Modeling and Control of 5 DOF Robot Arm Using Supervisory Control

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Abstract—**Robot manipulators are nonlinear systems, so it needs online tuning and monitoring during process control. Proportional integral derivative (PID) control and fuzzy logic control (FLC) are good controllers in industrial applications. Therefore it is a good idea to combine between the two controllers to form a fuzzy supervisory control (FSC) to overcome the limitation of PID control in nonlinear systems. This paper presents a fuzzy supervisory technique for PID controller. This technique seeks to tune the PID parameters online to improve the performance automatically. The simulation results show that the performance of fuzzy supervisory tuning is better than the performance of classical tuning methods for PID controller.**

Keywords: Fuzzy logic controller, PID controller, 5DOF Robot arm, Supervisory control.

I. INTRODUCTION

Over the past decades rapid changes in industrial and commercial applications such as robot manipulators urged human to develop and enhance the performance of control technique which uses to control robot manipulators because robots nowadays used in hazard, complex and boring tasks [1]. Robot manipulator is an important issue in control science because it has nonlinear characteristics, variable parameters and real time computing. Therefore it is necessary to control the path which enable the tool of the robot to follow with high accuracy to avoid robot or tool destruction.

In most control systems such as robots, PID controller considered the most and popular control algorithm is used, because of its simple structure, ease of design and the robustness in operating conditions. As refereed in [2] over 90% of control applications using PID control or its forms like PI or PD forms. Tuning of PID controller classified into two categories: first tuning the PID gains using Ziegler-Nicholas (Z-N) tuning formula [3]. Second tuning PID gains using supervisor control such as FLC.

In the first method, PID parameters are fixed during control algorithm after they have been chosen for the first time. Since the fixed PID parameters cannot produce satisfactory results in process operation with nonlinear or complex characteristics. Therefore this method is not a good choice in nonlinear circumstances. To overcome the drawbacks of the traditional tuning formula of PID gains it must be tuned on-line during process operation as referred in the second method. This method tends to change the proportional integral derivative gains during the operation process using supervisory controller. In this case the fuzzy control algorithm with human expert is used as supervisory control for PID parameters.

Fuzzy logic was proceeding in 1965 when Lotfi A. Zadeh presented his milestone paper on fuzzy sets [4], and introduced the concept of linguistic variable in 1973. Since fuzzy logic control was introduces by Mamdani **[5]**, several fuzzy controllers have been designed for diverse practical applications [6], [7]. Fuzzy logic controller provides a formal methodology for representing, manipulating and implementing a human's heuristic knowledge about how to control a system. Tuning of fuzzy controller is a successful way for dealing with nonlinear systems. It can give satisfactory results and achieve better performance than PID controller when there are very complicated processes. Therefore the popularity of PID and the advantages of FLC can be incorporated into a controller to achieve high control performance. This incorporation of the two controllers denoted as fuzzy supervisory PID controller or fuzzy self tuning PID controller. A lot of papers such as [4], [8], [9], [10] and [11] discussed the problem of self-tuning PID parameters. Designing of self tuning controller is presented under two steps. First using Z-N tuning formula to adjust the proportional gain, integral gain and derivative gain respectively. Secondly using fuzzy control as a self tuning for adjusting PID parameters on-line under process. Studying of fuzzy supervisory has attracted attention in many papers through the history of fuzzy logic control. Good presentation on this subject presented by Zhen-Yu [8] when he developed a fuzzy gain scheduling (FGS) of PID controller, the main idea was presented is how the parameters of the PID controller adapted on-line. The results showed that the varity of process can be satisfactory controlled by the FGS and these results better as compared to the PID results. Due to the variation in system characteristics in physical system, PID controller may not be sufficient. Therefore, [11], [12] presented solution for adapting PID parameters on-line. The results verified that the efficiency of the fuzzy supervisory control in improving the system response by making online modification to the original parameters

The main body of the paper comprises five sections as follows: section II presents and describes structure of simple PID controller. Section III presents the FLC and explains about the fuzzification, rule base, inference mechanism and defuzzification of fuzzy algorithm while section IV covers the idea of supervisory control technique. Section V gives the results and section VI concludes the paper.

II. PID CONTROLLER

PID controller [11] uses the error $e(t)$ between the reference input $r(t)$ and the output $y(t)$ as input, and then generates a control signal $u(t)$ for the controlled system. The transfer function of the PID controller has the following form:

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

where K_P, K_I, and K_D are the proportional, integral, and derivative gains respectively. Another useful equivalent form of the PID controller is in the form:

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

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

Tuning of PID parameters exist some rules for example.

- If the error $e(t) = r(t) - y(t)$ 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. Therefore this will speed the system output.
- If the current error is very small the PID parameters will have to be smaller value for proportional gain, larger value of integral time constant and larger value of derivative gain. So the speed of the system response will be small to reduce the overshoot of the output.

The above tuning technique may be boring if we use the conventional tuning methods such as manual tuning or other methods. So FLC is a good solution for tuning PID gains online.

III. FUZZY LOGIC CONTROL

FLC has four main components: the fuzzifier, knowledge base, inference mechanism and defuzzifier [6]. Fuzzifier converts a crisp input signal into a fuzzified signals identified by membership functions into fuzzy sets. The knowledge base consists of rule base and the data base. The inference mechanism evaluates which control rules are relevant at the current time and then decides what the input to the plant should be. Finally the defuzzification process converts the fuzzy output into crisp controlling signal.

Fuzzy PID controllers may be classified into two types: the direct action fuzzy control [13] and the fuzzy supervisory control. For the direct action type of fuzzy PID controllers, it replaced the PID control and placed with the feedback control loop to compute the action through fuzzy reasoning. In this type the control actions are determined directly by means of a fuzzy inference system. This type of fuzzy controllers is in essence like the conventional PID controller. Therefore, they are also called the PID-like controllers. For the fuzzy supervisory type, the fuzzy reasoning attempt to provide nonlinear action for the controller output. Therefore the PID gains are tuned based on a fuzzy inference system rather than the conventional Z-N approach.

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

- Define the input and output of FLC. 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. 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 of fuzzy mechanism used the most frequently used method is the center of gravity (COG) method. The control action is:

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

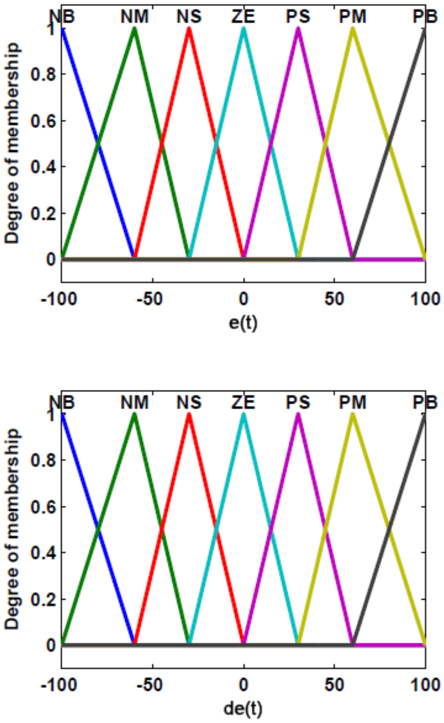

Figure 1. Membership function of $e(t)$ and $\Delta e(t)$.

IV. FUZZY SUPERVISORY CONTROL

Fig. 2 shows the PID control system with fuzzy control as supervisory controller.

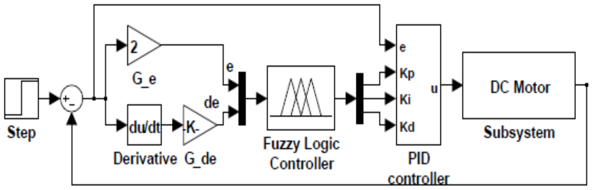

Figure 2. Fuzzy supervisory control

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.

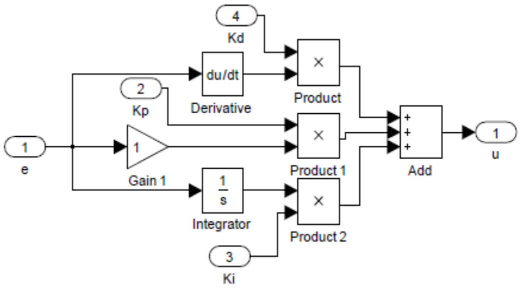

Figure 3. Structure of PID controller

As mentioned of fuzzy controller has two input $e(t)$ and $\Delta e(t)$ according to the following relations:

$$e(t) = r(t) - y(t) \tag{4}$$

$$\Delta e(t) = e(t) - e(t-1) \tag{5}$$

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 are determined experimentally 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:

$$K'_P = (K_{P_{\min}} - K_P) \big/ (K_{P_{\max}} - K_{P_{\min}}) \tag{6}$$

$$K'_D = \left(K_{D_{\min}} - K_D\right) \big/ \left(K_{D_{\max}} - K_{D_{\min}}\right) \tag{7}$$

$$K'_I = \left(K_{I_{\min}} - K_I\right) \big/ \left(K_{I_{\max}} - K_{I_{\min}}\right) \tag{8}$$

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.

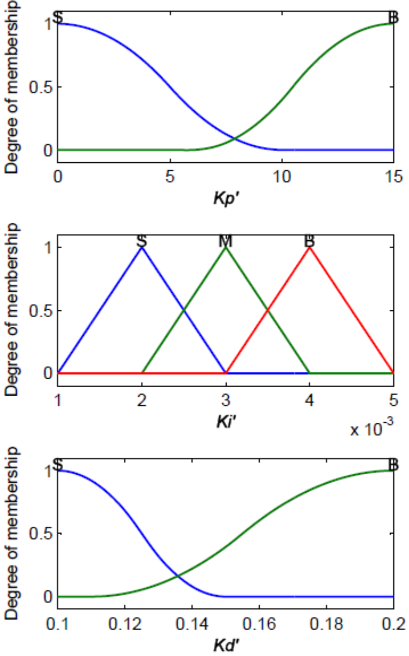

Figure 4. Membership function of $K_P{}', K_D{}'$ and $K_I{}'$

Generally fuzzy rule base are dependent on the characteristics of the controlled plant and the type of controller. These rules determined from the practical experience [14]. The rule base of the proposed controller is constructed using two forms: first multi input multi output (MIMO) fuzzy rule base and it has the form:

$$\begin{gathered} \text{If } e \text{ is } A_1 \text{ and } \Delta e \text{ is } A_2 \text{ then } K_P{}' \text{ is } B_1, K_D{}' \text{ is } B_2 \\ \text{and } K_I{}' \text{ is } B_3 \end{gathered} \tag{9}$$

The second method is multi input single output (MISO). Each one of PID gains has independent fuzzy tuner. The following formula represents the second method:

$$\text{If } e \text{ is } A_1 \text{ and } \Delta e \text{ is } A_2 \text{ then } K_P{}' \text{ is } B_1 \tag{10}$$

where e and Δe are the input 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.

As mentioned previously the tuning of PID gains should be adjusted carefully, so 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 fast rising time, smaller overshoot 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.

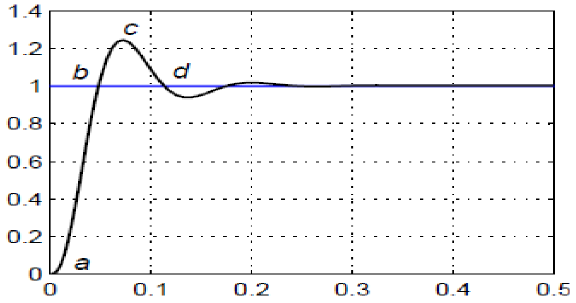

Figure 5. Unit step response

During region 1 around point (a) we need big control signal to achieve fast rise time. To produce big control signal the PID control should have large proportional gain, large integral gain and small derivative gain. The rule base which represents case 1 is written as follows:

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

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

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

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

TABLE I. FUZZY CONTROL RULE OF K_P'

K_P'		**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 K_D'

K_D'		**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 K_I'

K_I'		**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 applied to 5 degree of freedom (DOF) robot arm. The robot has 5 DOF each of them has DC motor with specific transfer function. As a case study we will present the output response of the first DOF of the robot arm and we will show the variation of the PID gains through process control. 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 as follows:

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

The results where obtained using MATLAB and SIMULINK. It shows the output response of the first DOF of robot arm using the proposed controllers.

The simulation result in Fig. 6 and Fig. 7 shows the output response of the proposed controllers with respect to the step input signal. The two figures show the performance of the PID using the conventional tuning (without fuzzy tuning) [17] 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.

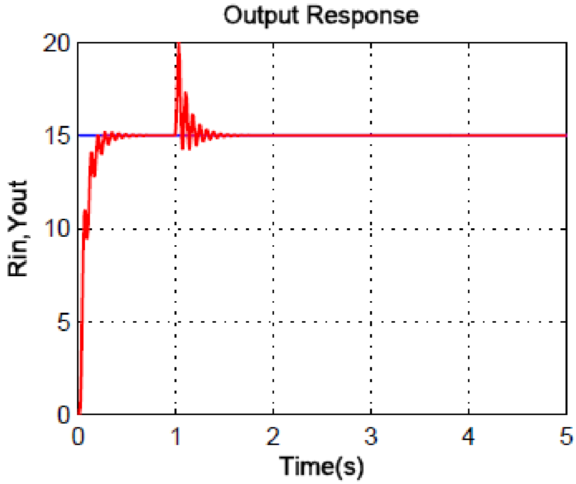

Figure 6. Output response using classical tuning methods

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.

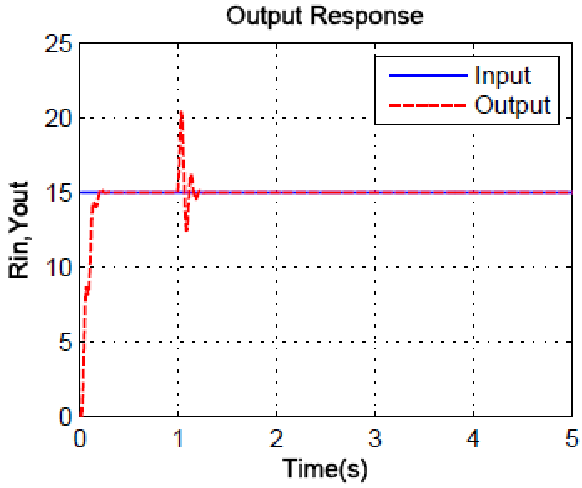

Figure 7. Output response using fuzzy supervisory control

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

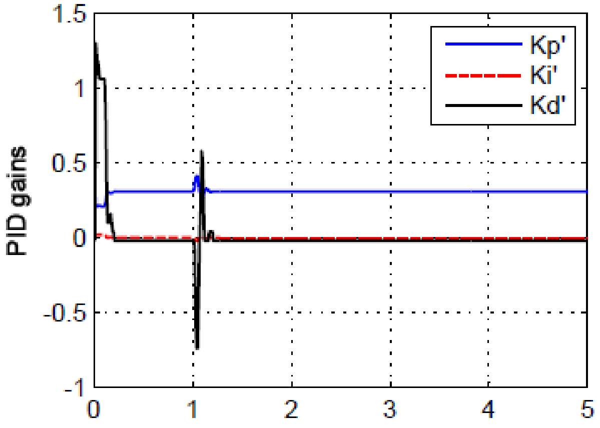

Figure 8. PID parameters variations

Fuzzy supervisory tries to vary PID parameters during process operation to enhance the system response and eliminate 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

PID controller is a good technique in control theory, but there are drawbacks when using in nonlinear systems. Tuning PID gains using traditional methods is boring and difficult to obtain the optimal results so the FLC is a good choice for tuning PID gains online during process. FSC is used for control 5DOF robot arm it uses fuzzy rules for determining PID gains. The output response of PID control using fuzzy tuning is compared with classical tuning. The results showed that tuning of PID parameters based on FLC is better than classical tuning methods.

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