Comparison between Classic Control Systems Techniques against Adaptive and Nonlinear Control Techniques in a Lower Limb Prostheses

Fermin C. Aragon, Joel C. Huegel, Adriana Vargas-Martinez, Jorge de J. Lozoya-Santos, Ricardo Ramirez-Mendoza and Ruben Morales-Menendez
School of Engineering and Science
Tecnologico de Monterrey, Monterrey, Mexico
e-mail: a0825397@itesm.mx, {jhuegel, adriana.vargas.mtz, jorge.lozoya, ricardo.ramirez, rmm}@tec.mx
Corresponding author: jhuegel@tec.mx

Abstract—**Foot prosthesis have been well documented, not one has successfully developed and verified that such a prosthesis can improve amputee gait compared to a conventional passive A Previous Work elastic prosthesis. One of the main hurdles that hinder such a development is the challenge of building an ankle- foot prosthesis that matches the size and weight of the intact ankle, but still provides a sufficiently large instantaneous power output and torque to propel an amputee [1-2]. A large number of motorized prototypes have been developed in prosthetic systems, the actuators, sensors and architectures developed have improved the performance of these for human walking in users who have this motor impairment, however the surgical technique used for amputation as well as the control techniques implemented have not had notable progress.**

This paper presents the design and simulation of the control system for a lower limb prostheses. Three control methods were compared (PD Classic Controller, Model Reference Adaptative Control (MRAC), and sliding mode control) and the behavior of the model was studied after its linearization and its identification through the matlab toolbox.

Keywords-control systems; Lower limb Prosthetic control; MRAC control; Slidingmode control; Adaptive control; Nonlinear systems

I. Introduction

The development of prosthetic elements has been a solution for users who suffer some type of amputation, its origins go back to Egyptian times and had a great evolution after the American Civil War. Passive, active and motorized prosthetic elements have been developed, consisting of mechanical, electrical and electronic elements that seek to mimic the behavior of the missing limb in users. The development of prostheses with embedded systems has existed since the 1980s [3]. Since then, classic control techniques have been widely used to stabilize the movement of actuators that can be linear or rotational. In 2010 J. Martin classified the microprocessor-controlled systems as Computationally Intrinsic Control and extrinsic interactive control [3].

The computationally intrinsic control (CIC) is that where the communication between the brain and the prostate system does not exist. The process of acquisition of input signals is simplified with implicit computational algorithms in the embedded system, the control techniques and feedback are performed within the embedded system algorithm, this response is sent to the performance systems to generate the desired movement.

Some computationally intrinsic control methods are:

- Muscle reflex control
- Finite state machine (FSM) impedance control
- Phase plane control
- Echo control
- Complementary Limb Motion Estimation (CLME)

Interactive extrinsic control (IEC) is the one where the user has communication from their nerve terminal with the robotic prostate system, the feedback of the system is performed with the embedded system, but the input signals are obtained using electromyographic sensors located in strategic areas of the prostatic stump.

Some Interactive extrinsec control methods are:

- Control based on residual joints,segments or organs
- EMG based control
- s'EMG based control
- NeuroMuscular mechanical fusion
- AMI signal Control

Geyer, Herr, Holgate and other experts of the subject have developed prosthesis prototypes based on these control methods. Within the existing literature, a large number of combinations of these techniques have been used with the control of classic control methods, however it is It is possible to implement more robust control techniques in conjunction with traditional techniques in embedded systems so that the system can respond better to the robustness of the non-linearity of the bipedaled march [4-9].

An article published in the IEEE was used as a reference on an already studied prostheses from which the parameters of the model were obtained to perform the simulations and the mathematical model. The analyzes were performed using matlab and simulink to carry out these tests and 3 experimental models were built, the first is the plant using a PID controller, the other 2 systems are based on adaptive control models (MRAC) and nonlinear control (sliding mode), the matlab function identification tool was used and the function of transfer to perform tests on the system. Fig.

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1 shows the freebody diagram for the lower limb prostheses and Table I shows the physical parameters.

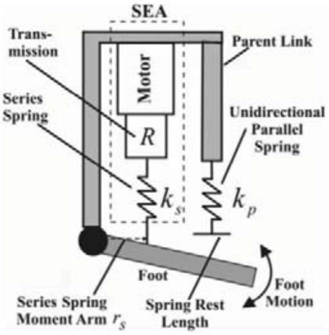

Figure 1. Prostheses Free Body diagram [1]

Table 1 Prostheses parameters

Parameter	***Fsat***	***Vsat***	***Me***	***Be***	***Ks***
Values	7654 N	0.23 m/s	170 kg	8250 Ns/m	1200 KN/m

Table I Shows the simulation parameters based on physic characteristics of the model where *Fsat* and *Vs*at are the maximum output force and maximun linear velocity of the motor respectively, *Ks* and *Be* represents the damper and spring coeficients, *Me* is the effective mass in the model.

Equation 1 shows the transfer function that describes the mechanical system behavior shown in Fig. 1. Equation 2 and 3 show the general form of the model using state variables, while Equations 4 and 5 shows the state space matrix based on the parameters of Table 1 in a symbolic way.

$$\frac{Fsatmax}{Fsat} = \frac{Ke}{Mes + \left(Be + \frac{Fsat}{Vsat}\right)s + Ke} \tag{1}$$

$$\dot{X} = Ax + Bu \tag{2}$$

$$Y = Cx + Du \tag{3}$$

$$\dot{X} = \begin{bmatrix} -\frac{B_e + \frac{F_{sat}}{V_{sat}}}{M_e} & -\frac{K_s}{M_e} \\ 1 & 0 \end{bmatrix} x + \begin{bmatrix} 1 \\ 0 \end{bmatrix} u \tag{4}$$

$$Y = \begin{bmatrix} 0 & \frac{K_s}{M_e} \end{bmatrix} x + [0]u \tag{5}$$

II. Control System Simulation

A linearized model was used, using the matlab toolbox, an open-loop model was constructed to obtain the ideal parameters for the response of the system, Figure 2 shows the generalized block diagram constructed by means of simulink.

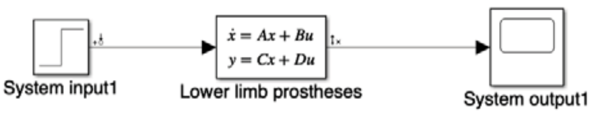

Figure 2. Open loop system block diagram

A. Stability Analysis

The concept of stability in the control systems is of great importance due to the response of the systems when they are modeled correctly. The stability of a system can be local or global and finding any of these possible answers allows to predict the behavior of the system in real time.

For the case study, Lyapunov's direct method was used to check the stability of the system. Equation 6 is the solution for the system of equations by means of the direct method of Lyapunov [10].

$$A^T P + PA = -Q \tag{6}$$

Matlab was used for the numerical solution of the problem, considering the system parameters and Q as an identity matrix with the same dimension of A, the *LYAP* command will provide us with the solution of the system of equations in terms of Lyapunov and using the function *eig* of this result will be obtained the proper values, the sign of these will tell us if the system is stable.

$$L = \begin{bmatrix} 14.45 & -0.5 \\ -0.5 & 0.0194 \end{bmatrix} \tag{7}$$

$$E = \begin{bmatrix} 0.0020 \\ 14.46 \end{bmatrix} \tag{8}$$

Equation 7 shows the resultant matrix of the *Lyap* command while equation 8 eigen values of it (system eigenvalues), both values are positive, which is why the system is considered to be global and asymptotically stable (G.A.S).

B. PD Controller System

In the existing literature are recorded various techniques of control and acquisition of myoelectric signals that are used to stimulate the implicit actuators in the motorized prosthesis. They are classified as intrinsic computer control (CIC) and interactive intrinsic control (IEC), the former requires bioinspired computational algorithms that generate signals similar to human ones, the second receives signals directly by means of EMG or sEMG sensors or neuromuscular models (the latter is a combination of both techniques) [4].

From the model of the generated state space, a block diagram was constructed, which is shown in Figure 2, with the system in open loop, the system generated with the system identification tool and the linearized model in conjunction with a PD (Proportional derivative) controller tuned using the simulation tool of Simulink. The Figure 3 shows linearized control system in close loop with a PID controller and the Figure 4 shows the system behavior with an arbitrary time of 100 seconds.

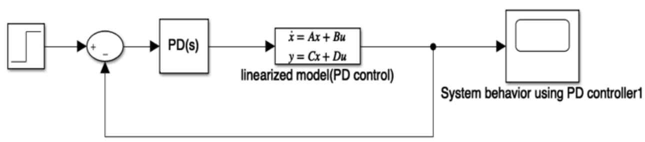

Figure 3. PD control system block diagram in close loop

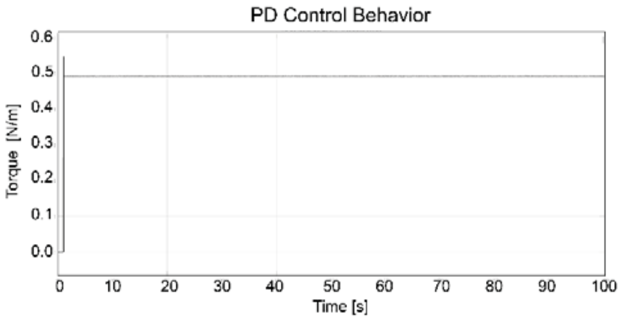

Figure 4. PD control system behavior in close loop

C. *Model Reference Adaptive Controller*

A control system is a device that regulates or controls the dynamics of any other plant or process. Adaptive control is one of the widely used control strategies to design advanced control systems for better performance and accuracy. Model Reference Adaptive Control (MRAC) is a direct adaptive strategy with some adjustable controller parameters and an adjusting mechanism to adjust them. As compared to the well- known and simple structured fixed gain PID controllers, adaptive controllers are very effective to handle the unknown parameter variations and environmental changes.

An adaptive controller consists of two loops, an outer loop or normal feedback loop and an inner loop or parameter adjustment loop [11].

Model Reference Adaptive Control strategy is used to design the adaptive controller that works on the principle of adjusting the controller parameters so that the output of the actual plant tracks the output of a reference model having the same reference input [11]. The generalized block diagram for this work is shown in Fig. 5 and the block diagram implemented for the case studies is shown in Fig. 6.

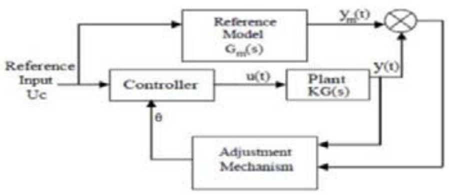

Figure 5. Model Reference adaptive controller generalized [10]

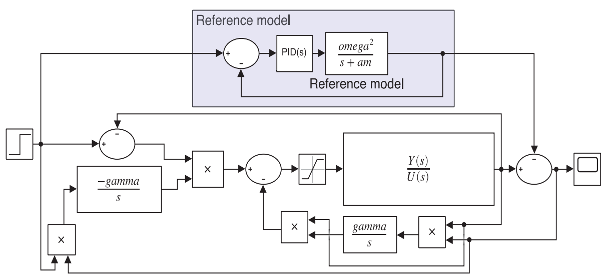

Figure 6. MRAC controller block diagram

For the simulation of the MRAC controller, a desired time of 100 seconds was used, a value of z with an overshoot of 15%, and a learning factor of 0.75 (for real systems the learning factor must be less than 1, to calculate the value of z with a MP desired the equation 9 was used.

$$z = \xi = \sqrt{\frac{(\frac{LnMp}{\pi})^2}{1 + (\frac{LnMp}{\pi})^2}} \tag{9}$$

Fig. 7 shows the system behavior with an MRAC controller implemented with and arbitrary time of 100 seconds.

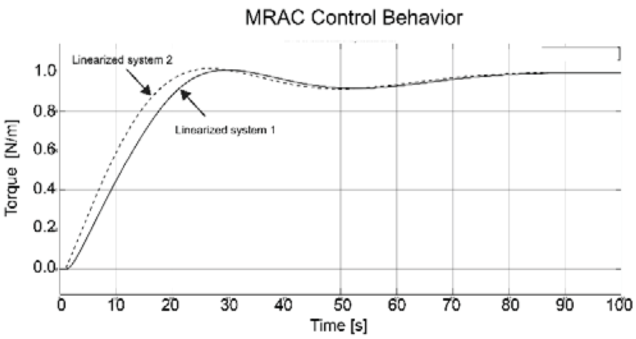

Figure 7. MRAC controller behavior

Fig. 7 shows the behavior on the MRAC behavior simulated by Simulink the black line represents the reference model like an ideal behavior in the system and the dotted line is the plant (the real system) it seems the stabilization rate and the similarities in the behavior, the MRAC is an adaptive control technique useful in supervisory systems and could be useful in biomimetic systems if the biological parameters are estimated correctly.

D. *Sliding Mode Control*

Sliding mode control (SMC) is a nonlinear control technique featuring remarkable properties of accuracy, robustness, and easy tuning and implementation. There are two main advantages of sliding mode control. First is that the dynamic behavior of the system may be tailored by the particular choice of the sliding function. Secondly, the closed loop response becomes totally insensitive to some particular uncertainties. This principle extends to model parameter uncertainties, disturbance and nonlinearity that are bounded. From a practical point of view SMC allows for controlling nonlinear processes subject to external disturbances and heavy model uncertainties. Figure 8 shows the sliding mode control block diagram used for the simulation, all the parameters have been specified in a matlab script in the state space matrix block.

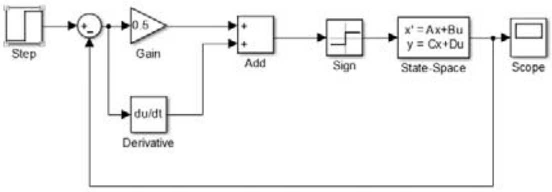

Figure 8. SMC block diagram

Fig. 9 shows the behavior of the sliding mode control in the system, In contrast to conventional systems the sliding mode control uses a switch (ON / OFF) with which it reaches stability.

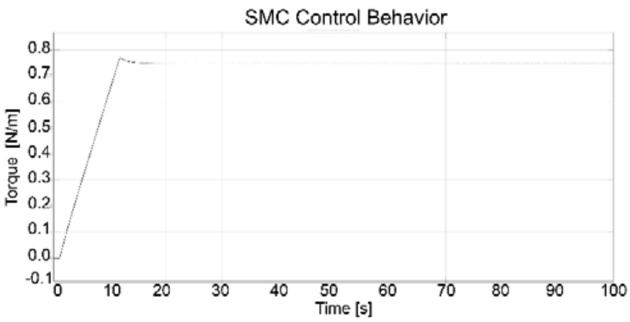

Figure 9. SMC behavior

In Fig. 9 a zoom was made to the graph to observe the state switching until reaching the stability of the system.

III. Conclusions and Future Work

The implementation of adaptive or nonlinear control systems in physical systems can provide a stabilization in them compared to traditional methods of control (P, PD, PID), however the scope of these systems allow that in conjunction with traditional methods you can control the non-linear parameters of the system, having a combination of robustness and speed of adaptation, all this is possible as long as the parameters and equations are properly bounded. It is expected that from this research tangible implementation will arise in real models of their own or in collaboration with other institutions or authors.

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