Supervisory Fuzzy Control for 5 DOF Robot Arm

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Abstract— **Controlling robot manipulators is challenging due to their nonlinearity nature. PID control is still the benchmark control in industry due to its simplicity. Nonlinear control techniques are very complex and are not attractive. However, fuzzy control is more attractive and provides good performance. This paper p combines fuzzy control with PID control to produce supervisory fuzzy PID controller for a 5DOF robot arm system. This proposed control works online to give better performance Simulation results using MATLAB/SIMULINK shows better results.**

Keywords- Fuzzy; supervisory control; 5-DOF; robot arm.

I. INTRODUCTION

This Nowadays, robots are becoming common in industrial, hazardous, and dangerous locations. Controlling robot becomes essential to robots success and modernization. Robot manipulators can be used to perform very specific tasks which require high level advanced control [1]. Robot manipulator has a nonlinear nature in its structure; thus, requires accurate modeling to present the nonlinear characteristics, uncertainty in parameters and real time computing. In order to avoid obstacles and destruction of the robot or its tools, a planned path should be followed with high accuracy.

PID control is considered the most popular control algorithm used in industry due to its simple structure and design. Typically, over 90% of control applications are using PID control or any of its components PI or PD forms. Several methods are available for tuning the parameters of the PID controller such as Ziegler-Nicholas (Z-N), Cohen-Coon, and some software [3]. Fuzzy logic can be used as supervisory control to tune the PID.

In traditional tuning such as Ziegler-Nicholas, PID parameters are selected, then fixed for the rest of operational time; however, fixed PID parameters cannot produce satisfactory results in process operation for nonlinear or complex systems. Therefore, this method is not a suitable choice for nonlinear systems. To cope with the nonlinear elements, the PID parameters or gains must be tuned on-line. Here, the PID parameters are tuned using supervisory control where the fuzzy logic and input from experts are combined to act as supervisory control for PID parameters tuning.

In 1965 Lotfi Zadeh presented fuzzy sets and fuzzy logic [4]. In 1973 Mamdani used fuzzy logic in control systems [5], and several fuzzy controllers were designed for diverse practical applications [6, 7]. Fuzzy logic control provides a formal methodology for representing, manipulating and implementing human's heuristic knowledge about how to control a system. Fuzzy control proves to be a successful methodology to deal with nonlinearities in systems. It achieves better performance than PID controller in complex processes. Combining the simplicity of PID and the robustness of FLC can achieve high control performance in a simple manner. This incorporation of the two controllers is known as fuzzy supervisory PID controller or fuzzy self-tuning PID controller. Many papers such as [4, 8, 9, 10] and [11] discussed the problem of self-tuning PID parameters.

Self-tuning controllers may be designed in two steps: first, using Z-N tuning formula to adjust the proportional gain, integral gain and derivative gain respectively; second, using fuzzy control as self-tuning for adjusting PID parameters on-line under process. Fuzzy supervisory was the topic of research recently. Zhen-Yu **[8]** developed a fuzzy gain scheduling (FGS) PID controller where the main idea was changing the parameters of the PID controller on-line. The results showed that the process can be satisfactory controlled by the FGS and showed better results than the traditional PID results. Due to the variation in system characteristics in physical system, PID controller may not be satisfactory. However, solutions to adjust PID parameters on-line were presented in [11] and [12]. The results verified that fuzzy supervisory control is improving the system response by making online modification to the original parameters.

This paper deals with controlling robot arm. It proposes to control robot arm with 5DOF such that the arm follow a predefined path. Its main contribution is using fuzzy logic in tuning PID parameters in order to control a 5DOF robot arm.

The paper is organized as follows: section 2 describes the structure of simple PID controller, section 3 presents FLC, section 4 covers supervisory control technique, section 5 presents the results, and finally section 6 concludes this paper.

II. PID CONTROLLER

PID controller transfer function takes one of the two formats: the first format is given such as

$$G_{PID}(s) = K_P + K_I/s + K_D s \qquad (1)$$

with K_P, K_I, and K_D are the proportional, integral, and derivative gains respectively. The second format is given as

$$G_{PID}(s) = K_P(1 + 1/(T_I s) + T_D s) \qquad (2)$$

with $T_I = K_P/K_I$, and $T_D = K_D/K_P$ are known as integral and derivative time constant respectively.

There are general rules of thumb for tuning PID parameters. Below are examples of such roles:

1. If the input is positive large, then the proportional gain K_P must be large, integral term K_I small and the derivative term K_D is small; thus, speeding the system output.
2. If the input is very small, then the PID parameters K_P should be smaller, K_I larger, and K_D larger; thus, the output will have reduced overshoot and faster response.
3. These types of rules are not easy to implement using traditional tuning methods; however, they are treasure using intelligent tuning methods such as fuzzy logic.

III. FUZZY LOGIC CONTROL

FLC has four main components: the fuzzifier, knowledge base, inference mechanism and defuzzifier [6]. Based on membership functions and fuzzy logic, the fuzzifier converts a crisp input signal to fuzzified signals. The knowledge base houses rule base and the data base. The inference mechanism fires relevant control rules and then decides what the input to the plant should be. Finally the defuzzification process converts the fuzzy output into crisp control signal.

Fuzzy PID controllers are classified into two types: the direct action fuzzy control [13] and the fuzzy supervisory control. The direct action type replaces the PID control with a feedback control loop to compute the action through fuzzy reasoning where the control actions are determined directly by means of a fuzzy inference. These types of fuzzy controllers are also called PID-like controllers. On the other hand, the fuzzy supervisory type attempts to provide nonlinear action for the controller output using fuzzy reasoning where the PID gains are tuned based on a fuzzy inference system rather than the conventional approaches.

The design process of the fuzzy controller [14] is described as follows:

- Define the input and output variables of FLC. In this paper, there are two inputs of FLC, the error $e(t)$ and error change $\Delta e(t)$ and three outputs K_P', K_I', and K_D' respectively.
- Fuzzify the input and output variables by defining the fuzzy sets and membership functions. Each variable of fuzzy control inputs has seven fuzzy sets ranging from negative big (NB) to positive big (PB), and the output of FLC has the following fuzzy sets: K_P' and K_D' has two fuzzy sets. K_I' has three fuzzy sets. Fig. 1 shows the inputs of FLC.
- Design the inference mechanism rule to find the input-output relation. This paper uses Mamdani (max-min) inference mechanism.
- Defuzzify the output variable. Here, the center of gravity (COG) method, the most frequently used method, is used. The control action is:

$$u = \frac{\sum_{i=1}^{m} \mu(x_i).x_i}{\sum_{i=1}^{m} \mu(x_i)} \qquad (3)$$

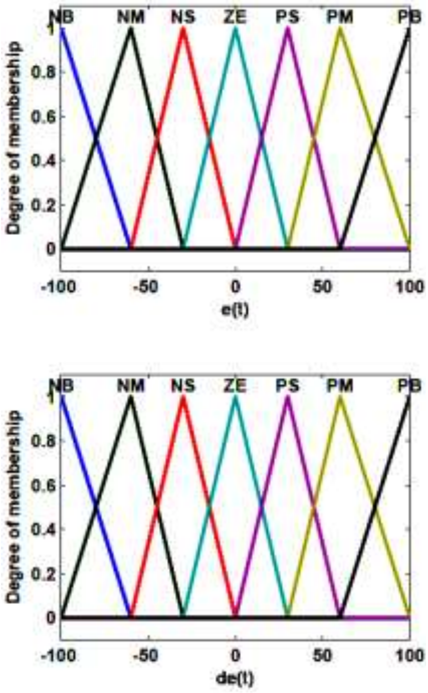

Figure 1. Membership function of $e(t)$ and $\Delta e(t)$.

IV. FUZZY SUPERVISORY CONTROL

The closed loop system with fuzzy supervisory PID control is shown in Fig. 2. The control system consists of a fuzzy logic part and a PID part.

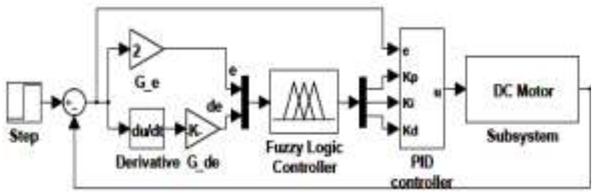

Figure 2. Fuzzy supervisory control

The FSC has the form of PID control [15, 16] but the three parameters of PID control are tuned using fuzzy controller based on the error and change of error as inputs to FLC.

The input signal is step input. The input to PID control is the error signal and the output of PID controller fed to the robot arm was obtained from the PID controller as shown in Fig. 3.

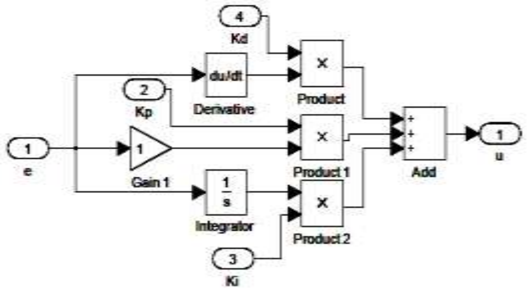

Figure 3. Structure of PID controller

The two input signals to the fuzzy controller are $e(t)$ and $\Delta e(t)$, where:

$$e(t) = r(t) - y(t) \quad (4)$$

$$\Delta e(t) = e(t) - e(t-1) \quad (5)$$

The output of fuzzy logic control are K_P', K_D' and K_I'. Suppose the range of these parameters are $[K_{P_{\min}}, K_{P_{\max}}]$, $[K_{I_{\min}}, K_{I_{\max}}]$ and $[K_{D_{\min}}, K_{D_{\max}}]$ respectively. The range of these parameters is determined experimentally such as, $K_P \in [0,15]$, $K_I \in [0.001, 0.005]$ and $K_D \in [0.1, 0.2]$. The parameters are described as follows:

$$K_P' = (K_{P_{\min}} - K_P)/(K_{P_{\max}} - K_{P_{\min}}) \quad (6)$$

$$K_D' = (K_{D_{\min}} - K_D)/(K_{D_{\max}} - K_{D_{\min}}) \quad (7)$$

$$K_I' = (K_{I_{\min}} - K_I)/(K_{I_{\max}} - K_{I_{\min}}) \quad (8)$$

where K_P', K_D' and K_I' are output variable of fuzzy control.

Fig. 4 shows the membership functions of K_P', K_D' and K_I' respectively. The membership functions used in the proposed method for the fuzzy PID parameters tuner are triangular, Gaussian, and sigmoid membership functions. K_P' and K_D' output has two membership functions in sigmoid shape chosen for the K_P' and K_D', and the fuzzy set variables are: Small (S) and Big (B). The term K_I' has three membership functions in triangular and it covered by three fuzzy set variables have the linguistic values: S, M (Medium), and B Big.

Generally fuzzy rule base are dependent on the characteristics of the controlled plant and the type of controller. These rules are determined based on practical experience or opinion of experts [14]. The rule base of the proposed controller is constructed using two forms: first multi-input multi-output (MIMO) fuzzy rule base such as:

$$\textit{If } e \textit{ is } A_1 \textit{ and } \Delta e \textit{ is } A_2 \textit{ then } K_P' \textit{ is } B_1, K_D' \textit{ is } B_2 \textit{ and } K_I' \textit{ is } B_3 \quad (9)$$

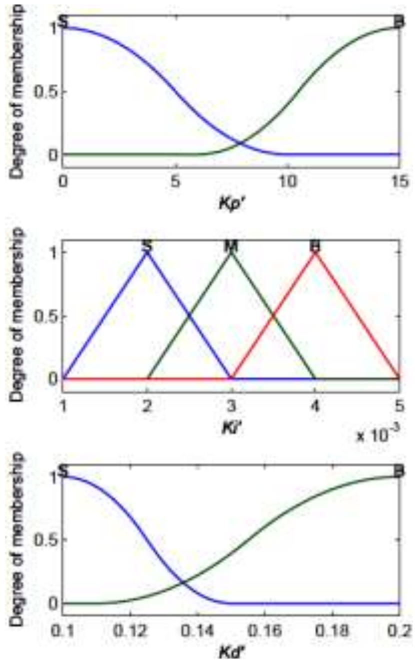

Figure 4. Membership function of K_P', K_D' and K_I'

The second method is multi-input single-output (MISO). Each component of PID gains has independent fuzzy tuner such as:

$$\textit{If } e \textit{ is } A_1 \textit{ and } \Delta e \textit{ is } A_2 \textit{ then } K_P' \textit{ is } B_1 \quad (10)$$

where e and Δe are the inputs of FLC. A_1, A_2, B_1, B_2 and B_3 are linguistic variable values of $e, \Delta e, K_P', K_D'$ and K_I' respectively.

The tuning of PID gains are adjusted carefully, such that the rule base table of the fuzzy supervisory for K_P', K_D' and K_I' must be chosen accurately to guarantee a system with a fast rising time, smaller overshot and no steady state error. Fig. 5 shows the unit step response for controlled system. The rule base must be written according to the step response. The step response is divided into four regions.

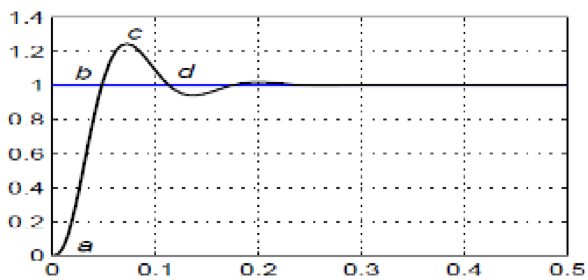

Figure 5. Unit step response

For region 1 around point (a), a big control signal to achieve fast rise time is needed. To eliminate the error, the integral gain has to be emphasized, and to speed up the response the derivative gain has to be there. To produce big control signal the PID control should have large proportional gain. The rule base which represents case 1 is written as follows:

$$If\ \ e\ is\ PB\ and\ \Delta e\ is\ Z\ then\ K_P{}'\ is\ B, K_D{}'\ is\ S\ and\ K_I{}'\ is\ S \tag{11}$$

When the error becomes negative during region 2 around point (b), the system needs to slow to reduce the overshoot. This is accomplished by decreasing the proportional gain, small integral gain and large derivative gain. Hence the rule base that represents this case is such as:

$$If\ \ e\ is\ Z\ and\ \Delta e\ is\ NB\ then\ K_P{}'\ is\ S_1, K_D{}'\ is\ B\ and\ K_I{}'\ is\ S \tag{12}$$

The other cases can be tuned as the same way. The rule base table of $K_P{}'$, $K_I{}'$ and $K_D{}'$ are shown in Table 1, Table 2 and Table 3 respectively.

TABLE I. FUZZY CONTROL RULE OF KP

KP		**ERROR**						
		NB	NM	NS	Z	PS	PM	PB
CANGE OF ERROR	NB	B	S	S	S	S	S	B
	NM	B	B	S	S	S	B	B
	NS	B	B	B	S	B	B	B
	Z	B	B	B	B	B	B	B
	PS	B	B	B	S	B	B	B
	PM	B	B	S	S	S	B	B
	PB	B	S	S	S	S	S	B

TABLE II. FUZZY CONTROL RULE OF KD

KD		**ERROR**						
		NB	NM	NS	Z	PS	PM	PB
CANGE OF ERROR	NB	S	B	B	B	B	B	S
	NM	S	B	B	B	B	B	S
	NS	S	S	B	B	B	S	S
	Z	S	S	S	B	S	S	S
	PS	S	S	B	B	B	S	S
	PM	S	B	B	B	B	B	S
	PB	S	B	B	B	B	B	S

TABLE III. FUZZY CONTROL RULE OF KI

KI		**ERROR**						
		NB	NM	NS	Z	PS	PM	PB
CANGE OF ERROR	NB	S	M	B	B	B	M	S
	NM	S	M	M	B	M	M	S
	NS	S	S	M	M	M	S	S
	Z	S	S	S	M	S	S	S
	PS	S	S	M	M	M	S	S
	PM	S	M	M	B	M	M	S
	PB	S	M	B	B	B	M	S

V. RESULTS AND DISCUSSION

The fuzzy self-tuning PID controller is applied to 5 DOF robot arm. The robot has 5 DOF each of them has DC motor with specific transfer function. To show the effectiveness of this approach, the output response of the first DOF of the robot arm is shown with variation of the PID gains. The output response of the other motors can be obtained in the same way.

The transfer function of the DC motor of the first DOF considered is defined as follows:

$$G(s) = \frac{19649}{s^3 + 201s^2 + 6290s} \tag{13}$$

The results were obtained using MATLAB and SIMULINK for the above transfer function which represents the output response of the first DOF of robot arm using the proposed controllers.

The simulation results in Fig. 6 and Fig. 7 show the output response of the proposed controllers with respect to step input signals. The two figures show the performance of the PID using conventional tuning (without fuzzy tuning) and using the supervisory tuning respectively. In addition, they show the effectiveness of the two controllers for rejection disturbance inputs.

If a load torque with -0.5 *N.m* is applied on the first angle, the result obtained shows the effect of the disturbance on the output response after one second and the efficacy of the FCS controller for tuning PID parameters and eliminating the disturbance.

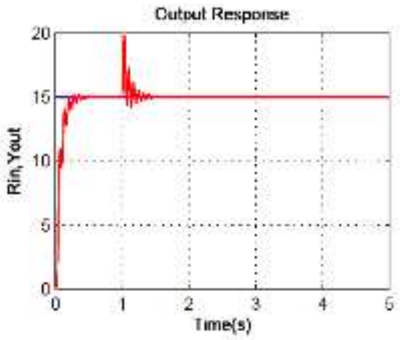

Figure 6. Output response using classical tuning methods

It is cleared that the fuzzy logic control achieve better performance for tuning the PID gains than conventional tuning methods such as eliminating overshoot, rising time and steady state error.

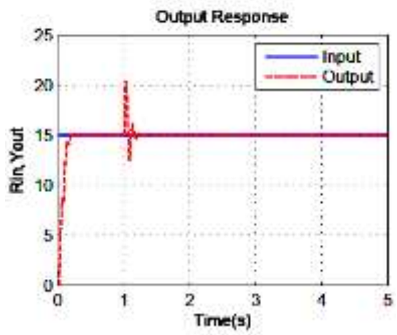

Figure 7. Output response using fuzzy supervisory control

The above figures show the effect of small disturbance after one second and effectiveness of the fuzzy supervisory controller for eliminating the presence disturbances.

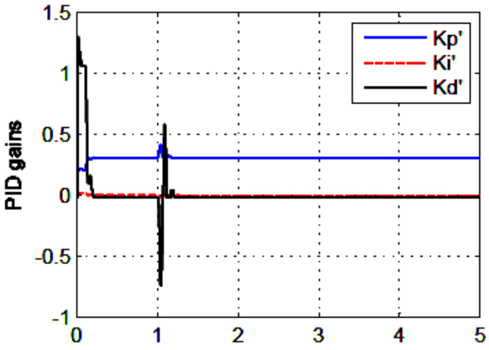

Figure 8. PID parameters variations

The fuzzy supervisory tries to vary the PID parameters during process operation to enhance the system response and eliminates the disturbances. Fig. 8 shows the variation of the PID gains during the operation using fuzzy control as supervisory controller. Performance of proposed controllers is summarized in Table 4.

TABLE IV. PID PERFORMANCE RESULTS

Controller type	**System characteristics**		
	OS %	t_r **(s)*sec***	*SSE*
Classical PID control	0.08	0.3	0.03
Fuzzy supervisory control	0.001	0.15	0

VI. CONCLUSION AND FUTURE WORK

Although PID control is the standard control for linear systems, it faces problems dealing with nonlinear systems and is limited when we talk about robustness. Several traditional methods are available for tuning PID parameters; however, they are time consuming and depend on the starting points. Fuzzy logic is utilized in the process of turning PID's parameters; thus, leading to fuzzy supervisory control. FSC was used to optimize the process of tuning PID's parameters in order to control a 5DOF robot arm. The output response of Fuzzy supervised PID controller outperformed classical PID response. This showed that tuning PID parameters using fuzzy logic outperforms classical methods.

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