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Teleoperation of a 6 DOF Anthropomorphic Manipulator: Test of Different Joint Control Techniques

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Abstract

This paper evaluates different joint control strategies' performance for controlling electric actuators' angular position of a 6 DOF anthropomorphic manipulator. The set point or input of the system is the motion data captured by an upper limb exosuit, which send wirelessly the information (teleoperation) to the robotic arm actuators or outputs. The carried out experiments demonstrated that plant cancellation method as a derivation of dead-beat control technique is a proper strategy to control angular position of DC motors as an alternative to traditional PID controllers. This work includes, plant estimation, control algorithms design and comparison, experimental validation of developed algorithms on the real and virtual system throughout the toolbox SimMechanics from Matlab.

Keywords: Joint control, plant cancelation technique, dead-beat controller, teleoperation, anthropomorphic robotic arm, upper limb exosuit.

INTRODUCTION

Most of mechatronic systems, including the present case of study (robotic arm tele operated) require ways to guarantee their proper function according to desired conditions without (at least as much as possible) the supervision of a human operator, this is the main aim of automation, which based its performance in control loops that force systems to behave depending on specific parameters determined by the user and some inherent properties of the mechanisms [1].

Therefore, the research of controllers that grant monitored functionality and precision to mechatronic systems is a task that is still carried out today [2], searching every time for more powerful techniques that provide superior accuracy, robustness to treat external disturbances, adaptability and simplicity to bring the possibility of implementing them for different plants under distinct conditions [3].

Some examples of systems where controllers may be used are DC motors (current case) [4], [5], cauldrons [6], cooling systems [7], industrial tanks, hydraulic cylinders [8], and most common control variables are speed, position (current case), temperature, flow rate, voltage, among others.

Controllers or control techniques can be compared not only by evaluating the fulfillment of desired parameters, but also according to their feasibility of being implemented on real conditions and taking into account the plant output signals, since, despite the fact two different controllers been able to satisfy the proposed requirements/desired conditions [9], it does not suggest they are equally adequate to the plant, it is because for instance, one of them can offer smoother output curve or require a minor quantity of samples to reach the reference (the ideal behavior expected from the plant), these aspects could convert a specific controller in a better option to be applied to certain system [10].

At industrial level, the PID (Proportional Integrative Derivative) controller is one of the most spread techniques in automation due to its relatively simple implementation [11]. However, although the controller is functional and it has a good performance, it does not guarantee an optimum plant control or system's stability [12], as a consequence of its *tuning* requirement in which each parameters' gain from PID must be computed with respect to the others in order to get a balanced control output [13]. Many researchers have been developing methods to optimize this control technique, having success for particular cases, nevertheless, it gets complicated to obtain generalized solutions due to the divergent nature of the systems to be controlled [14] [15].

On the other hand, plant cancellation technique bases its principle on dead-beat controller [16] [17], reason why it does not require to find a number of optimal parameters to control a system, instead it just needs to compute a transfer function that suppresses the dynamic of the plant and includes the dynamic of the desired response (for instance, the output of a generic first order's system), which forces the system to follow the behavior of the last one. The most significant advantages of this method is the response of the controlled plant won't depend of the order of itself avoiding in certain part possible overshoots or instabilities on the system's output signal since the original dynamic of the plant is not virtually present [18].

The present work is motivated by real-time master-slave systems existing in robotics, commonly used to operate electromechanic limbs, remotely [19], as the exposed case in Fig. 1, which requires the robotic manipulator to replicate with accuracy and in a short period of time the movements (angular positions of the joints that form the kinematic structure) coming from human operator's upper extremity, looking simultaneously smoothness on the actuators output signal.

The document is organized as follows: Section 2 has a detailed description of the proposed controllers. Performed experiments that validate the concepts and verify the methods are presented in section 3 with results explained in section 4. Possible improvements and comparisons of these control techniques are dealt with in section 5, discussion.

MATERIALS AND METHODS

In order to control any system it is necessary to identify the dynamic of the plant (system), in simple terms, characterize the plant's response against a known input, which can be mathematical represented as a transfer function [20].
Since exist systems that are common on industrial or laboratory environments, some transfer functions' generic structures have been created with the purpose of synthetizing the general dynamic behavior of those mechanisms, this is the case of DC motors, whose dynamics is normally approximated to first or second order equations [21]. Most of the time, first order expression is enough good to test control techniques.

There are many methods to obtain the real transfer function of a DC motor, for this study the toolbox ident of Matlab was selected, the process consists in using a data acquisition unit or a digital oscilloscope to register the values corresponding to input and output of the plant on the time while the DC motor was powered with a step voltage signal (input) and a sensor attached to motor's shaft measured the angular velocity generated in terms of a proportional voltage (output). Afterwards, the data collected was entered in Matlab's toolbox, which computed a transfer function for the system with a high level of adjustment respect to the given information. The graphical results gotten by ident are portrayed in Fig. 2, and the estimated transfer function that represents the studied actuators (DC motors) is shown in Eq. (1).

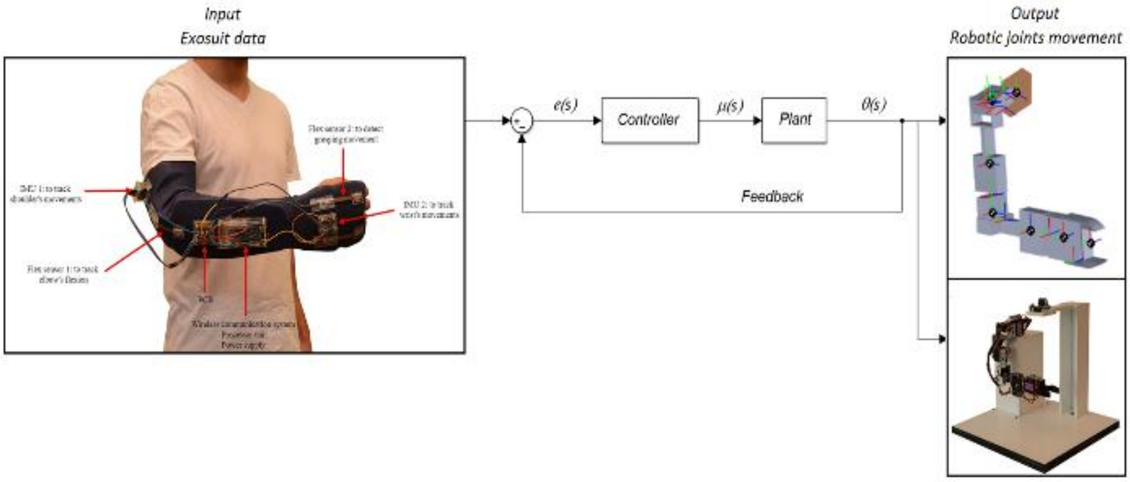


Figure 1. General architecture of the control system, where input or reference is the data acquired from the upper limb exosuit, which estimates arm's joints angular displacements, this information is sending wirelessly to the controller, whose output is the equivalent signal to make DC motors spin the required angular position, moving the robotic arm structure (simulated and real) and closing the teleoperation loop.

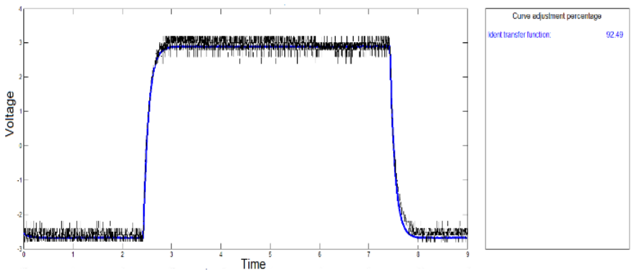


Figure 2. DC motor response in open loop. Black curve represents the real values gotten from the plant, registered with digital oscilloscope and blue curve represents the response obtained from the ident's estimated transfer function.

$$Gp(s) = \frac{5,512}{s + 9,87} \quad (1)$$

Above expression relates an input of voltage to an output in terms of angular velocity. Nevertheless, the current work requires as output's variable the angular position, which can be easily gotten by integrating the response of the system or seen from other perspective by multiplying the transfer function by $\frac{1}{s}$ Eq. (2).

$$Gp(s) = \frac{5,512}{s^2 + 9,87s} \quad (2)$$

Based on plant (DC motor) mathematical expression, controllers can be designed with the aim of forcing system's dynamics to performance according to desired parameters, settling time (t_s) and signal overshoot percentage M_p or $X_i(\xi)$, in the current case, values selected were $t_s = 0{,}4s$ and $M_p = 1\% \rightarrow \xi = 0{,}95$. These parameters look to obtain a smooth signal that reaches the reference or input in a period of time slightly shorter than the natural response of DC motors.

Different controllers following the general architecture presented in Fig. 3 and the desired parameters stablished above were tested to evaluate their properties to control the actuators (DC motors) of the robotic arm in the most proper way (smoothly and robustly).

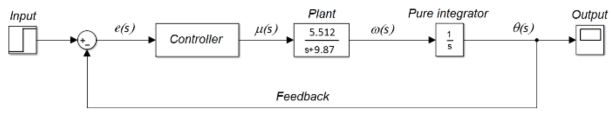


Figure 3. General control architecture for the DC motor system.

PID controller (continuous and discrete)

As it was mentioned before, PID controllers represent the most common control methodology implemented in real applications. PIDs are the merge of three different basic control actions proportional K_p, searches to reach the reference; integrative K_i, suppresses stationary error generated by proportional action and derivative gain K_d, reduces oscillations generated by integrative action [22], the addition of these principles provide a good performance in system's dynamics manipulation [3].

The functionality of both, discrete and continuous PID is basically the same, the difference lies in the mathematical representation, as is shown in table 1.Continuous PID is composed by analog electronic devices. Hence, it works on real time (delays are virtually nonexistent), but it is limited for the commercial values of the elements (resistances, capacitors, op-amp, etc.), thus, in many cases is not possible to exactly build the calculated circuits that represent the controller, which can generate discrepancies with respect to the expected behavior of the plant controlled with it.

Otherwise, discrete PID uses digital electronic, this is why there are not limitations in terms of parameters values, however a sample time is required in order to controller be able to process the signals coming from the plant, which sometimes implicates brief delays and the necessity of including data acquirement systems and/or processing units in the control loop [23], [24], [25].

Table 1. Controllers in continuous and discrete time

Type	Continuous	Discrete
Proportional Control	$u(t) = K_p e(t)$	$u(k) = q_0 e(k)$
Integral Control	$u(t) = K_i \int_0^t e(t)dt$	$u(k) = \frac{q_1}{1 - z^{-1}} e(k)$
Derivative Control	$(t) = K_d \frac{d}{dt} e(t)$	$u(k) = q_2 z^{-1} e(k)$

These elements can be fused in a single equation as portrays Eq. (3) for continuous time, where $e(t)$ is the system error, $u(t)$ the control variable, K_p, K_d and K_i are the proportional, derivative and integrative time constants, respectively.

$$u(t) = K_p \left[e(t) + T_d \frac{d}{dt} e(t) + \frac{1}{T_i} \int_0^t e(t)dt \right] \quad (3)$$

And Eq. (4) for discrete time, where $e(k)$ is the system error, $u(k)$ the control variable, q_0, q_1 and q_2 are the proportional, derivative and integrative time constants, respectively.

$$u(k) = q_0 e(k) + \frac{q_1}{1 - z^{-1}} e(k) + q_2 z^{-1} e(k) \quad (4)$$

Plant cancellation controller

This controller mathematically annul the dynamic of the plant (modeled as a transfer function) and incorporate the transfer function of the desired response from the system [17]. If a simple closed-loop of a system with a controller integrated on it is mathematically analyzed, the transfer function that represents it, is the showed in Eq. (5), from which is obtained the expression to calculate the controller Eq. (6), where $G_p(z)$ is the plant in time discrete, $D_c(z)$ is the controller, $I(z)$ is the input of the system and $O(z)$ is the output.

$$\frac{O(z)}{I(z)} = M(z) = \frac{D_C(z)G_P(z)}{1 + D_C(z)G_P(z)} \quad (5)$$

$$D_C(z) = \left(\frac{1}{G_P(z)}\right)\left(\frac{M(z)}{1 - M(z)}\right) \qquad (6)$$

In Eq. (6), it can be noticed that the first factor cancels the plant and the second factor determine the response for the system. Hence, in order to successfully control the plant, it is just required to choose an appropriate $M(z)$ expression, which corresponds to the expected system response, for this case the natural response of a first order system was selected Eq. (7), taking into account that $t_s = 5\tau$ and the sampling time $t_m = \frac{t_s}{40}$ (normally a sample time of $t_m = \frac{t_s}{10}$ is acceptable for most of the plants, nevertheless, in this particular case is necessary to take more samples to the signal to avoid small disturbances between each of them), equaling this expressions, we obtained a relation between t_m and τ (Eq. (8)).

$$M(z) = \frac{1 - e^{-\frac{t_m}{\tau}}}{z - e^{-\frac{t_m}{\tau}}} \qquad (7)$$

$$t_m = 0.125\tau \qquad (8)$$

Replacing the Eq. (8) into Eq. (7), and this result into Eq. (6).We obtained the transfer function in discrete time of the cancelling plant controller.

EXPERIMENTS

In order to validate the controller's performance over the DC motor application, 2 trials were carried over the system; both of them implemented in Matlab's toolbox, Simulink. In the first one, each of the elements that compose the close-loop system for the different controllers were attached into the toolbox platform, as can be seen in Fig. 4, 5 and 6, then the system received a unitary step signal as input to excite it, this with the aim of observing the stationary response of the controlled plant.

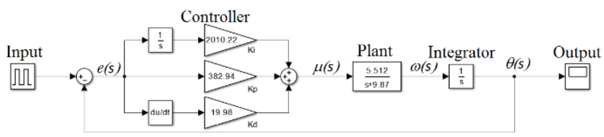


Figure 4. Simulink system model for the analog PID controller.

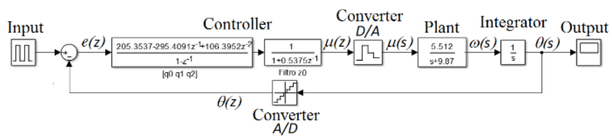


Figure 5. Simulink system model for the discrete PID controller.

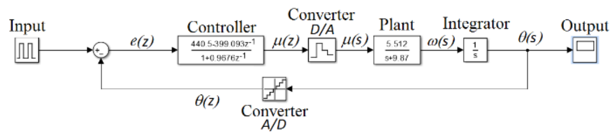


Figure 6. Simulink system model for the cancelling plant controller.

In the second one, a kinetic validation was realized; A simplified 3D model that included the physical features of the real 6 DOF robotic arm was developed into SimMechanics (Fig. 8), each of the manipulator's joints were attached with the different closed loop control architectures showed above (Fig. 9), with the objective of controlling DC motors' angular position. In this case, the input was directly the data coming from upper limb exosuit.

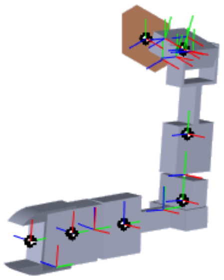


Figure 8. SimMechanics 3D model of the 6 DOF manipulator.

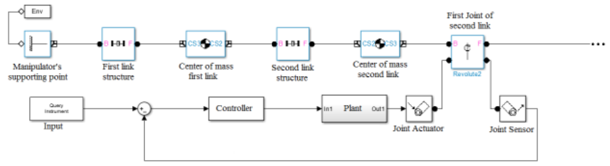
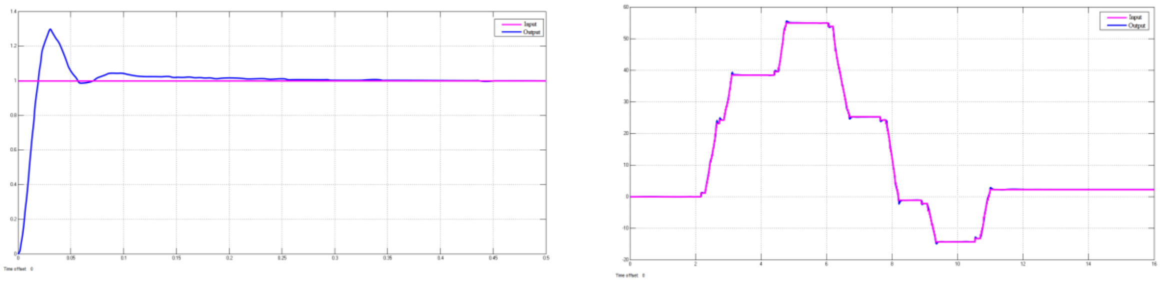


Figure 9. Control loop general architecture for a joint of the robotic manipulator implemented on SimMechanics.

RESULTS

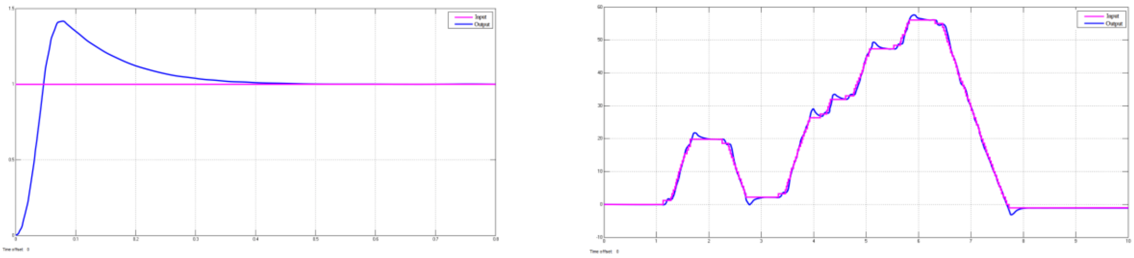
The data obtained from the experiments is shown in Fig. 8, Fig. 9 and Fig. 10. In these ones, the input and output of the closed loop system with the different architectures of controllers are plotted using Matlab®.

Finally, a visual validation of the tele operation system (upper limb exosuit or reference and 6 DOF robotic arm or output) is realized. It can be clearly observed in Fig. 11.



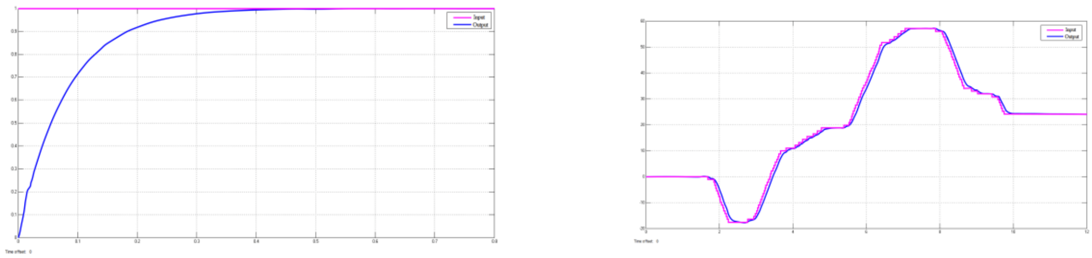
(a) (b)

Figure 8. PID controller in continuous time performance evaluation when: (a) system's input is a step signal (b) input is the data from upper limb exosuit. Pink line corresponds to the reference and blue line is the output of the controlled plant.



(a) (b)

Figure 9. PID controller in discrete time performance evaluation when: (a) system's input is a step signal (b) input is the data from upper limb exosuit. Pink line corresponds to the reference and blue line is the output of the controlled plant.



(a) (b)

Figure 10. Cancelling plant controller performance evaluation when: (a) system's input is a step signal (b) input is the data from upper limb exosuit. Pink line corresponds to the reference and blue line is the output of the controlled plant.

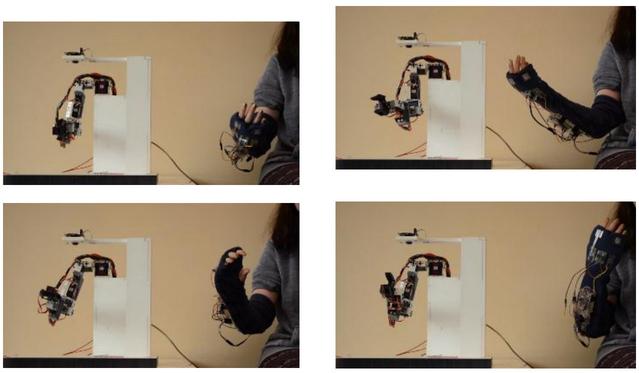


Figure 11. Visual comparison of the movements executed by the user wearing the upper limb exosuit and the movements replicated by the robotic arm, teleoperation validation.

DISCUSSION

The desired parameters selected to computed the controllers to be implemented into the application were adequate because the settling time (delay) was enough short to permit developing a successful teleoperation process of the robotic arm on "real-time", following faithfully the reference signal from upper limb exosuit.

In general terms all the tested controllers achieved to reach the reference signal in the expected settling time, nevertheless, continuous and discrete PID presented a considerable percentage of overshoot, being in discrete one more notorious, and this effect is specially inconvenient to the current angular position's control application since it may generate oscillations throughout the mechanic structure of the robotic arm. Otherwise, the response of the system with the cancellation plant controller described a smooth curve with null oscillations, fact which makes it a most proper option to control the DC motors.

Cancellation plant technique with first order system's output signal as chosen response demonstrated to be an easy and adaptive (in terms of it might be generalized) alternative to traditional control techniques, that partially avoids plant's instabilities, allowing gotten the desired system's response, regardless, plant's nature (order, grade, etc.). Additionally, it can be implemented in real systems without mayor complications than a discrete PID.

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