Design of Intelligent Position Control for Single Axis Robot Arm

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Abstract—This paper describes design, modeling and control issues of a simple one DOF positioning robot arm. Mathematical and Simulink model of this electromechanical DC machine is developed. Different classical PD control strategies and structures are applied to return data to analyze the arm system performance and meet desired specifications. Also an intelligent PD employing the soft computation policy is also designed for this system. PD-Fuzzy inference parameters which include the rule base and the shapes of the membership functions are tuned via simulation for better control performance. The intelligent PD control system was compared with the classical PD controls. The feasibility of system is simulated and issue of implementation such intelligent control is established. It is seen that the use of the proposed strategy results in some desirable characteristics.

Index Terms—Fuzzy control, PD control, Robot Arm, Modeling/Simulation, DC machine.

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1. INTRODUCTION

Because of the ease with which they can be controlled, systems of DC machines have been frequently used in many applications requiring a wide range of motor speeds and a precise output motor control [1-2]. Based on the Newton's law combined with the Kirchoff's law, the mathematical model of PMDC motor, describing electric and mechanical characteristics of the motor can be derived.

The accurate control of motion is a fundamental concern in Mechatronics applications, where placing an object in the exact desired location with the exact possible amount of force and torque at the correct exact time is essential for efficient system operation [3].The robot is a controlled mechanism, which has to be able to track different trajectories depending on the actual task [4-6].

Robot arm, having both electrical and mechanical parameters, is an application example of a Mechatronics electromechanical system used in industrial automation [3]. Different control approaches can be proposed to control arm's output angular position, including PD-controller structures, as well as, fuzzy control. This paper addresses modeling, design and control issues of a simple one DOF positioning robot arm to meet desired specifications, based on comparing and analyzing both PD-and Fuzzy logic controllers up on given robotic arm positioning system.

2. SYSTEM MODELING, SIMULATION, CHARACTERISTICS AND ANALYSIS.

In modeling process, to simplify the analysis and design processes, linear approximations are used as long as the results yield a good approximation to reality [7]. As shown in Fig. 1, one DOF robot arm system consists of three main parts; arm, connected to actuator through gear train with gear ratio, *n* [8-9].

In [7,9] based on different approaches, detailed derivation of different and refined mathematical models of PMDC motor and corresponding Simulink models, as well as, a function blocks with its function block parameters window for open loop DC system, motor selection, verification and performance analysis are introduced. The PMDC motor open loop transfer function without load attached relating the input voltage, $V_{in}(s)$, to the motor shaft output angular motion, $\theta_m(s)$, is given by Eq.(1).

There are dynamic requirements, which have to be satisfied depending on the motion and trajectories, where if fast motions are needed, these dynamic effects may dominate static phenomena, [4-6]. To model, Simulate and analyze the open loop Robot arm system, considering that the end-effecter is a part of robot arm, the total equivalent inertia, J_{equiv} and total equivalent damping, b_{equiv} at the armature of the motor are given by Eq.(2). To compute the total inertia, J_{equiv} , robot arm is consider as thin rod of mass *m*, length ℓ, (so that $m = \rho*\ell*s$) , this rod is rotating around the axis which passes through its center and is perpendicular to the rod, end-effecter is assumed of cuboid shape, the rod is rotating around the axis which passes through its center and is perpendicular to the rod. The moment of inertia of the robot arm can be found by computing integral is given by Eq.(2), The moment of inertia of the cuboid end-effecter can be found by Eq.(4). General torque required from the motor is the sum of the static and dynamic torques, assuming the robot arm is horizontal, that is, the weight is perpendicular to the robot arm, the motor required torque is given by Eq.(5), substituting arm and effecter inertias in Eq.(5), and manipulating, gives Eq.(6). The robot arm has the following nominal values; arm mass, M_1= 8 Kg, arm length, L=0.4 m, and viscous damping constant, b = 0.09 N.sec/m, end-effecter mass M_2=0.2 Kg , b=h=0.05 m,. The following nominal values for the various parameters of eclectic motor used: $V_{in}=12$ Volts; J_m= 0.271 $kg{\cdot}m^2$; b_m = 0.271; K_t =

1.1882 *N-m/A;* K_b = 1.185 *V-s/rad;* R_a *=1 Ohm;* L_a*=0.23 Henry;* T_{Load}, gear ratio, for simplicity can be ,n=1.
Based on Eqs. (1, 6) and refereeing to[5,7] the Simulink models shown in Fig. 2 is proposed.

$$G_{angle}(s)=\frac{\theta(s)}{V_{in}(s)}=\frac{K_t}{\left\{\left[\left(L_aJ_ms^3+(R_aJ_m+b_mL_a\right)s^2+(R_ab_m+K_tK_b)s\right]\right\}} \tag{1}$$

$$\begin{gathered} b_{equiv}=b_m+b_{Load}\left(\frac{N_1}{N_2}\right)^2 \\ J_{equiv}=J_m+J_{Load}\left(\frac{N_1}{N_2}\right)^2 \end{gathered} \tag{2}$$

$$\int_{-l/2}^{l/2}\rho x^2 sdx=\rho s\frac{x^3}{3}\Big\|_{-l/2}^{l/2}=\frac{M_1}{sl}s2\frac{l^3/8}{3}=\frac{1}{12}M_1L^2 \tag{3}$$

$$J_{effector}=\frac{bh^3}{12} \tag{4}$$

$$T=J\frac{d^2\theta}{dt^2}+L\left(0.5\cdot M_1\cdot g\cdot L+M_2\right) \tag{5}$$

$$T=\left(\frac{bh^3+M_1L^2}{12}\right)\cdot\frac{d^2\theta}{dt^2}+L\left(0.5\cdot M_1\cdot g+M_2\right) \tag{6}$$

There are many control strategies and structures that may be more or less appropriate to a specific type of application; each has its advantages, disadvantages and limitations. The designer must select the best one for specific application.

3. CONTROL STRATEGY SELECTION, MODELING, DESIGN AND ANALYSIS

In this paper, both classical PD and intelligent PD-Fuzzy controllers are to be applied, evaluated and compared, to move the robot arm to the desired output angular position, θ_L *=[0 : 180]*, corresponding to the applied input voltage, V_{in}*=[0 : 12]* with overshoot less than 5%, a settling time less than 1 second and zero steady state error, Potentiometer constant is select to be K_{pot} *=0.0667.*

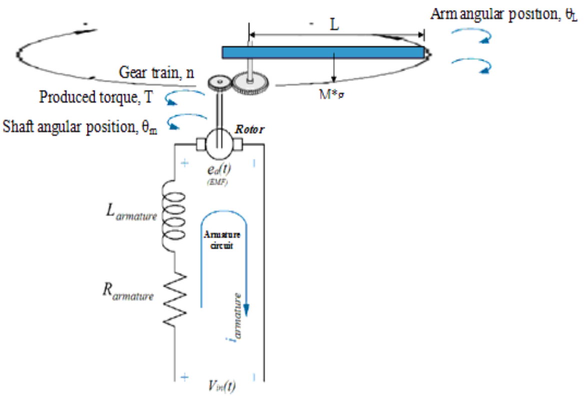

Fig. 1 Simplified schematic model of one DOF robot arm and DC electric machine used to drive arm horizontally [7].

3.1 PD control strategies.

The PD controller can be chosen, because it provides the ability to handle fast process, load changes (e.g. in Pick and place robot), also PD controller reduces the amount of overshoot [10-11].
Running Simulink model with PD only controller for defined parameters, and total arm with load mass of 20kg, will result in response curve shown in Fig. 3(a), the controller's gains and response measures are shown in Table 1, analyzing the response curve and data, show slow response and existence of big steady state error, to overcome this negative effect of PD zero a Prefilter with transfer function given by Eq.(7), is added to cancel negative effects.

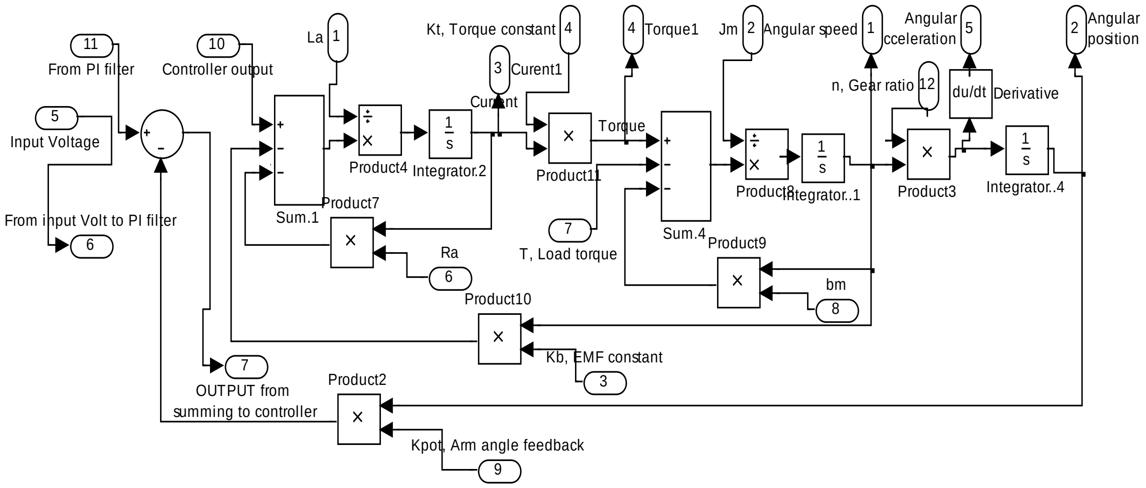

Fig. 2 (a) DC machine subsystem model

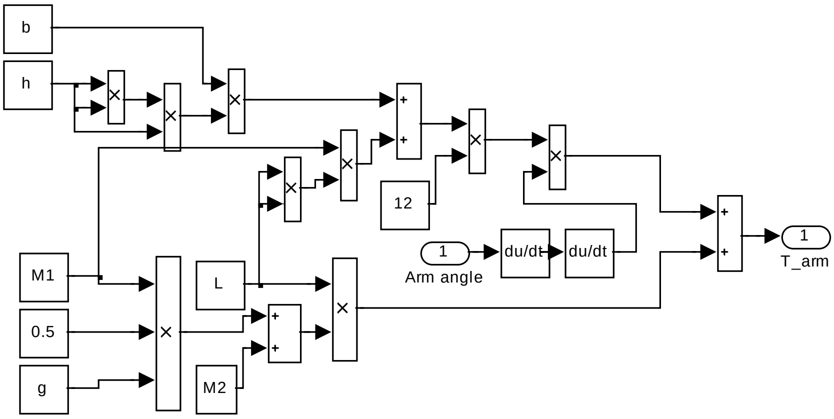

Fig. 2 (b) Robot arm torque Simulink model

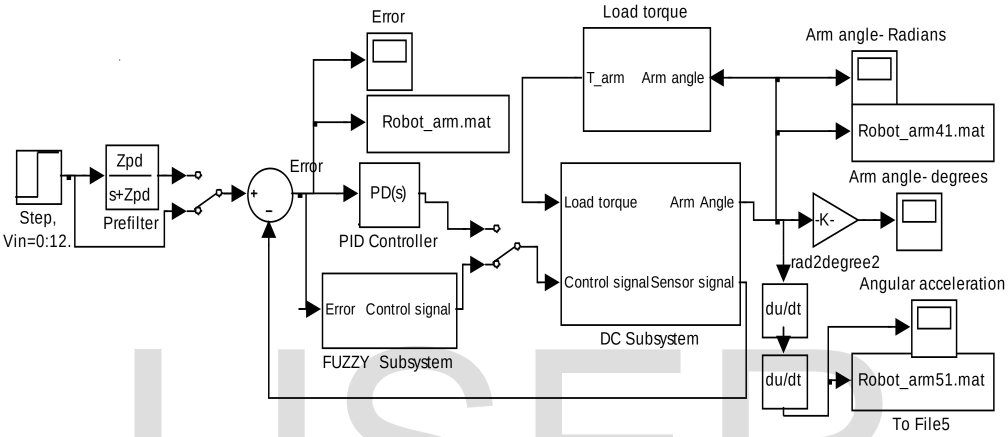

Fig. 2 (c) Simulink model used to test PD and fuzzy algorithms

Running model with PD controller and prefilter will result in response curve shown in Fig. 3(b), the controller's gains and response measures are shown in Table 1. Keeping controller gains fixed and increasing the load mass to result in total mass to be 30 , 32 kg, and running the model for each of both cases, will result in response curve shown in Fig. 3(c)(d), controller's gains and response measures are shown in Table 1, analyzing data and response show that increasing load result in increasing overshoot, error and generally slowing the response, further increasing load mass will result in reaching limitations of the DC motor and controller ability to maintain control, up to instability.

$$G_{Prefilter}(s)=\frac{Z_{PD}}{(s+Z_{PD})},\quad Where:\ Z_{PD}=\frac{K_P}{K_D} \qquad (7)$$

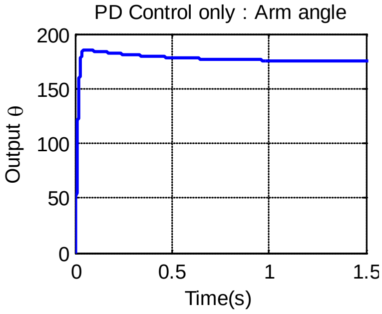

Fig. 3 (a) Arm response with only PD controller

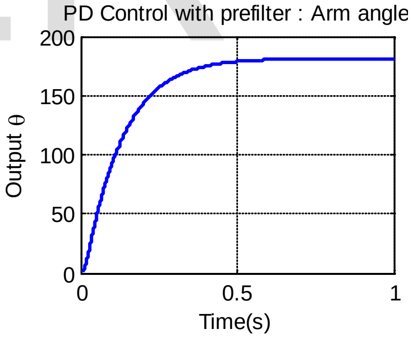

Fig. 3 (b) Arm response with PD and prefilter.

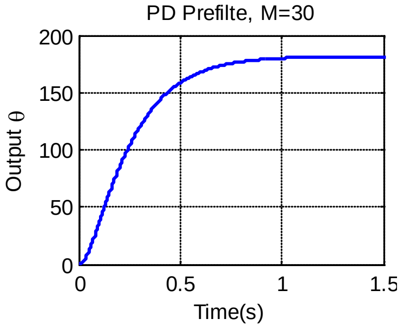

Fig. 3 (c) Arm response with total Mass=30

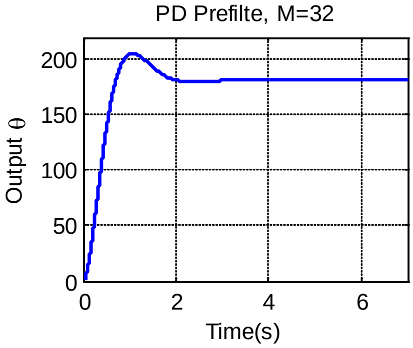

Fig. 3 (d) Arm response with total Mass=32

3.2 *Fuzzy position control of a single axis robot arm*

A.. Controller Design

There are a number of different ways to implement the fuzzy inference engine. Among the very first such proposed techniques is that due to Mamdani [12], which describes the inference engine in terms of a fuzzy relation matrix and uses the compositional rule of inference to arrive at the output fuzzy set for a given input fuzzy set. The output fuzzy set is subsequently defuzzified to arrive at a crisp control action. A review of ranging inferencing techniques is given by Kosko [13]. The inference methodology we employ here is discussed in [14].

Let the input variables be e_p for $1 \leq p \leq P$. The i^{th} membership function in the fuzzifier corresponding to the p^{th} input is $\{\mu_p^i | 1 \leq i \leq N_p\}$. We denote the single output by *f*, with corresponding defuzzification membership functions $\{v^g | 1 \leq g \leq G\}$.

Generalization of inference and adaptation techniques to more than one output is straightforward. In the following analysis, for TEC system, we consider $P = 2$. Defining $N_p = N$ for $p = 1$, and $N_p = M$ for $p = 2$, for a given output membership function v^g, the rules are of the form:

$$if\ e_1\ is\ \mu_1^i\ and\ e_2\ is\ \mu_2^j\ OR\ e_1\ is\ \mu_1^l\ and\ e_2\ is\ \mu_2^m\ OR....$$

$$Then.......\ f\ is\ v^g$$

Define a set

$$S_g = \{l, m | \mu_1^l\ and\ \mu_2^m\ are\ antecedents\ of\ a\ rule$$
$$with\ consequent\ v^g\}$$

The familiar operations to arrive at the output are as follows:

1. Perform a pair wise fuzzy intersection *T*, on each of the membership values of e_1 and e_2 in μ_1^l and μ_2^m for every rule with consequent v^g, forming activation values ζ:

$$\zeta_{lm}^g = \underset{l.m \in S_g}{T} \left(\mu_1^l(e_1) - \mu_2^m(e_2) \right) \qquad (8)$$

Let us assume that the (*T*-norm) operator *T* itself is parameterized by α, i.e., $T = T(\alpha)$.

2. Collect activation values for like output membership functions and perform a fuzzy union T^*, where $T^* = T^*(\beta)$

$$w_g = \underset{l,m \in S_g}{T} \left(\zeta_{lm}^g \right) \qquad (9)$$

3. These values are defuzzified to generate the output estimated value, $f(e_1, e_2)$, by computing the centroid of the composite membership function μ:

$$\mu = \sum_{g=1}^{G} w_g v^g \qquad (10)$$

$$y(e_1, e_2) = \frac{\sum_{g=1}^{G} w_g C_g A_g}{\sum_{g=1}^{G} w_g A_g} \qquad (11)$$

where

$$A_g = \int v^g(e)de;\ C_g = \frac{\int e v^g(e)de}{\int v^g(e)de} \qquad (12)$$

A_g and C_g are, respectively, the area and centroid of the consequent membership function v^g.

B. Adaptation In Fuzzy Inference Systems

All the stages of Fig. 4 are affected by the choice of certain parameters. A list follows.

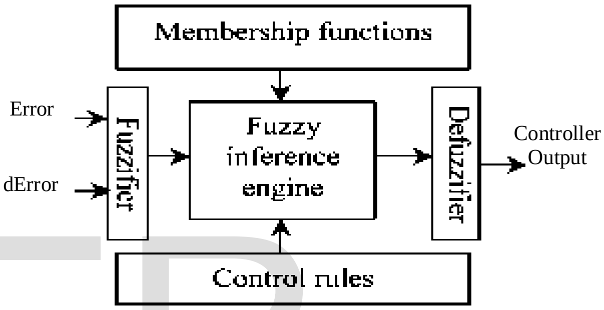

Fig. 4 Block diagram of a fuzzy inference system

1. The Fuzzifier

The fuzzifier in Fig. 5(a) maps the input onto the possibility domain and has the following design parameters:

- The number of membership functions.
- The shape of the membership functions (e.g. triangle, Gaussian, etc.)
- The range of the membership function.

2. The Defuzzifier

The defuzzification stage in Fig. 5(b) maps fuzzy consequents into crisp output values. Its design requires choice of

- The number of membership functions.
- The shape of membership functions.
- The definition of fuzzy implication, i.e., how the value of the consequents from the inference engine impact the output membership functions prior to defuzzification.
- A measure of central tendency of the consequent altered output membership functions. The center of mass is typically used, although use of medians and modes can also be used to arrive at the crisp output.

3. The Inference Engine

The inference engine is the system "decision maker" and determines how the system interprets the fuzzy linguistics. Its parameters are those of the aggregation operators. which provide interpretation of connectives "AND" and "Or". The inference engine surfaces of the rules bases and its membership function is shown in Fig. 6.

It is thus seen that both the fuzzification and defuzzification stages require choices of cardinality, position and shape of membership functions. The defuzzification operation itself can be parameterized, and the inference engine requires choices to be made among numerous fuzzy aggregation operators, which could be parameterized.

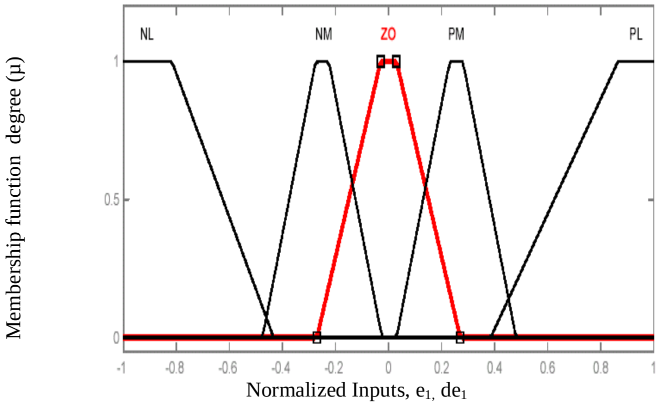

Fig. 5 – a Trapezoidal Membership function of Error and change in Error.

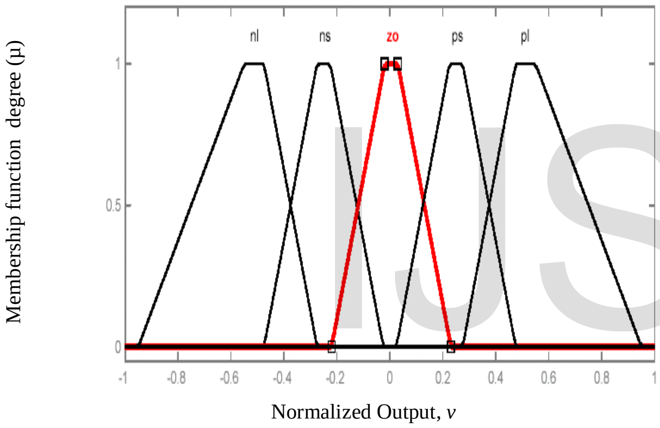

Fig. 5 – b Trapezoidal Membership function of controller output

As part of the fuzzy design categories, we present a technique for choosing the shape of membership functions, as well as a broad methodology for tuning generalized aggregation operators in a fuzzy inference system.

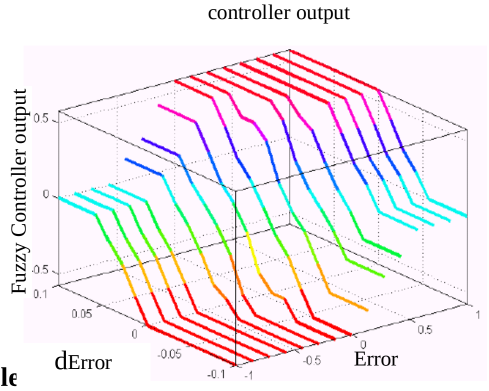

Fig. 6 Surfaces of the rules bases and its membership function.

Running the designed PD fuzzy controller for defined parameters will result in response curve shown in Fig. 7, controller's gains and response measures are shown in Table 1. Keeping PD Fuzzy gains fixed and increasing the load torque and running the model for each case, will result in the same response curve shown in Fig. 7(a), with similar response measures shown in Table 1. Increasing the load torque to be 15 time bigger and running simulation, will result in response curve shown in Fig. 7(b), for such high variation of plant dynamics the response changed with very small values.

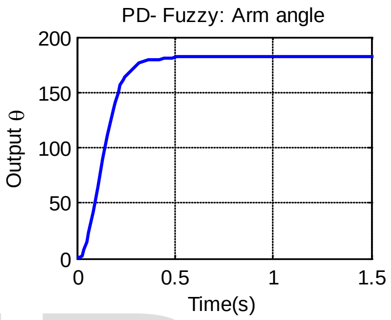

Fig. 7(a) step response applying PD-Fuzzy control structure.

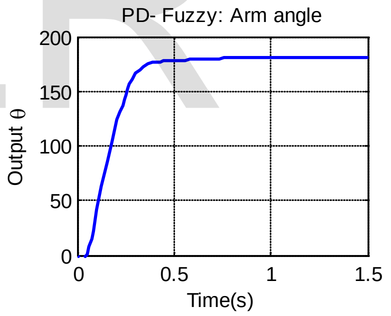

Fig. 7(b) step response applying PD-Fuzzy control structure, when load torque is highly varied

4. CONCLUSIONS

This paper presented the design, the mathematical model, and the control of an electromechanical system. Results from the simulation verified the feasibility and the superiors of the PD-fuzzy control strategy compared with the classical PD control system.

This also indicates that the present PD-fuzzy controller has a good performance in resistance to the variation of plant dynamics which is quit important for a controller design.

Table

Configuration	Total Mass	K_P	K_D	M_P	5T	DC gain	E_{SS}
Only PD	20	7e+6	3e+6	10.9612	**1**	174. 6578	5.3422
PD with prefilter Z_{PD}=8	20			-	0.6	179.865	0.1350
	30			0.4093	1.1	179.6707	0.3293

	32			24.0362	3.2	181.4158	-1.4158

	Total load	K_P	K_D	K_U	$\mathbf{M_P}$	**5T**	**DC gain**	$\mathbf{E_{SS}}$
PD Fuzzy control	**20**	0.01999	1e-04	2e06	-	0.5	180.03	0.03
	30							
	32				-	0.5	180.03	0.03

Appendix: Table 1 Nomenclature

Symbol	Quantity	UNIT
V_{in}	The applied input voltage	Volt, V
R_a	Armature resistance,(terminal resistance)	Ohm ,Ω
$\mathrm{R_f}$	Stator resistance	Ohm ,Ω
i_a	Armature current	Ampere, A
K_t	Motor torque constant	N.m/A
K_b	Motor back-electromotive force const.	V/(rad/s)
ω_m	Motor *shaft* angular velocity	rad/s
T_m	Torque produced by the motor	N.m
J_m	Motor armature moment of inertia	$\mathrm{kg.m^2}$
J_{total}	Total inertia=Jm+Jload	$\mathrm{kg.m^2}$
L_a	Armature inductance	Henry , H
b_m	Viscous damping, *friction coefficient*	N.m/rad.s
$\mathrm{e_a}$	The back electromotive force, $EMF = K_b d\theta/dt$	$\mathrm{e_a}$,*EMF*:
θ_m	Motor shaft output angular position	radians
θ_L	The actual robot arm position	radians
ω_m	Motor shaft output angular speed	rad/sec
$\mathrm{K_{pot}}$	The potentiometer constant	V/rad
$\mathrm{K_{tac}}$	The tachometer constant	Vs/rad
V_p	The potentiometer output voltage	V
T_{load}	Torque of the mechanical load	T_{load}

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