller's hardware was selected concerning the processing period required ($T=0.005s$) and concerning the possibility to control up to four motors. The controller proposed (controller's hardware and software) attended the project requirements.

In the online stage, the real time environment was prepared, this environment consists on a target station provided with a robust processor and a real time system operation, I/O boards are responsible to connect the target with the real system. The host station consists of a personal computer with a system of monitoring. Host and target communicate each other through Ethernet.

The whole system model was firstly simulated in real time, at this simulation it was tested the parameters modification and the response monitoring. Each real system element were inserted in the simulation, the interface was done by the IPs. The first HIL simulation was implemented to test the controller's hardware capacity of real time operation. After the real servo amplifier and the DC motor were inserted to the HIL environment and the second HIL simulation was done to validate the models. Both models were validated as well as the controller's hardware proved to be able to control the angular position of the hand's joint.

In the third HIL simulation it was tested the system response for a movement like a human hand movement. One virtual finger's joint was driven by a real actuator, and in synchronism a virtual actuator drove a virtual joint. Both systems experimented the same input (movements to close the joint). The low difference observed between them proposes that the actuator system deals with the application. In the fourth HIL simulation, to show the flexibility and the capability of HIL techniques, a full control system for one finger were tested, at this a real actuator system (controller's hardware and software, servo amplifier and DC motor) worked together with another three full simulated system, in this simulation a manipulation trajectory was applied as input to the system. The results shows that the system project is able to execute manipulation tasks.

The analysis of the actuator system and of the control designed was possible to realize without the necessity to construct a hand prototype. Different work conditions was verified such as tests for movements under different time of execution. It was also analyzed the hand behavior in a manipulation task while only one real system was implemented.

With HIL simulation it is possible to replace system components with their dynamical models and perform its operational behavior. Thus, HIL simulation allows developers to test different system configuration in the development step. Another advantage of using HIL simulation is that in a nearly stage of development the whole system can be performed,

even though not all the hardware is available. The real time environment showed to be effective and easy to use in applications that require flexibility and capacity to simulate and to experiment complex systems.

It was presented in this paper an application of HIL simulation mechatronic project. The subsystems were described and modelled, tested and simulated, in the first stage. In the inline stage, simulations were done to test the devices selected, to analyze the controller designed, to validate the models and to verify the system behavior under different work conditions. As a conclusion, HIL simulation is able to improve the development of advanced mechatronic projects, reducing time and allowing more complex system development.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

- Ang, K.H., Chong, G. and Li, Y., 2005, "PID control system analysis, design, and technology" *Control Systems Technology*, Vol.13, pp.559-576.
- Benante, R.C., Pedro, L.M., Massaro, L.C., Belini, V.L., Araújo, A.F.R. and Caurin, G.A.P., 2007, "A Self-Organizing State Trajectory Planner applied to an Anthropomorphic Robot Hand". (Submitted to) *IEEE/RSJ Int. Conf. on Intelligent Robots and Systems - IROS 2007*.
- Bullock, D., Johnson, B., Wells, R. B., Kyte, M. and Li, Z., 2004, "Hardware-in-the-loop simulation", *Transportation Research Part C: Emerging Technologies Journal*, Vol.12, pp.73-89.
- Caurin, G.A.P., Albuquerque, A.R.L. and Mirandola, A.L.A., 2004, "Manipulation strategy for an anthropomorphic robotic hand" *IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, Vol.2, pp.1656-1661.
- Chiou, J.C. and Lin, Y.J., 2006, "Modeling and verification of the double frequency effect using a MEMS device", *Microsyst Technol*, Vol.12, pp. 796-802.
- Cosic, K., Kopriva, I., Kostic, T., Slamic, M. and Volarevic, M., 1999, "Design and implementation of a hardware-in-the-loop simulator for a semi-automatic guided missile system", *Simulation Practice and Theory*, Vol.7, pp.107-123.
- Dias, A. L., 2006. "Estudo e implementação de rede de campo em um sistema de controle de tempo real", *Relatório de Iniciação Científica, Processo FAPESP n°2005/04029-7*.
- Linjama, M., Virvalo, T., Gustafsson, J., Lintula, J., Aaltonen, V. and Kivikoski, M., 2000, "Hardware-in-the-loop environment for servo system controller design, tuning and testing", *Microprocessors and Microsystems*, Vol.24, pp.13-21.
- Park, T.J., Han, C.S. and Lee, S.H., 2005, "Development of the electronic control unit for the rack-actuating steer-by-wire using the hardware-in-the-loop simulation system", *Mechatronics*, Vol.15, pp.899-918.
- Pedro, L. M., 2005. "Projeto de um Sistema de Acionamento Aplicado a um Projeto de Mão Artificial Robótica", *Relatório de Iniciação Científica, Processo CNPq n°111360/2004-8*.
- Pollini, L. and Innocenti, M., 2000, "A synthetic environment for dynamic systems control and distributed simulation", *IEEE Control Systems Magazine*, Vol.2, pp.49 -61.
- Terwiesch, P., Keller, T. and Scheiben., E., 1999, "Rail vehicle control system integration testing using digital hardware-in-the-loop simulation", *IEEE Trans on Control System Technology*, Vol.3, pp.352-362.
- Vath, A., Lemes, Z., Mäncher, H., Söhn, M., Nicoloso, N. and Hartkopf, T., 2006, "Dynamic modelling and hardware-in-the-loop testing of PEMFC", *Journal of Power Sources*, Vol.157, pp. 816-827.
- Ziegler, J.G. and Nichols, N.B., 1942, "Optimum setting for PID controllers". *Transactions of the ASME*.

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