Humanoid Robot
Development of a simulation environment of an entertainment humanoid robot

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***Abstract-* This dissertation was developed in collaboration with Robosavvy Ltd and boosted the creation of the Humanoid Robotics Laboratory of IDMEC-Center of Intelligent Systems, at Instituto Superior Técnico (*http://humanoids.dem.ist.utl.pt/*). The developments presented include: i) the software development for interfacing the Matlab® Real TimeWorkshop Toolbox® with the Bioloid humanoid robot servos; ii) the identification of the internal and external dynamic parameter of the humanoid servos and structure, respectively; iii) the dynamics modeling and simulation of the humanoid robot using the SimMechanics® and Virtual Reality Toolbox® ; iv) the deduction of the equations of motion for an underactuated n-link inverted pendulum. The main objective of the Humanoid Robotics Laboratory, for the time being, is to develop a humanoid robot able to make complex motions like walking, running and jumping through real-time feedback control techniques. This dissertation presents a LQR controller for the simulation and control of the humanoid robot doing the handstand on a high bar, by considering it as an underactuated 3-link inverted pendulum.**

***Keywords-* Humanoid Identification, Servo Identification, Humanoid Simulation, Linear Quadratic Regulator (LQR), underactuated Inverted Pendulum, Non-Minimum Phase-System.**

I. INTRODUCTION

A long-standing desire that human-like robots could coexist with human beings has made the researchers think that the humanoid robotics industry will be a leading industry in the twentieth-first century [4]. This thought comes from the fact that technology is finally getting ready for this purpose. Fastest micro-processors, super computers, high-torque servo-actuators, precise sensors along with new advances in control techniques, artificial intelligent and artificial sound/vision recognition, all embedded in better and better mechanical design machines made the believe that this dream might became true in a nearly future. But, humanoid robots will not only be able to socialize with the human-being but will also be able to replace him even in the tedious and dangerous tasks, ranging from rescuing situations to interplanetary exploration [10].

However, current commercially available humanoid robots are still designed to perform motions using open-loop control providing the users a simple paradigm to create pre-orchestrated multi-DOF walking gaits. These robots are usually not able to move on uneven terrain and it is difficult or impossible to get them to perform movements that require instantaneous reaction to momentary instability. A popular way to compensate for these predicaments is to over-capacitate servo torques and to incorporate large foot soles, low center-of-mass and better shock absorption, resulting in humanoid robots with little resemblance to the human physique.

The long term objectives, however, are to allow affordable commercial humanoid robots to run, skateboard, jump and in general to react in a human-like physical way in dynamically unstable situations and uneven terrain. These goals can be achieved by applying closed-loop control techniques to the humanoid robot servos. The input data stream should consist of a multitude of sensors including servo position and torque, acceleration and inertial moment.

This paper shows the steps undertaken in order to prepare the necessary work environment for achieving these goals. They are:

- The selection of a humanoid with high-torque servos.
- The establishment of a real-time protocol communication between the PC, using Matlab/Simulink® Real-Time Workshop and the robot, for acquiring and sending data to the servos-actuators.
- The identification of the physical and mechanical properties of the humanoid robot.
- The identification and study of the behavior and responses of the high-torque servos.

It ends with the formulation of the equations of motion for an underactuated n-link inverted pendulum along with the implementation of Linear Quadratic Regulator [2,3,5,6,11] (LQR) controller for stabilizing the humanoid robot while doing a handstand on a high bar, by considering it as an underactuated 3-link inverted pendulum.

II. Architecture and Developments

A. Humanoid

The humanoid of choice, was the Bioloid (Figure 1) from Korean manufacturer Robotis.com., due to its well designed servo controllers that provide current, voltage, position and temperature sensing. It has a well documented open controller board and its well documented servo control protocol. The humanoid Robot has 18 degrees of freedom (DOF) powered by DC servos.

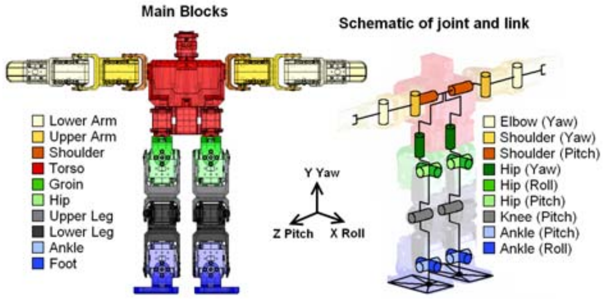


Figure 1: Bioloid humanoid

B. Hardware architecture

Figure 2 shows the existing humanoid architecture and the control architecture we are using.

The humanoid controller named CM5 is connected to the controllers of the servos through a RS485 bus. The usual approach to teach the robot is the use of the humanoid proprietary software that connects to a PC through the RS232 serial line.

The CM5 has however an Atmega128 microcontroller with a bootloader which allows users to change the code and access directly to the servo controllers parameters.

We developed a small program in the CM5 controller to implement a protocol for transmitting/receiving thought the serial port the data from/to the servos.

C. Software architecture

In the computer running Simulink / RTW / Real Time Windows Target we developed the device drivers to send/receive data to/from the servos using the protocol we defined. For doing this, we created a C-MEX S-function written in C to communicate with the CM-5 throughout UART (universal asynchronous receiver / transmitter). Hereafter, it was necessary to establish a protocol for the serial communication between PC and the CM-5. Finally, we wrote a little C program for Atmega128 for completing the serial communication bridge. Hence we implemented this architecture that transparently maps Simulink variables into servos motion.

We have now a way to identify the parameters of the Humanoid models making online experiments, as MATLAB/SIMULINK® is a unique tool, widely used, for System Identification and control. However we still have to check if the delays introduced by the serial line, CM5 and RS485 are compatible with the sampling time of the controller.

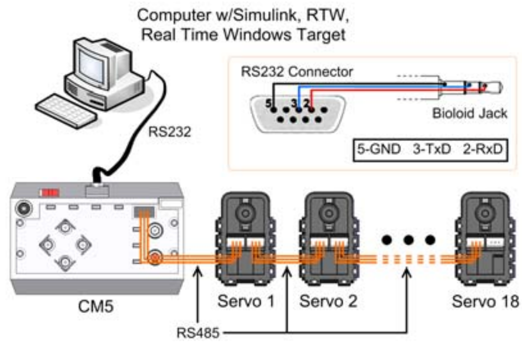


Figure 2: Humanoid control architecture

III. System Identification

A. Description of the measured signals from the servos

A set of output signals can be retrieved from the Humanoid Robot servos. These signals provide information regarding the actual servos angular position, angular velocity, DC current, temperature and voltage. The angular position, temperature and voltage signals are sampled at 100 Hz, while the angular velocity and load are sampled at a rate 10 times slower. Furthermore, these last two signals, do not present a direct correspondence between encoders and the units of the international system of units (SI).

B. Close loop position control

By default the servos are configured for position control. In fact, all servos have an internal feedback position control loop. This characteristic can be easily confirmed by the simple experiment shown in Figure 2. The servo tries to follow the desired time varying sinusoidal reference position by changing its actual D/C current (load) charge through time, even in the presence of an external torque applied at time instant t=6 sec.

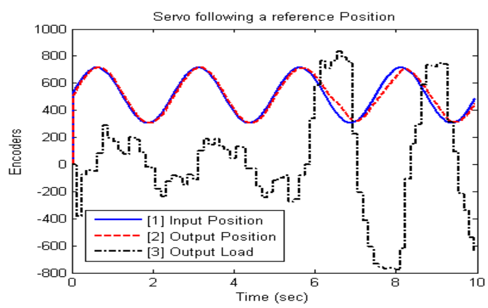


Figure 2: Servo following a position (close loop control)

C. Open loop velocity control

In contrast, experiments suggest that the servos do not have internally any angular velocity feedback control. This can be experimentally confirmed by applying an external torque to the servo while in constant rotating velocity. From

Figure 3 it can be concluded that the current consumption is not able to respond accordingly after the fifth second, when a torque is applied, so the reference angular position cannot be followed.

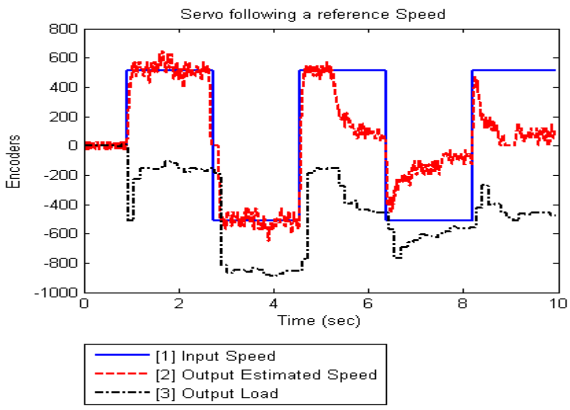


Figure 3: Servo following a reference velocity with open loop velocity control

D. *Stiction*

Stiction is a physical phenomenon that is present in almost any system with moving components. Therefore, its characterization is essential for obtaining an accurate dynamic model of the servos. A simple way to quantify stiction can be made through the following experiment: starting with the servo rotating at a constant speed in one direction, progressively slowing it down until it stops, and then slowly increase its rotating speed in the opposite direction. With this experiment it should be possible to identify the typical dead-zone effect due to stiction. In our case this was clearly quantified to be around 7-10% of the full range in case no load is applied to the servo, as can be seen from Figure 4.

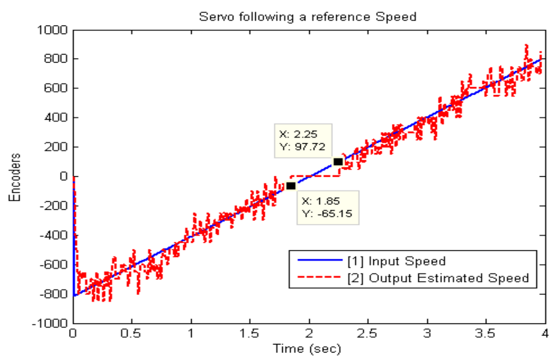


Figure 4: Stiction dead-zone

E. *Voltage supply*

Another parameter with relevance to the behavior of the system is the voltage supplied to the servos. Experiments show that the output estimated velocity error is proportional to the voltage supplied to the servo. In fact, good output velocity estimation is achieved only if the battery is charged around 9.8 V, as can be seen from Figure 5.

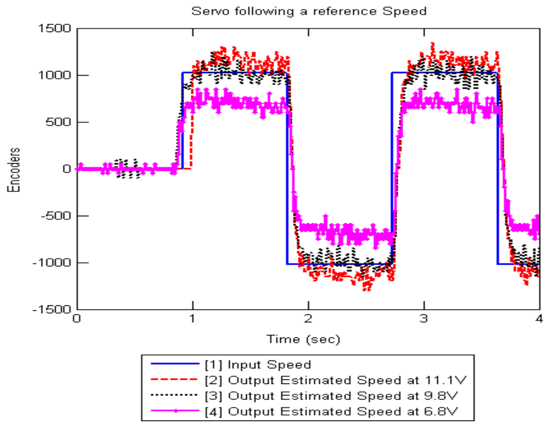


Figure 5: Effects of the supplied voltage to the servos in the outputs velocity response

F. *Temperature*

Temperature was the last parameter to be test in order to check its influence in the behavior of the servos. During the tests, the temperature of the servos were within the interval of 25º to 40º. At these conditions, no visible effect in the response of the servo were seen and therefore the effect of temperature is negligible.

G. *Torque*

Torque is a very important variable when it comes to control a mechanical system. The humanoid controller do not accept torque as an input signal but a desired angular position and a desired angular velocity. When the servo receives the desired speed, it converts into the necessary average voltage consumption. Since current intensity is proportional to the voltage and the torque to the current intensity, therefore, a proportional gain can be deduced from torque and angular velocity input signal. This gain was deduced making a servo lifting a well known mass, for various input angular speed signals (Figure 7). As observed in Figure 7, the relation between the output of the servo and the input angular speed is not linear, due as seen before to the dead zone of the servo. Nevertheless, it was obtained the real relation of Torque-Speed of the linear zones when the nominal voltage is 9.8V.

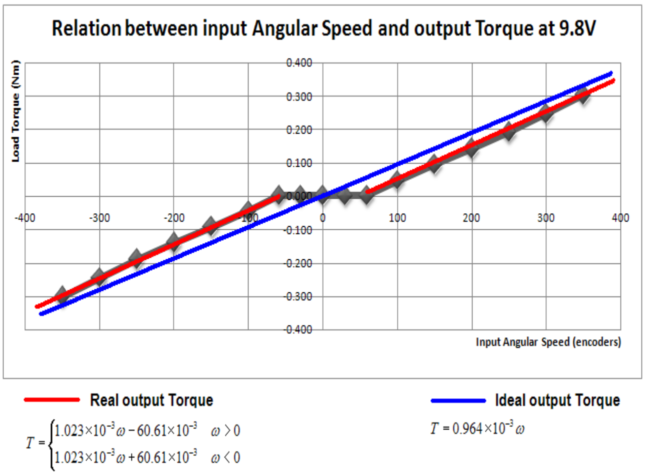


Figure 7: Speed to Torque Relation

H. *Humanoid identification*

In order to capture the static and the dynamic properties of the Humanoid Robot, both the mechanical properties of all its components, such as mass and inertia, as well as its servos dynamic responses, must be known to a certain degree of accuracy. These dynamic properties will be used in Simulink and simMechanics in order to get an accurate simulator for the real Humanoid Robot aiming at a good control strategy.

1) Mechanical properties identification

An accurate static model of the Humanoid Robot can be obtained based on the physical properties of their components. Typically, by knowing the mass, center of mass and the inertia tensor of each element of the humanoid robot it is possible to get a quite reliable model that can be further used in simulation and control. For quantifying the masses of each element, a precision scale with a resolution of 0.05 grams was used. The centroid of each mass was then found by using the SolidWorks® software package, after the detailed elements of all the pieces involved were drawn in this 3D CAD software. It was assumed here that, except for the servos, all the pieces are of isotropic nature. A simple experiment has shown that the maximum error obtained for the geometric position of the centroid is of 0.5 mm on each Cartesian direction. Finally, the inertia tensor of each element was determined through the SolidWorks® software.

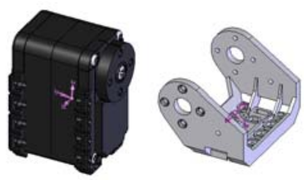


Figure 8: 3D models of a servo and a component of the humanoide robot showing the centroid and the principal axes of the moment of inertia tensor.

2) Dynamic properties identification

For the identification of the dynamic behavior of the servos it was considered the relation between the reference input velocity and the correspondent estimated velocity obtained through the following equation:

$$\hat{\dot{\theta}}(\mathrm{t}) = \frac{\theta(\mathrm{t}) - \theta(\mathrm{t}-1)}{\mathrm{Ts}} \qquad (1)$$

Where

- $\hat{\dot{\theta}}(t)$ is the estimated estimated velocity at time instant t,
- $\theta(t)$ is the angular position at time instant t
- $\theta(t-1)$ is the angular position in the previous time instant
- Ts=0.01 sec. is the sampling period.

The classical prediction error method was used for the identification of the servo dynamic model [1,7], using the identification data shown in Figure 9.

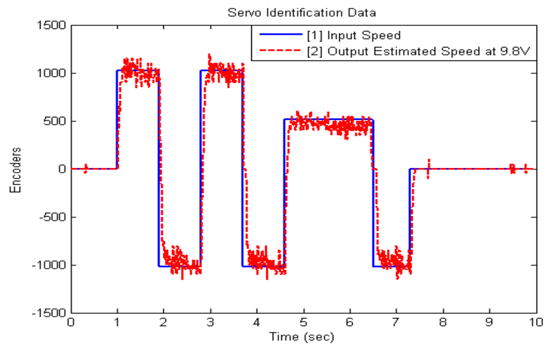


Figure 9: Servo Identification Data

After testing several tentative models with different orders, a Box Jenkins (2,1,2,1) was found to best approximate the desired dynamical behavior of the servo. The BJ model that results in the best data fit is the following:

$$\mathrm{TF} = \frac{0.06217\mathrm{z}}{\mathrm{z}^2 - 1.469\mathrm{z} + 0.5544} \qquad (2)$$

Figure 10 compares the real output of the servo with the one estimated by the BJ model for the validation data. It can be concluded that the dynamic characteristics of the servo are well captured by the BJ model.

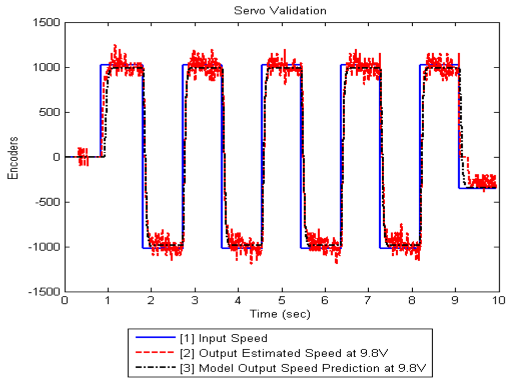


Figure 10: Servo Validation Data

IV. Control and Simulation Results

A. Equations of motion

In order to have the humanoid robot doing the handstand on a high bar, a special configuration of the humanoid robot was studied. In this configuration the humanoid is seen as being compound of three main blocks (arms, torso and legs) with two active joints (shoulder and hips), resembling an underactuated 3-link inverted pendulum (Figure 11). The angular displacement and velocity of the link i (l_i) is represented respectively by q_i and $\dot{q}_i$.

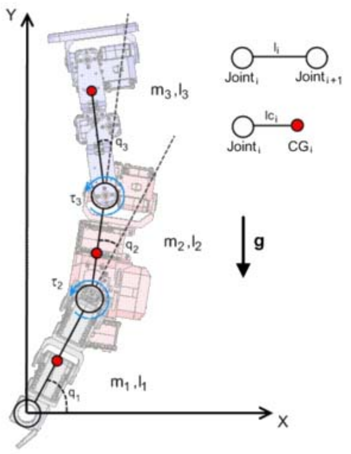


Figure 11: Representation of the humanoid robot seen as an underactuated 3-link inverted pendulum.

	l (mm)	lc (mm)	m (g)	I (gcm^2)
Link 1 (Arms)	143.6	68.7	367.6	7890.7
Link 2 (Torso)	115.8	57.5	981.5	32898.6
Link 3 (Legs)	184.0	116.3	576.4	11328.0

Table 1: Physical properties

The equations of motion for a generic n-link underactuated inverted pendulum can be deduced from the Euler-Lagrange equations [8]. Resolving for n=3, then we obtain the equations of motion for the humanoid robot.

$$\begin{bmatrix} m_{11} & m_{12} & \cdots & m_{1n} \\ m_{21} & m_{22} & \cdots & m_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ m_{n1} & m_{n2} & \cdots & m_{nn} \end{bmatrix} \begin{bmatrix} \ddot{q}_1 \\ \ddot{q}_2 \\ \vdots \\ \ddot{q}_n \end{bmatrix} + \begin{bmatrix} \phi_1 \\ \phi_2 \\ \vdots \\ \phi_n \end{bmatrix} + \begin{bmatrix} h_1 \\ h_2 \\ \vdots \\ h_3 \end{bmatrix} = \begin{bmatrix} \tau_1 \\ \tau_2 \\ \vdots \\ \tau_n \end{bmatrix} \quad (3)$$

With:

$$m_{ij} = \sum_{k=j}^{n} \left\{ m_k \left[\sum_{a=j}^{k} l_a + \sum_{b=i}^{k} \sum_{c=j \wedge j \neq i}^{k} l_b l_c \cos\left(\sum_{d=1}^{|b-c|} q_{d+\min(b,c)} \right) \right] + I_k \right\}, \quad i \le j$$

$$m_{ji} = m_{ij}, \quad i > j$$

$$\phi_i = g \sum_{k=i}^{n} \sum_{a=1}^{k} m_k l_a \cos\left(\sum_{b=1}^{a} q_b \right)$$

$$h_i = C_i + \sum_{j=i}^{n} \dot{m}_{ij},$$

$$C_i = \sum_{k=i}^{n} \sum_{b=i}^{k} \sum_{c=1 \wedge j \neq i}^{k} m_k l_b l_c \left(\sum_{d=1}^{\min(b,c)} \dot{q}_d \right)^2 \sin\left(\sum_{d=1}^{|b-c|} q_{d+\min(b,c)} \right), \quad iff \ \min(b,c) < 1 \quad (4)$$

$$\dot{m}_{ij} = -\sum_{k=i}^{n} \sum_{b=i}^{k} \sum_{c=i \wedge j \neq i}^{k} m_k l_b l_c \left(\sum_{d=1}^{|b-c|} \dot{q}_{d+\min(b,c)} \right) \sin\left(\sum_{d=1}^{|b-c|} q_{d+\min(b,c)} \right), \quad iff \ \min(b,c) \ge 1$$

and

$$l_i = \begin{cases} lc_i & i = k \\ l_i & i \neq k \end{cases}$$

Where:

- m_{ij} are the inertial terms
- ϕ_i are the gravitational terms
- h_i are the Corriolis and the centrifugal terms
- τ_i are the input torques

B. State Space model

The above equations of motion of the system are highly non-linear. Therefore, and in order to use linear control algorithms, the system dynamics is linearized, using a first order Taylor's expansion at the vertical unstable equilibrium, $q=[\pi/2,0,0]^T$ and $\dot{q}=[0,0,0]^T$. Letting the state space vector $x=[q_1 - \pi/2,\ q_2,\ q_3,\ \dot{q}_1,\ \dot{q}_2,\ \dot{q}_3]^T$ and using the values of Table 1, yields:

$$\dot{x} = Ax + Bu \quad (5)$$

Where:

$$A = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 74.2389 & -117.8764 & 0.0028 & 0 & 0 & 0 \\ -81.5857 & 348.7777 & -76.0776 & 0 & 0 & 0 \\ 7.3471 & -230.9113 & 215.8591 & 0 & 0 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ -176.2065 & 97.5517 \\ 527.7831 & -467.2635 \\ -467.2635 & 697.9566 \end{bmatrix}$$

C. *Linear Quadratic Regulator*

By analyzing the zeros and poles of the system, it can be concluded that system is a non-minimum phase one and therefore an optimal or nonlinear control technique is desirable. Hence, a Linear Quadratic Regulator was chosen, since it is a popular stabilization technique which provides a linear state feedback control law for the system. This law has the following form:

$$u = -k^T x \qquad (6)$$

where k is a 6x2 matrix for our system that contains the state feedback gains (Kalman gains) and can be obtained by minimizing the following performance index:

$$J = \int_0^\infty \left(x^T Q x + u^T R u\right) dt \quad (7)$$

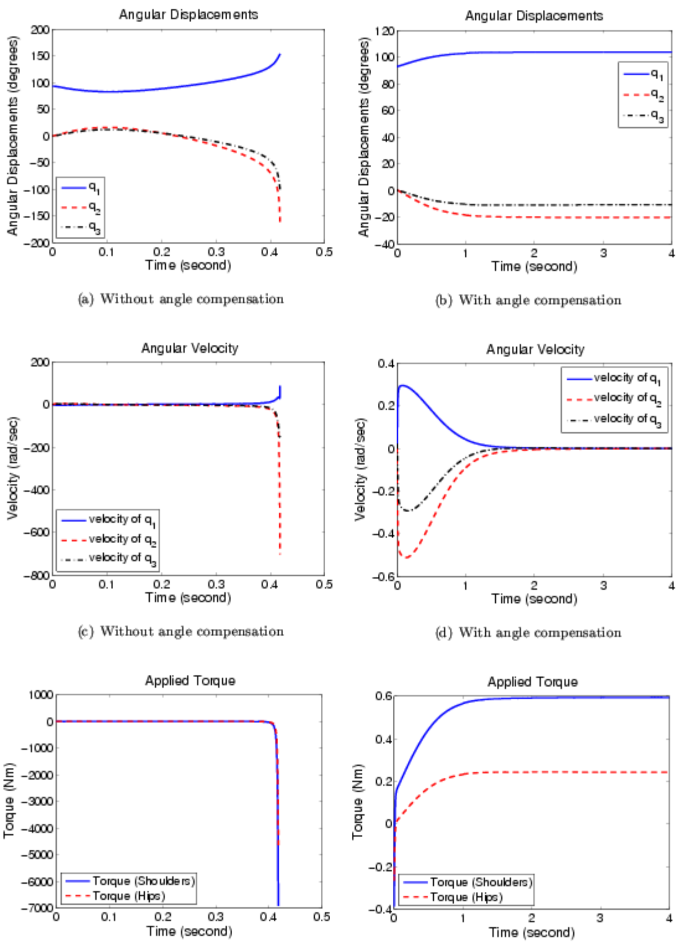
Where Q and R are the "weighting matrices". Q is a 6x6 matrix and R a 2x2 one.

The solution of equation (7) is found by solving to P (Lyapunov function matrix) the Algebraic Riccati Equation (8) and then equation (9). A and B are the A and B matrices of the humanoid state-space model. Then:

$$k^T = \begin{bmatrix} -114.7206 & -63.3382 & -23.2078 & -25.2863 & 11.8534 & -5.0644 \\ 92.6369 & -41.0629 & -13.3245 & -15.8651 & 8.1298 & -2.2096 \end{bmatrix}$$

D. *Results*

The plots shown in Figure 12 (a,c,e) show the behavior of the LQR controlled system when the state vector is defined as $x=[q_1 - \pi/2,\ q_2,\ q_3,\ \dot{q}_1,\ \dot{q}_2,\ \dot{q}_3]^T$. As it can be seen, the system could not be stabilized. The reason is simple, since the effect of the real localization of the centers of gravity of the arms; torso and legs were not taken into account when building the model. Nevertheless, this problem can be solved, by finding and compensating the system with the angle of the resultant center of gravity (plots of Figure 12 (b,d,f) . The system stabilized.



(a) Without angle compensation (b) With angle compensation

(c) Without angle compensation (d) With angle compensation

(e) Without angle compensation (f) With angle compensation

Figure 12: Simulation using Linear Quadratic Regulator for balancing without and with angle compensation

Since the humanoid robot is controlled through the PC, a digital controller needs to be designed. It was used for this case the discrete Linear Quadratic Regulator (DLQR), which formulation is similar to the LQR. The discrete state-space model was obtained by using the emulation method and assuming a zero order hold (ZOH) for the input. The plots of Figure 13 (a,c,e) show the evolution of the system using angle compensation for the three joints and sampled at 0.01s. As it can be seen, the input torques is smaller than in continuous mode and stable. The Q matrix is the identity matrix times 100 and the R matrix is the identity matrix. In the rest of simulations used these parameters.

The plots in Figure 13 (b,d,f) show the behavior of the system when the angular position resolution of a real servo (10 bits resolution for 300 degrees) is used. As it can be seen, the system starts to present some chattering, although the controller stabilizes it.

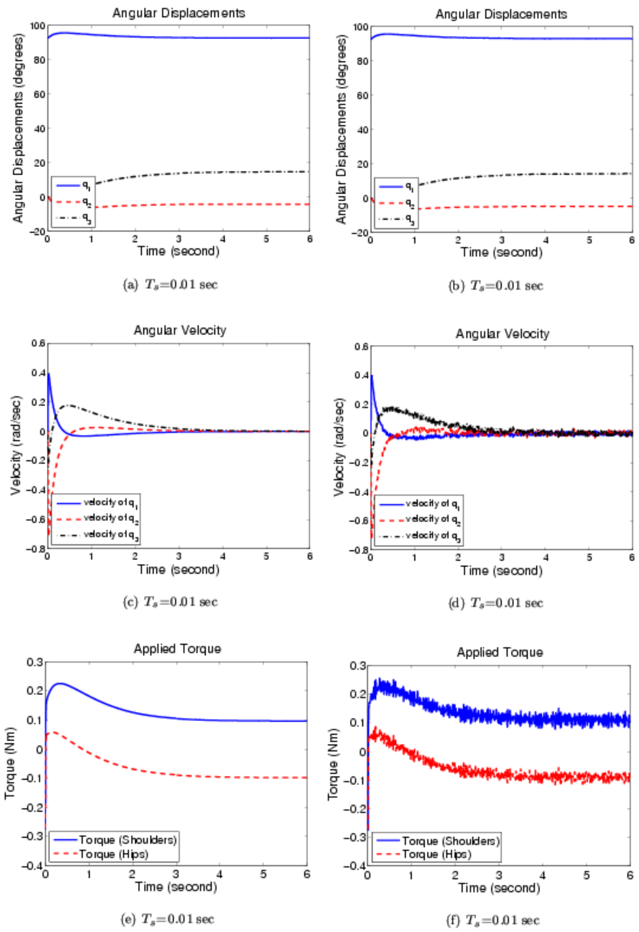


Figure 13: Simulation using angles compensation for the three joint and simulation corrupted by servos position resolution

The problems begin when simulating the gyroscope resolution used in the laboratory for measuring the angular velocity of the arms. Since the resolution of the gyroscope is only 10º/s, the system presents a higher amplitude input control actions in order to compensate the lack of information from the gyro. Nevertheless, the controller is still able to stabilize the system, even with constant perturbations (plots in Figure 14 (a,c,e)).

If the dead zone of the servos for lower velocities (10\% of the full range of 10 bits resolution) are considered, then it can be seen from the plots in Figure 14 (b,d,f) that the system are not able to stabilize. Moreover, the system input torques saturate since the maximum allowable value is 2 Nm.

Concluding, the Linear Quadratic Regulator controller is not able to handle the nonlinearities of the servos. Therefore, other solutions have to be arranged.

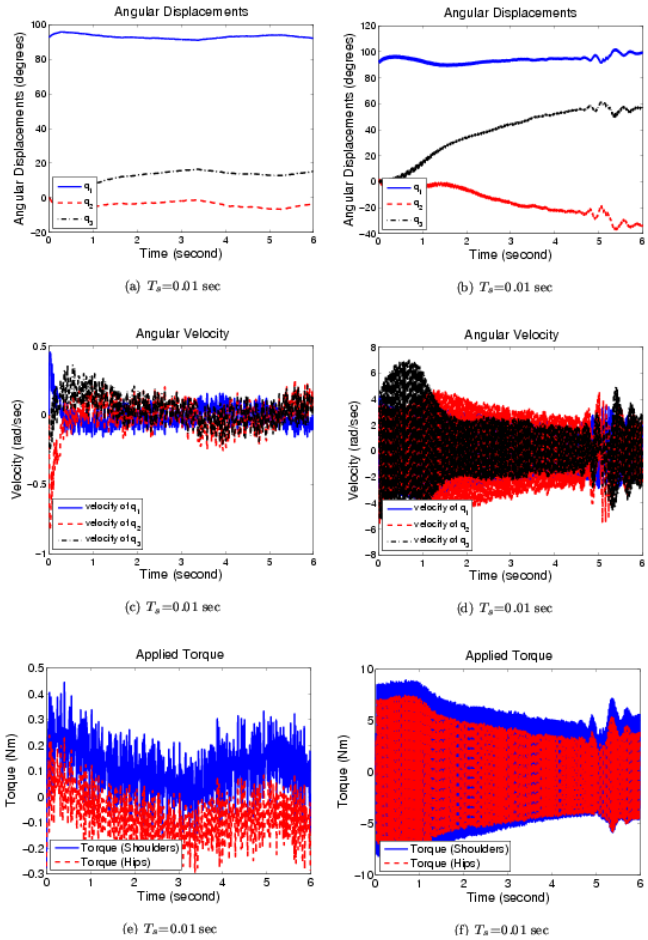


Figure 14: Simulation after adding gyroscope resolution and simulation with dead-zone response of the servos

V. CONCLUSIONS AND FUTURE WORK

This project can be seen responsible for the creation of the strong foundations for future developments in humanoid robots. It is important to note also, that the process of modeling the multi-body structure of a humanoid robot, either for the purpose of doing a handstand on a high bar or for generating a stable walking motion, is a very complex one. One must deal with the formulation and solution of highly nonlinear dynamics equations of a very large size since a standard humanoid robot has typically 18 servos.

During this project, the following topics have been successfully achieved:

- The construction of a serial protocol communication using Matlab/Simulink® Real Time Workshop Toolbox® and a humanoid robot.
- The external physics parameter identification of the humanoid structure, such as the mass, inertia tensor and centers of gravity of its main parts.
- The dynamic analysis and identification of the internal behavior of the servo-actuators.
- The development of a simulator for the humanoid doing a handstand on bar using virtual reality as animation.
- The two sets of the humanoid 3D CAD drawing and its constituents. One set is detailed, resembling the reality pieces for mechanical analysis, while a less detailed one with precise real measurements is used in virtual reality animation.
- The dynamics modeling and simulation using SimMechanics® and Virtual Reality Toolbox® for the equilibrium phase of the humanoid doing a handstand on a high-bar.
- The deduction of the equations of motions for a n-link inverted pendulum and its linearization along the vertical unstable position, and ways to control a n-link inverted pendulum with eccentrics masses using a linear quadratic regulator controller.
- The simulation of a linear quadratic regulator controller for the equilibrium phase of the humanoid doing a handstand on a high bar.

In terms of control and simulation, the humanoid was treated as a three body serial chain in an inverted pendulum configuration. The system is underactuated, being the motion of the legs and torso prescribed in order to stabilize the full body of the humanoid above the high bar. Optimal control methodologies were explored, being the Linear Quadratic Regulator (LQR) adopted in this thesis due to its easy implementation and well-known robustness. This strategy was successfully applied in the stabilization of the humanoid on a high-bar although only in simulation. In fact, the real-time implementation of this controller proved to be unfeasible due to the high nonlinearities present on the servo dynamics, namely their dead-zone. This controller was shown not to be able to handle the nonlinearities present on the servos, and hence a new type of controllers must be developed and tested. The sliding mode control [9,12] is seen at this moment a good alternative since it can handle uncertainty in a robust way.

The dynamics of the humanoid robot used by the controller neglected the servo dynamics, despite their transfer functions have been accurately identified. Therefore these transfer functions should be considered in a future implementation of the controller.

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