International Journal of Applied Engineering Research ISSN 0973-4562 Volume 13, Number 18 (2018) pp. 13584-13588

Emulation of an Animal Limb with Two Degrees of Freedom using HIL

Iván Bautista Gutiérrez, Fabián González Téllez, Dario Amaya H.

Abstract

The Bio-inspired robotic systems have been a focus of great interest in engineering given its versatility and efficiency in many applications, trying to emulate biological organisms that have demonstrated skills in risky environments and performing tasks that would be impossible to do by a human being. This document describes the model process of a simplified version of a animal leg with two degrees of freedom, with the objective of simulate this dynamic on a mechanical structure with the SimMechanics® software.

Keyword: Matlab®, SimMechanics®, pendulum, model.

INTRODUCTION

In the area of robotics and control are frequently found nonlinear systems, especially if it is taken as a reference an existing model in nature [1]. This is because rarely find a completely defined or controlled robot, because although the mechanism is anchored to the ground and has sufficient degrees of freedom to reach any point in space, in the real world always will have restrictions. Some restrictions such as a limited torque in its actuators or movement conditions that change when picking an object of greater dimensions and weight [2].

The implementation of HIL models for simulation of physical devices, is being widely exploited in industry, allowing work with approximate models to reality with the advantage that its cost is considerably lower; so is the prototyping [3]. What supposes an advantage when working with bio-inspired systems as these require several sensors and actuators, that have a significant cost and are in continuous changes by design decisions.

In contrast to industrial manipulators robots, the mobile mechanisms provide greater freedom when faced with unknown environments. This implies developing systems with robust controls that can overcome the different situations, trying to emulate the behavior of living beings [4]. For this reason, the modeling process and simulation before the implementation are essential, because many times and especially as relates to mobile robots, control is performed for specific system behaviors.

To reach a coherent model, the first is start with the basics, as is the behavior of a simple pendulum applied to the system, which is frequently used in this type of mechanisms even when working on complex robots [5].

Today the industry uses specialized research centers in HIL for prototyping and evaluation of projects in the robotics field, centers like DLR Robotics and MobileRobots Inc. These centers are specialized on use HIL techniques to provide solutions in mobile robotics and manipulators; optimizing the control tasks, power consumption and data analysis [6].

This work presents an introduction to the topic, followed by a section of methods and materials where the joint model is developed, continuing with the analysis of results of the operating graphics obtained, finally are presented the conclusions and future prospects.

METHODS AND PROCEDURES

A. *Modeling*

The joint to model has two degrees of freedom anchored to a base, a simplified version of this is illustrated in Figure 1, a system known as double pendulum [7].

The Initial masses position m_1 and m_2 are defined according to the angles θ_1 and θ_2, that are represented as the vector q (Equation 1), this will serve for the energies analysis.

$$\boldsymbol{q} = \begin{bmatrix} \theta_1 \\ \theta_2 \end{bmatrix} \tag{1}$$

$$\begin{aligned} s_1 &= \sin(\theta_1), \\ s_2 &= \sin(\theta_2), \\ c_1 &= \cos(\theta_1), \\ c_2 &= \cos(\theta_2), \\ s_{1+2} &= \sin(\theta_1 + \theta_2), \\ c_{1+2} &= \cos(\theta_1 + \theta_2) \end{aligned} \tag{2}$$

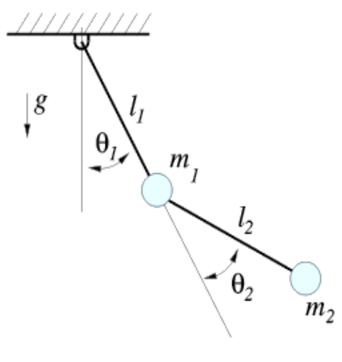

Figure 1. Simplified schematic of the double pendulum.

The positions and velocities for the masses are defined in equations 3 - 6. Being these a vector in a 2D plane, which will be sufficient to represent the behavior of the double pendulum.

$$\boldsymbol{p}_1 = l_1 \begin{bmatrix} s_1 \\ -c_1 \end{bmatrix} \quad (3)$$

$$\boldsymbol{p}_2 = \boldsymbol{p}_1 + l_2 \begin{bmatrix} s_{1+2} \\ -c_{1+2} \end{bmatrix} \quad (4)$$

$$\dot{\boldsymbol{p}}_1 = l_1 \dot{\boldsymbol{q}}_1 \begin{bmatrix} c_1 \\ s_1 \end{bmatrix} \quad (5)$$

$$\dot{\boldsymbol{p}}_2 = \dot{\boldsymbol{p}}_1 + l_2(\dot{\boldsymbol{q}}_1 + \dot{\boldsymbol{q}}_2) \begin{bmatrix} c_{1+2} \\ s_{1+2} \end{bmatrix} \quad (6)$$

With the above vector is possible to define the kinetic and potential energies, as shown in equations 7 and 8

$$T = \frac{1}{2} m_1 \dot{\boldsymbol{p}}_1^T \dot{\boldsymbol{p}}_1 + \frac{1}{2} m_2 \dot{\boldsymbol{p}}_2^T \dot{\boldsymbol{p}}_2$$

$$T = \frac{1}{2}(m_1 + m_2) l_1^2 \dot{\boldsymbol{q}}_1^2 + \frac{1}{2} m_2 l_2^2 (\dot{\boldsymbol{q}}_1 + \dot{\boldsymbol{q}}_2)^2 + m_2 l_1 l_2 \dot{\boldsymbol{q}}_1 * (\dot{\boldsymbol{q}}_1 + \dot{\boldsymbol{q}}_2) c_2 \quad (7)$$

$$U = m_1 g\, y_1 + m_2 g\, y_2$$

$$U = -(m_1 + m_2) g l_1 c_1 - m_2 g l_2 c_{1+2} \quad (8)$$

Taking the partial derivatives of (7) and (8) with respect to the vector q, which represent the Lagrangian, the equations of motion (9, 10) are obtained. Where τ_1 and τ_2 represent a torque input, for this case will be unit value, because the control system has not yet defined.

$$(m_1 + m_2) l_1^2 \ddot{\boldsymbol{q}}_1 + m_2\, l_2^2 (\ddot{\boldsymbol{q}}_1 + \ddot{\boldsymbol{q}}_2) + m_2 l_1 l_2 (2\ddot{\boldsymbol{q}}_1 + \ddot{\boldsymbol{q}}_2) c_2 - m_2 l_1 l_2 * (2\dot{\boldsymbol{q}}_1 + \dot{\boldsymbol{q}}_2) \dot{\boldsymbol{q}}_2 s_2 + (m_1 + m_2) g l_1 s_1 + m_2 g l_2 s_{1+2} = \tau_1 \quad (9)$$

$$m_2\, l_2^2 (\ddot{\boldsymbol{q}}_1 + \ddot{\boldsymbol{q}}_2) + m_2 l_1 l_2 \ddot{\boldsymbol{q}}_1 c_2 + m_2 l_1 l_2 \dot{\boldsymbol{q}}_1^2 s_2 + m_2 g l_2 s_{1+2} = \tau_2 \quad (10)$$

The equations (9) and (10) describe the behavior of the system, a matrix representation, based on the equations 11 and 12 will facilitate its implementation in an embedded system, to emulate this dynamic, under the concept of HIL.

$$\boldsymbol{u} = \begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix} \quad (11)$$

$$\mathbf{H}(\mathrm{q})\ddot{\mathrm{q}} + \mathbf{C}(\mathrm{q}, \dot{\mathrm{q}})\dot{\mathrm{q}} + \mathbf{G}(\mathrm{q}) = \mathbf{B}(\mathrm{q})\mathrm{u} \quad (12)$$

Equation (12) shows the variables in state space that are extracted from the Lagrangian, the terms are represented by H as the inertial matrix, C contains the Coriolis forces, G is defined as the matrix of potential energies and B is filled with the control u.

$$\mathbf{H}(q) = l_1 \begin{bmatrix} (m_1 + m_2) l_1^2 + m_2\, l_2^2 + 2 m_2 l_1 l_2 c_2 & m_2\, l_2^2 + m_2 l_1 l_2 c_2 \\ m_2\, l_2^2 + m_2 l_1 l_2 c_2 & m_2\, l_2^2 \end{bmatrix} \quad (13)$$

$$\boldsymbol{C}(q, \dot{q}) = \begin{bmatrix} 0 & -m_2 l_1 l_2 * (2\dot{\boldsymbol{q}}_1 + \dot{\boldsymbol{q}}_2) s_2 \\ m_2 l_1 l_2 \dot{q}_1 s_2 & 0 \end{bmatrix} \quad (14)$$

$$\mathbf{G}(q) = g \begin{bmatrix} (m_1 + m_2) g l_1 s_1 + m_2 g l_2 s_{1+2} \\ m_2 g l_2 s_{1+2} \end{bmatrix} \quad (15)$$

$$\mathbf{B}(q) = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \quad (16)$$

B. *Simulation*

Once the dynamics of system behavior, we proceed to make a first simulation. The simulation was performed with the help of Drake library [8] for Matlab®, This tool allows describe the system in the same manner of the equation 12 and run a quick simulation for the developed manipulator.

Tables 1 and 2 contain the values with which the system simulation was performed, the biggest difference is the friction constant, this value will allow the stabilization of the system at the angle 0 for both cases without control loop.

Table 1. Frictionless

Parameter	Value
m_1	1kg
m_2	1kg
l_1	1m
l_2	1m
b_1	0
b_2	0
g	$9.8 \mathrm{m/s^2}$

International Journal of Applied Engineering Research ISSN 0973-4562 Volume 13, Number 18 (2018) pp. 13584-13588

Table 2. With high friction

Parameter	**Value**
m_1	1kg
m_2	1kg
l_1	1m
l_2	1m
b_1	8
b_2	8
g	$9.8 m/s^2$

In Figure 2 the behavior of the system is illustrated, with initial a value of 0.7 rad for $\theta_1$and θ_2, responding only to gravity, in a time of 10 seconds.

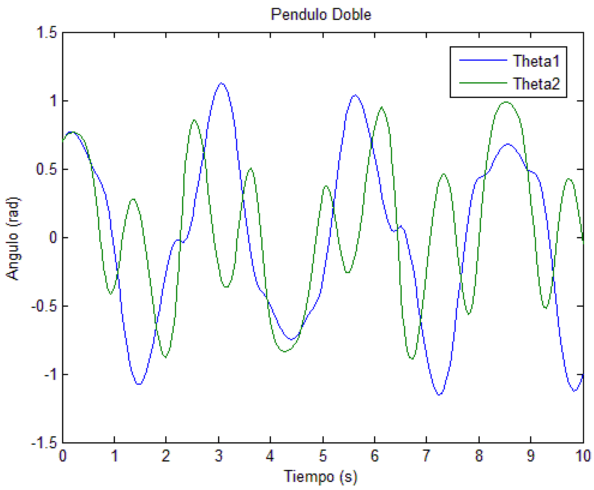

Figure 2. System behavior versus gravity.

Since are expected in an actual implementation, motors with a high coefficient of friction when not powered, an analysis with the table 2 parameters was performed. It demonstrated that the system behavior is slower but stabilizes at 0 degrees by action of gravity, as shown in Figure 3.

C. *PD Control*

The system developed has an actuator for each degree of freedom, for the above is possible to perform a proportional-differential control for the angle. If the system only had one actuator or was not anchored to the ground it would be different. For these closest cases to biological models are required more complex control techniques [1].

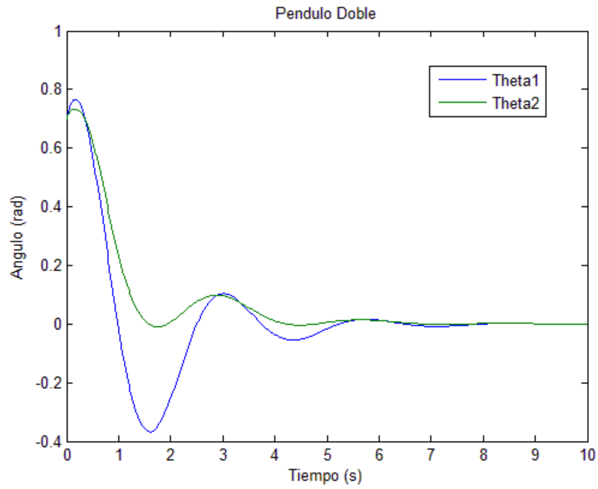

Figure 3. System behavior with high friction.

The control loop is closed as observed in Figure 4. Where K corresponds to Kp and Kd constants of the equation 17 and 18.

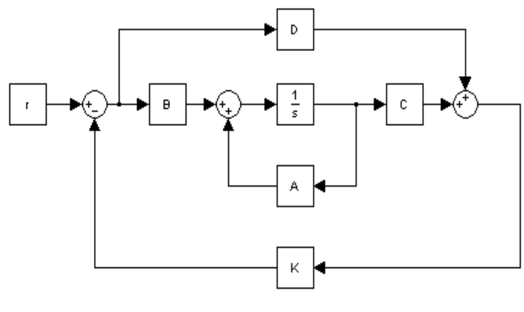

Figure 4. Control Loop in state space. Public domain image taken from Wikipedia.org

$$\boldsymbol{K_p} = \begin{bmatrix} 108.22 & 0 \\ 0 & 82.3 \end{bmatrix} \qquad (17)$$

$$\boldsymbol{K_d} = \begin{bmatrix} 6.89 & 0 \\ 0 & 10 \end{bmatrix} \qquad (18)$$

The control result is illustrated in Figure 5. For the simulation was specified to an angle 0 the set point for mass 1, while the mass 2 is moved according to the function sin (t / 2).

D. *Mechanical Structure*

The manipulator design was performed in SolidWorks® that allows export the assemblies to Matlab® using the SimMechanics extension. This was done in order to observe the behavior of the system in a more realistic environment and for future work can be use it as an interface that allow testing and visualization of control systems designed.

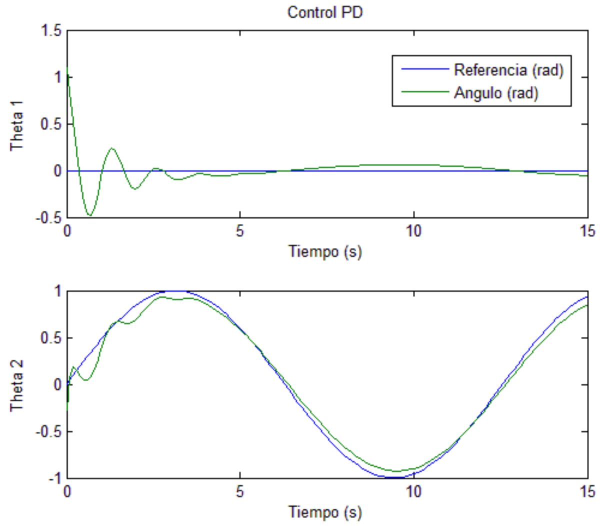

Figure 5. Response PD control

The SimMechanics tool generates a diagram file compatible with Simulink blocks in this way can be used all the tools of Matlab® package on the mechanical structure. The resulting blocks can be seen in the figure 6.

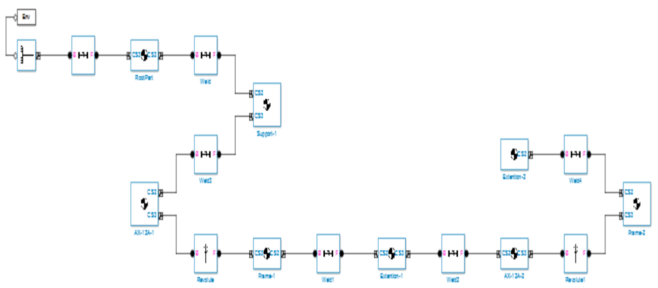

Figure 6. SimMechanics model

RESULTS

Through simulation, it is evident that the model obtained is consistent with real systems and is observed as friction affects the system bringing it to a point of reference. The model is shown in figure 7.

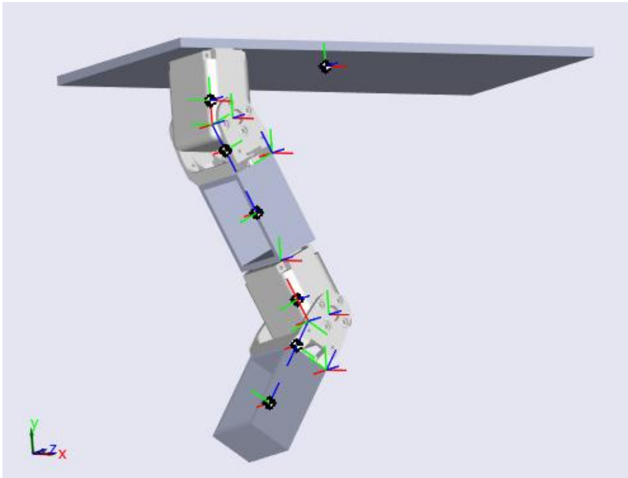

Figure 7. Mechanical structure to simulate.

It is expected that the model obtained will be useful in the design of controllers for any robotics joint or bio-inspired systems that emulate animal movements.

In Figure 8 are observed the system behavior emulated signals response, Up θ_2 and down θ_1 . It is possible compare these signals with the simulation result of Figure 3, which represents the response of the system in open loop.

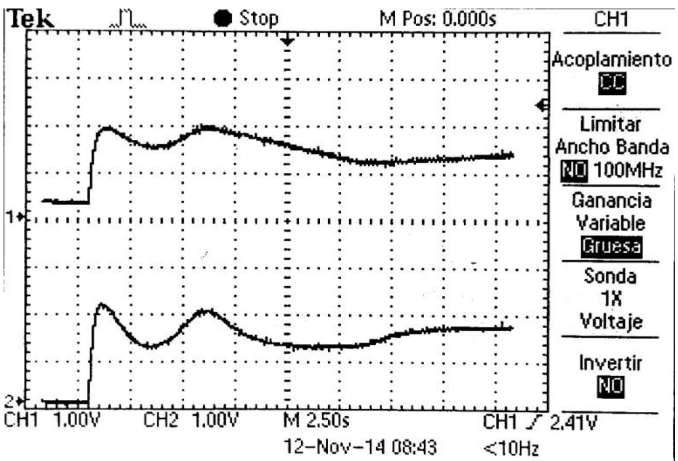

Figure 8. Signals result of emulation on pcDuino and Teensy 3.1

For the response is implemented a PWM module in the embedded card, with a scale of 0 to 3.3V

CONCLUSIONS

In robotic the behavior of simple pendulum is used to develop many systems, as manipulators or steps robots. Understanding this model, is possible to make close approaches to more complex systems as the pendulum, that are characterized by nonlinearity.

Depending on the complexity of the model and the simulation time, it may be necessary to use external libraries that allow calculations more efficiently, MatLab® is a tool that is known for being versatile to do calculations and implementations of algorithms optimization using specialized extensions.

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