A MIMO Fuzzy Controller for tracking: Robot control

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Abstract

In the formulation of most practical robot control problems the analytical model used in the controller design may neglect certain nonlinearities or system dynamics in order to simplify the design. Furthermore, unknown load dynamics can also effect the response of the system. For many model-based controllers, these discrepancies can lead to poor performance or even instability. This is especially true of Multi-Input Multi-Output (MIMO) systems. Therefore, it is important to develop robust MIMO controllers that can account for such discrepancies, and uncertainties.

To address these issues, this work describes the development and implementation of a MIMO hybrid fuzzy controller for a two-link robot arm. The presented MIMO formulation is generic in nature and can readily be integrated into existing applications with minimal effort. The hybrid structure of the controller takes advantage of classical proportional-derivative control logic while maintaining a significant degree of robustness, performance and portability. A two-link robot simulation study is used to illustrate the merits of the proposed scheme.

1. Introduction

Robots have revolutionized the manufacturing, medical, and entertainment industries. In manufacturing, robots are used in a wide varity of applications, such as material handling, spraying painting, spot welding, inspection, assembly, etc. Current control research in the area of robotics examines ways to improve the robustness of the position and or force control for tracking and regulation. Advancements in technology have led to the development of complex multi-functional systems such as multi-link kinematic systems (Scharf 1985), autonomous vehicles Adsit (95), etc. In the case of robotic system, formulating an analytical description of the dynamics or kinematics requires a significant amount of analysis and insight. There are many inherent difficulties in defining the nonlinear damping in the joints (Smaili and Sannah 1994) and formulating the inverse or forward kinematics. In many cases it is impractical to formulate an accurate analytical expression of these dynamics. In these situations intuitive information can be used to design a traditional controller in an ad hoc manner, or synthesis of a non-model based intelligent controller. In addition these controllers must account for uncertainty and disturbance. The problems associated with designing a controller in this environment are compounded with issues associated with a Multiple Input Multi-Output (MIMO) system.

Some of the most common and intuitive robot control techniques such as those developed by Arimoto and Miyazaki (1983) utilize the PID schemes. As system complexity increases, more robust schemes such as output feedback (Wang et al. 1989) are required to achieve the desired performance. This is especially true when uncertainty is taken into consideration. For example, Lin and Brandt (1998) described an optimal control approach based on the work of Lin (1992) for robust control of a robot manipulators. This work extends optimal controllers to account for uncertainties and disturbances. Like sliding mode control (Slotine 1984), uncertainty bounds are required to design the controller. In addition, the design process can become complicated and a significant amount of effort is required to implement the controller.

The problem of designing MIMO control laws for systems with a significant amount of nonlinearities in the dynamics is the primary motivation for investigating the development of MIMO fuzzy control schemes. The scheme presented in this paper is straightforward, easy to implement, and utilizes the designer's intuition. This work deals with the development of intelligent MIMO controllers that utilize the designer's heuristic knowledge as well as any mathematical description of the system to provide a reasonable controlled response. The proposed controller combines the traditional Proportional-Derivative (PD) control law with a fuzzy controller in a MIMO framework to create a scheme that can be integrated into a variety of existing systems with minimal effort.

1.1 Benefits of fuzzy logic for complex systems

Fuzzy logic is one of the most promising intelligent control schemes for complex, nonlinear systems. In the literature, Single-Input Single-Output (SISO) fuzzy logic controllers have been successfully applied to numerous applications in the military (Gonsalves and Caglayan 95), industry (Bartolini 1985), and research (Lee, et. al. 94). Fuzzy logic allows operator experience and system knowledge to be encoded into the controller through membership functions and rules rather than complex mathematical models. For this reason, it lends itself to the control of complex time-varying SISO systems, which are not always practical to model accurately. Since many systems in real-world applications are MIMO, it is essential that a MIMO version be formulated to control systems such as multi-link robots. To make this scheme practical, issues associated with MIMO control, accuracy, and implementation must be addressed.

2. Theory

2.1 PD Control Law

There is an immense knowledge base associated with classical controls. Any textbook on classical controls can provide detailed theory on the design, analysis, and implementation of these controllers (Ogata 97). Classical controllers can be integrated into most existing linear SISO system. As the system complexity increases the design process becomes difficult and the performance may be degraded. The classical PD controller is characterized by the following time-domain expression:

$$u_c = K_p e + K_d \frac{de}{dt} \qquad (1)$$

where *e* is the error between the reference value and the actual value.

2.2 Fuzzy Logic

The power of fuzzy logic is its tolerance for ambiguity and its ability to increase robustness. It interprets controller information in a linguistic manner via the membership functions. In the linguistic domain the input/output relationship is defined by a set of rules. These rules and the membership functions are used to produce the appropriate control effect. Membership functions convert crisp inputs into linguistic variables or visa versa. A given input value can belong to one or several membership functions, and the degree to which it belongs to each membership function is given by the fuzzy value between zero and one.

If-then rules are evaluated in parallel for the fuzzified inputs. Each rule evaluation forms a fuzzy output set. The individual output sets are aggregated to form a final fuzzy output set, which is refereed to as defuzzification. The Center-of-gravity (COG) is the most common defuzzification method (Kosko 1997). The entire process is depicted graphically in Figure 1.

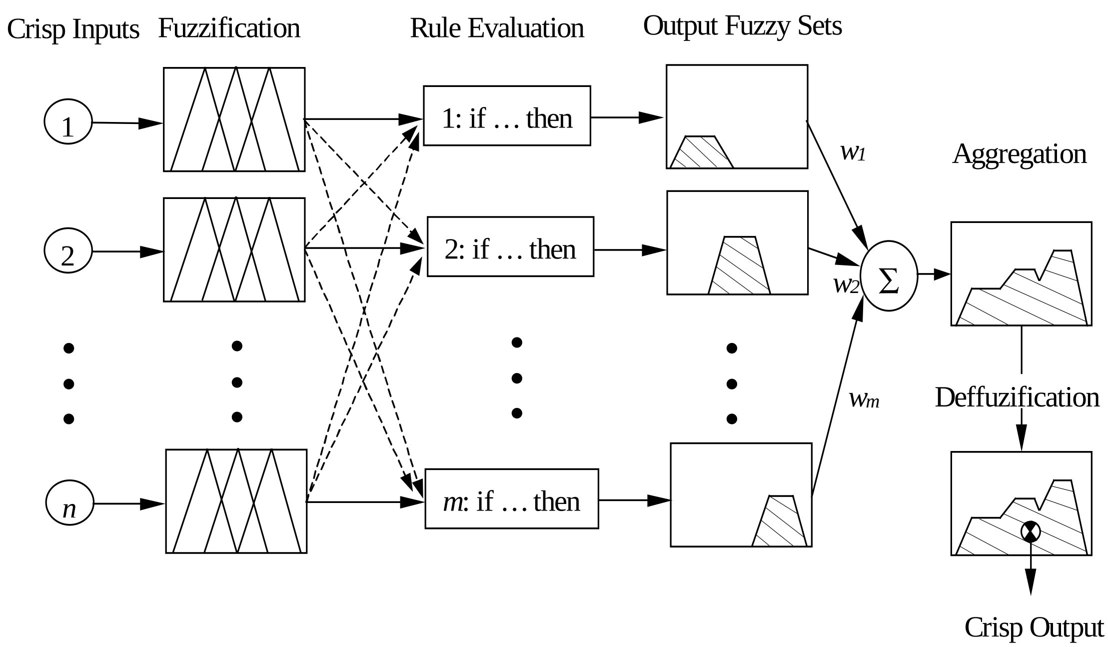

Figure 1. The Fuzzy Inference Process.

2.3 Hybrid Structure

The motivation behind developing a hybrid scheme, which is a combination of various types of controllers, is to take advantage of the attributes of various controllers while accounting for their weaknesses. Recent research in intelligent controls has incorporated classical control techniques into fuzzy control structure, stability analysis (Wang, et. al. 96, Spooner and Passino 96, Petroff et al. 98), and controller design methodology (Walchko et al. 98). These intelligent controllers are referred to as fuzzy hybrids. One of the most used hybrids is the fuzzy PID (Brehm and Kuldip 94, Misir 96). Due to their structure, hybrids provide a more defined control structure over fuzzy control while increasing the accuracy and portability of the controller. An example of a hybrid structure is given in Figure 2.

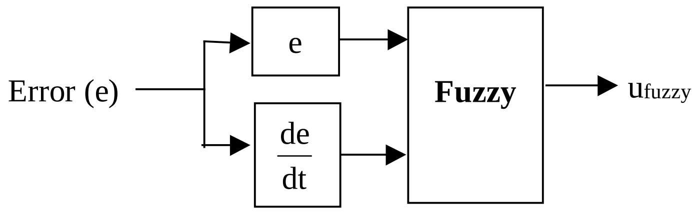

Figure 2. The hybrid fuzzy PD structure.

2.4 MIMO development

In this section the MIMO fuzzy controller is formulated by extending the SISO fuzzy concepts to the vector domain. This formulation resolves the control vector into a direction, magnitude and position-derivative ratio. By reducing the control vector into these components, the MIMO problem of solving for the appropriate control effort is reduced to a scalar one.

In the standard SISO system the fuzzy PD hybrid controller uses the error and its derivative as the inputs to the fuzzy inference system to determine the corresponding scalar output control effort u_c.

$$u_c \Rightarrow fuzzy(e, \dot{e})$$

In the MIMO case, the error terms are vectors. If the system can be assumed uncoupled, three SISO fuzzy PD can be utilized to achieve the desired response. If the system is coupled the required rules and membership functions significantly increase as the number of states and outputs increase, which makes the control design impractical.

In this work a SISO fuzzy inference system produces a magnitude, K_{mag}, and a position-derivative ratio, T_d. Given e *and* $\dot{e}$ the fuzzy control law is

$$u_c = K_{mag}\left(e + T_d \dot{e}\right) \tag{2}$$

Since, the magnitude is a positive number, all negative MF’s are removed and the complexity of fuzzy inference system is significantly reduced.

In order to extend the SISO controller to a MIMO framework, the control law is resolved into unit vectors, a position-derivative ratio and a magnitude.

$$u_c = K_p K_{units}\hat{e} + K_d \dot{K}_{units}\hat{\dot{e}} = \tilde{K}_p \cdot \hat{e} + \tilde{K}_d \hat{\dot{e}} = K\left(\hat{e} + \frac{\tilde{K}_d}{\tilde{K}_p} \cdot \hat{\dot{e}}\right)$$

$$u_c = K\left(\hat{e} + T_d \hat{\dot{e}}\right)$$

where K_p, K_d are controller gain, $\hat{e}$ is the unit vector of the error and K_{units}, and $\dot{K}_{units}$ represents the units of the error (meters) and it’s time derivative (meters/sec). These constants are conversion factors. For example $K_{units} = N$, therefore, the output of $K_p K_{units}\hat{e}$ .is torque.

$$u = K_{mag}\left(\vec{e} + T_D \cdot \vec{\dot{e}}\right) \tag{3}$$

Note that equation (2) is the same as the SISO fuzzy controller. The fuzzy MIMO controller uses the norm of the error and it’s derivative in the inference system to determine a fuzzy magnitude and a position-derivative ratio.

$$\lfloor K_{mag}, T_d \rfloor = fuzzy\left(norm\left(e_d\right), \cdot norm\left(\dot{e}_d\right)\right) \tag{4}$$

The T_d term is crucial to ensure a damped response. Table 1-3 contains the simplified fuzzy rules for this MIMO robotic application.

Table 1 Magnitude rules for error

e	BP	MP	P	SP	Z
	BP	MP	P	SP	Z

Table 2 Magnitude rules for err_dot

$\dot{e}$	BP	MP	P	SP	Z
	BP	MP	P	SP	Z

Table 3 Td rules for error and it's derivative

$e/\dot{e}$	BP	MP	P	SP	Z
BP				SP	
MP				SP	
P			BP		
SP			BP		
Z					SP

2.5 Robot Model Description

In order to illustrate this concept, a simple a two-link robot is used in the simulation study. The model of the robot is obtained from Slotine and Li (1991). Figure 3 contains a picture of the robot. This two-link robot system utilizes quaternion angles for computation stability. The model of the system is given below.

$$\begin{bmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{bmatrix} \begin{bmatrix} \ddot{q}_1 \\ \ddot{q}_2 \end{bmatrix} + \begin{bmatrix} -h\dot{q}_2 & -h\dot{q}_1 - h\dot{q}_2 \\ h\dot{q}_1 & 0 \end{bmatrix} \begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \end{bmatrix} + \begin{bmatrix} g_1 \\ g_2 \end{bmatrix} = \begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix}$$

Where $q = [q_1 \quad q_2]^T$ are the joint angles, $\tau = [\tau_1 \quad \tau_2]^T$ are the input torques and

$$H_{11} = m_1 l_{c1}^2 + l_1 + m_2 \left[l_1^2 + l_{c2}^2 + 2 l_1 l_{c2} \cos(q_2) \right] + l_2$$
$$H_{22} = m_2 l_{c2}^2 + I_2$$
$$H_{12} = H_{21} = m_2 l_1 l_{c2} \cos(q_2) + m_2 l_{c2}^2 + I_2$$

$$h = m_2 l_1 l_{c2} \sin(q_2)$$
$$g_1 = m_1 l_{c1} g \sin(q_1) + m_2 g \left[l_{c2} \cos(q_1 + q_2) + l_1 \cos(q_1) \right]$$
$$g_2 = m_1 l_{c2} g \cos(q_1 + q_2)$$

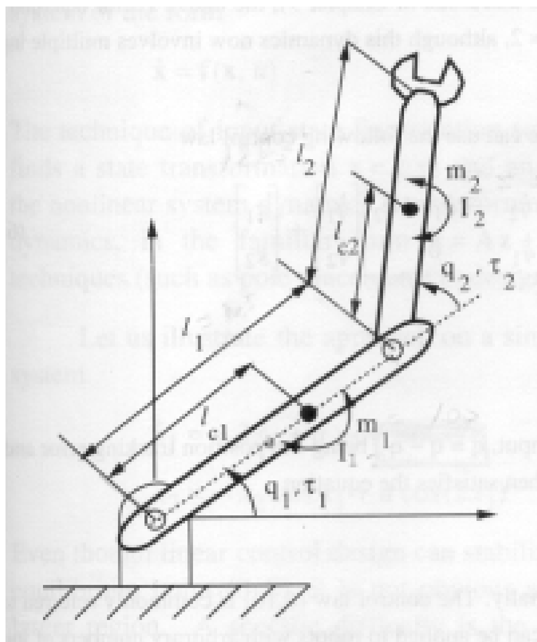

Figure 3. Robot system

2.5 PD and Feedback Linearization controllers

Two common types of controllers used in robotic control are the classical PD scheme and the Linearization feedback method. These methods are model dependent and require some insight to tune the controllers. Since the robotic system is a MIMO system the PD controller is defined as.

$$u = K_P e + K_D \dot{e} \tag{5}$$

where K_p, K_d are scalar constants. This allows for a simple intuitive design.

The Feedback Linearization (FL) controller is a conceptually simple scheme. However, implementation and design can be involved and time consuming. The basic concept behind the LF controller is to replace the system dynamics with the desired dynamics. This is achieved by defining the control torque as

$$\begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix} = \begin{bmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} + \begin{bmatrix} -h\dot{q}_2 & -h\dot{q}_1 - h\dot{q}_2 \\ h\dot{q}_1 & 0 \end{bmatrix} \begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \end{bmatrix} + \begin{bmatrix} g_1 \\ g_2 \end{bmatrix} \tag{6}$$

Where

$$\boldsymbol{v} = \ddot{q}_d - 2\lambda\dot{\tilde{q}} - \lambda^2\tilde{q}$$

$\boldsymbol{v} = [v_1 \quad v_2]^T$ and $\tilde{q} = q - q_d$. Plugging $\boldsymbol{v}$ into equation 6 produces the tracking error $\ddot{\tilde{q}} + 2\lambda\dot{\tilde{q}} + \lambda^2\tilde{q} = 0$, which converges to zero if λ is a positive value. The rate of convergence is a function of the model accuracy and lambda. In addition, this method is very sensitive to saturation and load disturbances.

3. Results

The simulations studies consists of two parts. The first simulation examines the performance of a fuzzy MIMO hybrid controller in ideal conditions. This will be compared against a standard PD controller and a feedback linearization (FL) scheme. In the next study, an unknown load disturbance is added to the system and the performances of the controllers are compared.

In the first case study all the dynamics are assumed known and the performance of the three controllers are compared. The position errors of the first and second state are shown in Figure 3-4. All three controller produced about the same response time. However, the fuzzy scheme was a little faster position response in the second link. In the velocity errors the fuzzy controller response was slightly more damped. Upon further inspection one can see that the FL and the PD schemes produce a larger steady state error than the fuzzy scheme (Figure 5). In addition, the control effort of the FL and the PD are larger than the fuzzy scheme (Figure 6). Overall the fuzzy scheme out performs the other controllers. It should be noted that the fuzzy scheme can be altered to produce a faster, damped response by altering the rules. However, this was not done to show how a simple set of rules can produce a response that is better than a model based controller.

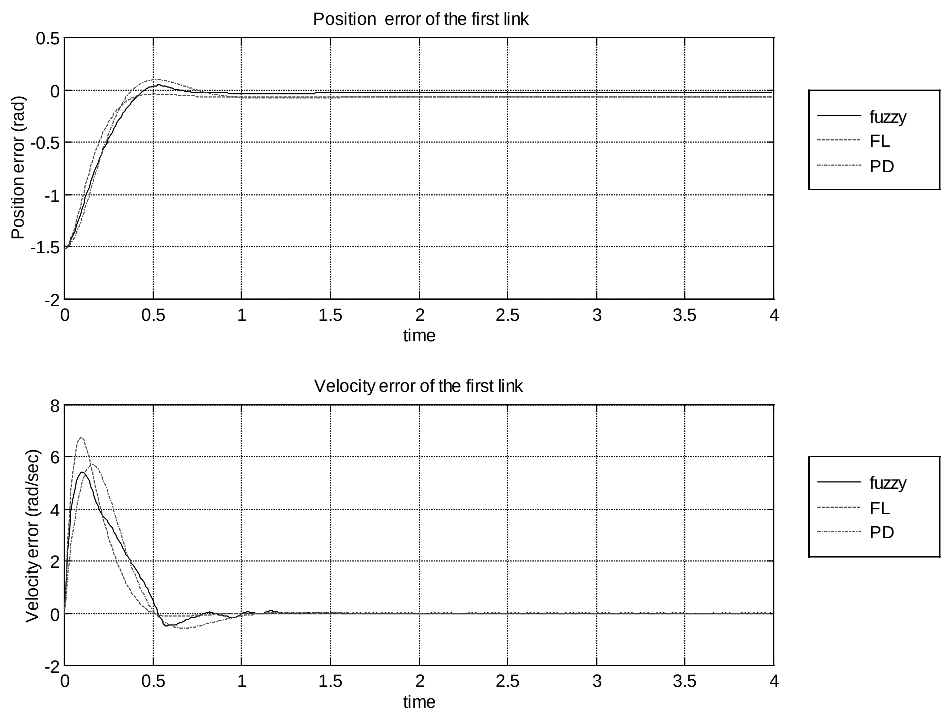

Figure 3. Position and velocity errors of the first link

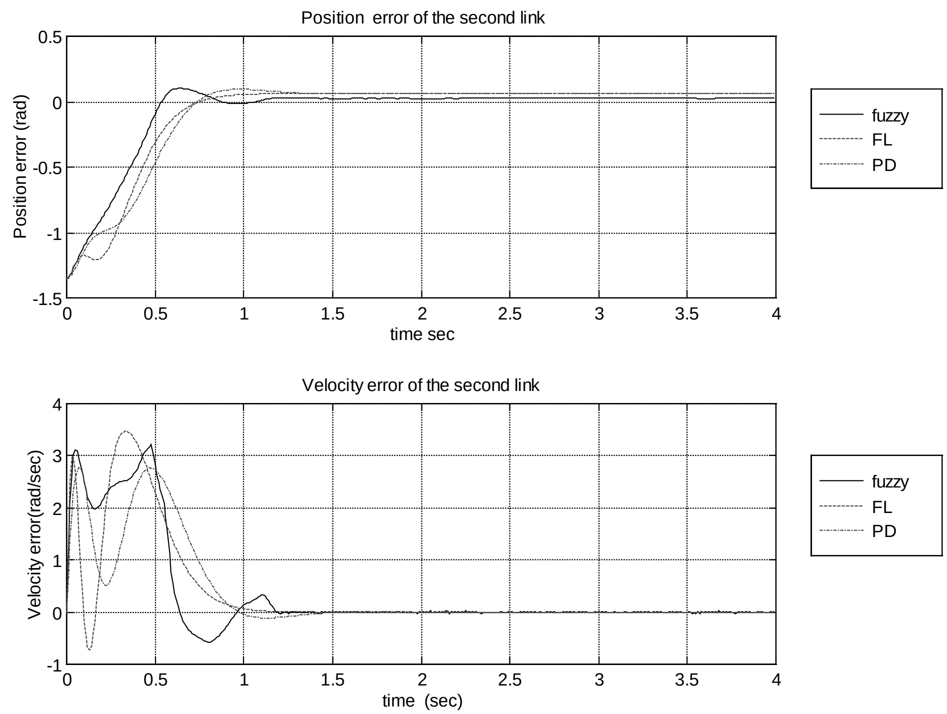

Figure 4. Position and velocity errors of the second link

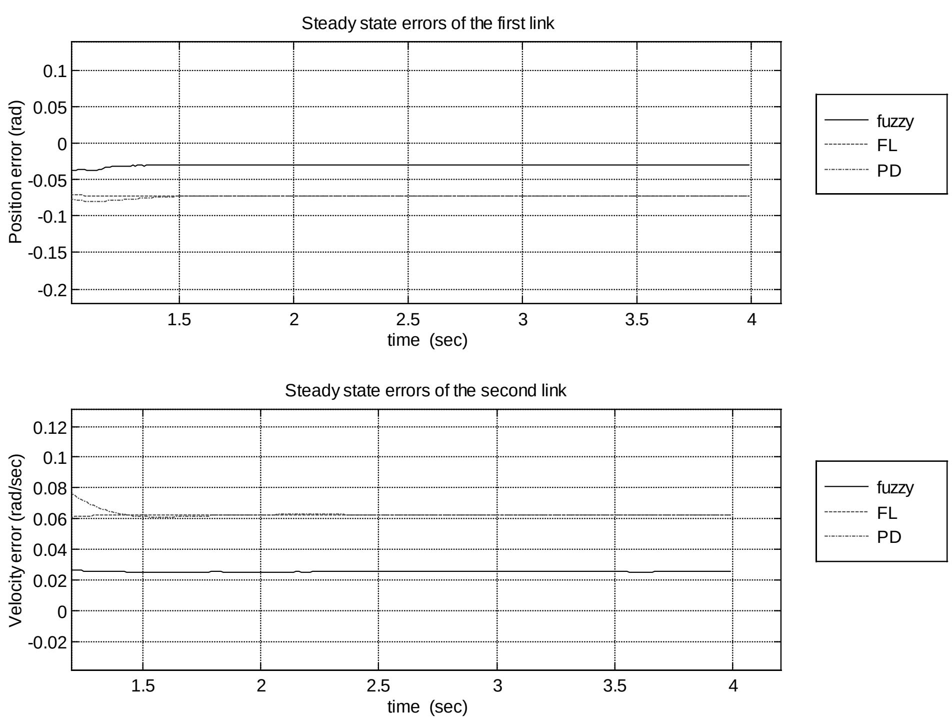

Figure 5. Position steady state errors

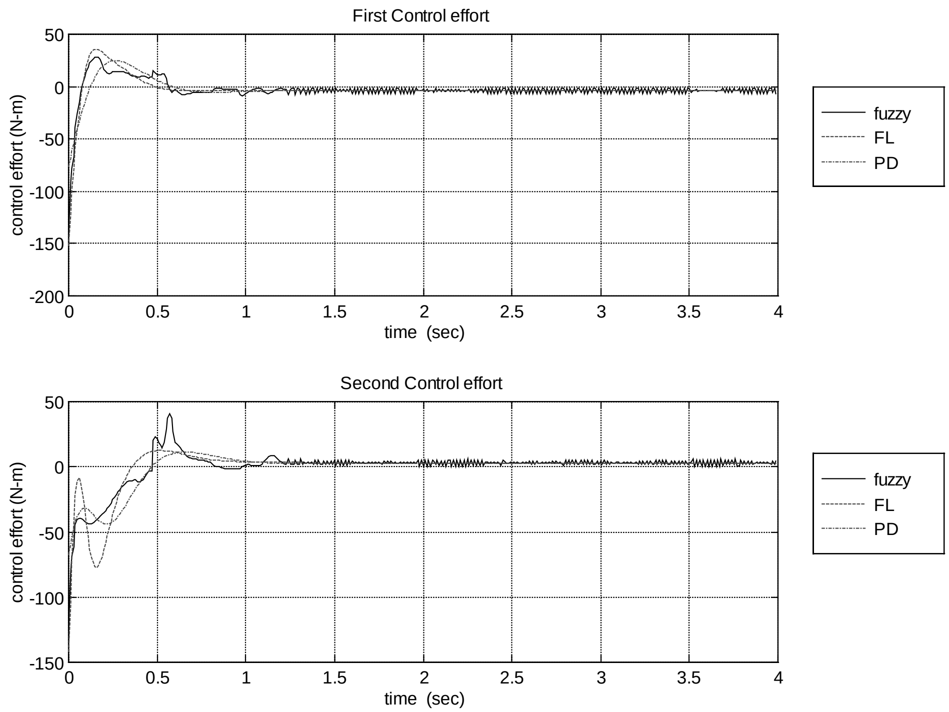

Figure 6. Control effort

In the second study a disturbance, which is a combination of a random and a deterministic source, is added to the system (Figure 11) and the performance of the three controllers are compared. The position errors of the first and second state are shown in Figure 7-8. Again, all three controller produces about the same response time. However, the effects of the disturbance degrade the accuracy of the controllers. This is especially true when a deterministic portion of the disturbance. The fuzzy was able to account for the stochastic and deterministic disturbance better than the PD of the FL schemes. This is especially true for the steady state response of the PD and FL scheme (Figure 9). Finally, the control effort of all controller was about the same.

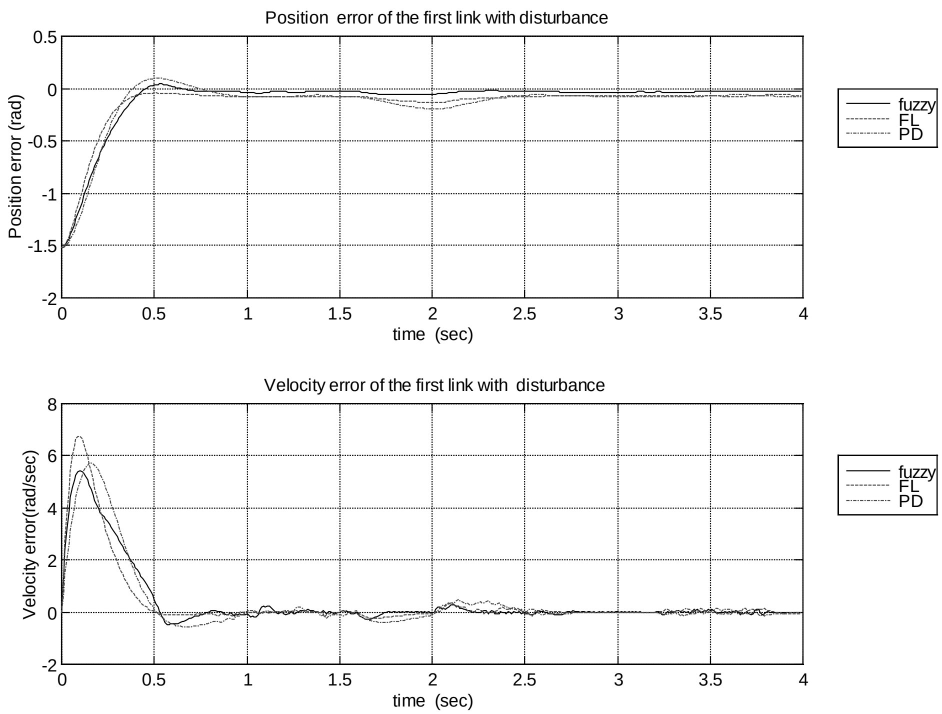

Figure 7. Position and velocity errors of the first link with disturbance

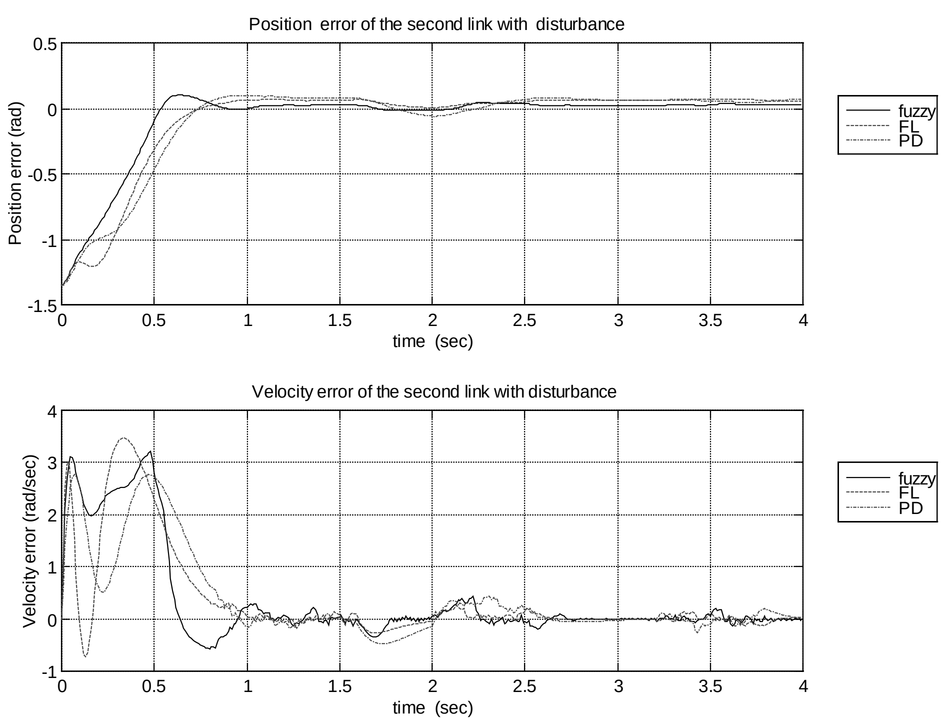

Figure 8. Position and velocity errors of the second link with disturbance

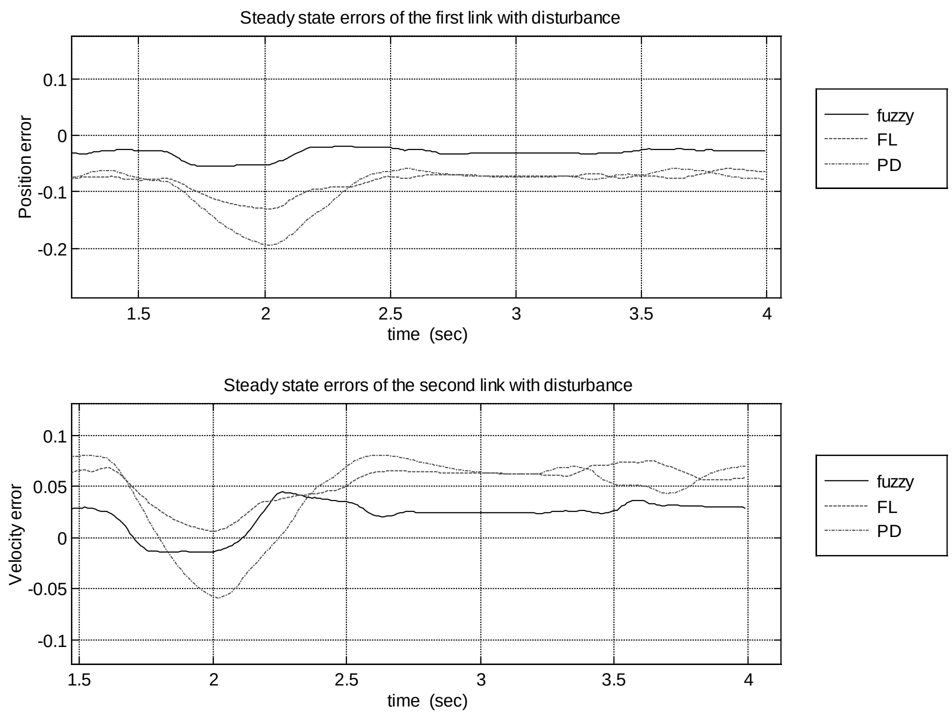

Figure 9. Position steady state errors with disturbance

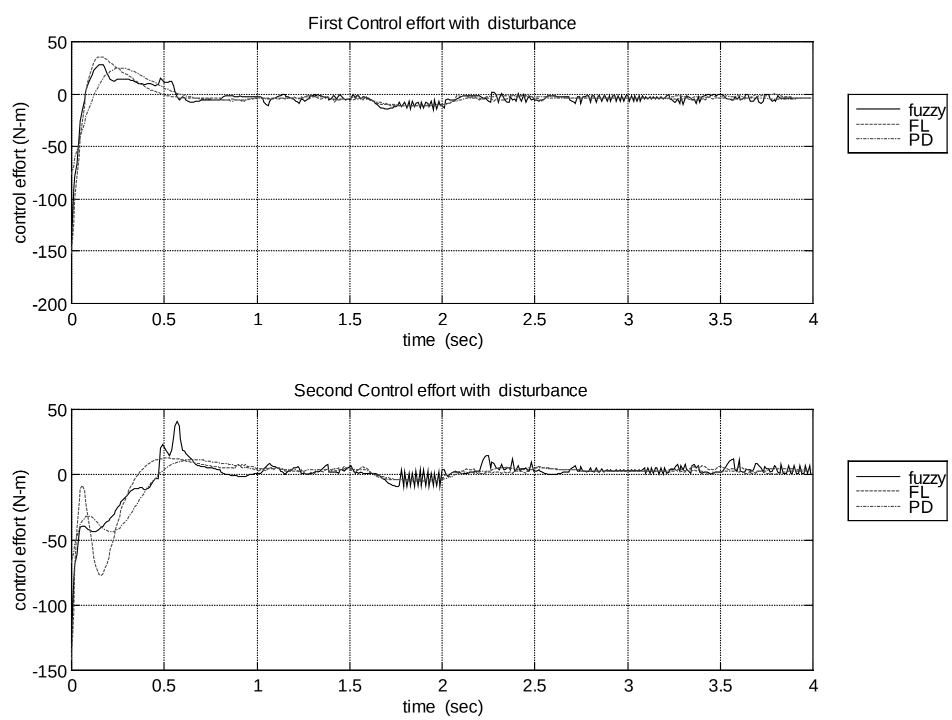

Figure 10. Control effort with distrubance

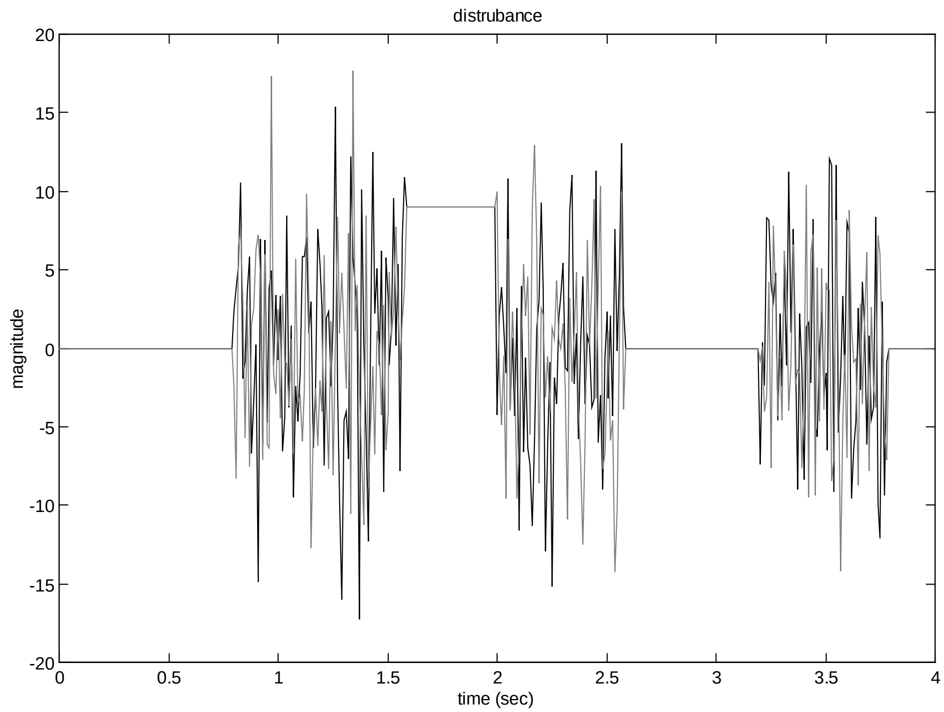

Figure 11. Distrubance

4. Conclusions

This paper described the development and implementation of a fuzzy MIMO controller, which can compensates for unmodeled disturbances in a robotic application. Based on the results, the MIMO fuzzy outperformed the FL and the PD controllers. This is due to the fact that these controllers are fixed gain controllers and can not easily compensate for uncertainty in the dynamics. In addition, the fuzzy scheme required the same or less control effort to achieve a reasonable response. This is significant point in real applications.

One of the main advantages the fuzzy scheme has is its portability. Unlike the fixed gain schemes, the fuzzy controller can be easily ported to another robot with minimal effort. Furthermore, the fuzzy scheme is more robust to random and deterministic disturbances. In summary, this work is a crucial step in the development of a more robust MIMO fuzzy technique, which can be implemented, in various MIMO robotic applications.

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