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Novel Adaptive Fuzzy Inference Controller for Highly Nonlinear System

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Abstract

Robot manipulators are multi inputs-multi outputs, nonlinear and time variant system, therefore control of this system is the main challenge in robotic science. Control robot arm according to linear methodology are often having lots of problems because robotic systems are always highly nonlinear. Design accurate controller for robot manipulator is difficult because some dynamic parameters such as compliance and friction are not well understood and some robot parameters such as inertia are difficult to measure accurately and caused to variation in dynamic response. Fuzzy logic controllers have been applied in many applications. One of the important methods to solve above challenge is design adaptive controller based on fuzzy logic. In this paper, intelligent control of robot arm using Proportional-Integral-Derivative (PID) Adaptive Fuzzy Gain scheduling (PID-AFGS) is design for two degrees of robot arm.

Keywords: *Fuzzy logic controller, PID controls, adaptive methodology, adaptive gain scheduling methodology*

1. Introduction

Robot manipulators have many applications in aerospace, manufacturing, automotive, medicine and other industries. Robot manipulators consist of three main parts: mechanical, electrical, and control. In the mechanical point of view, robot manipulators are collection of serial or parallel links which have connected by revolute and/or prismatic joints between base and end-effector frame. The robot manipulators electrical parts are used to run the controllers, actuators for links motion and sensors, which including the following subparts: power supply to supply the electrical and control parts, power amplifier to amplify the signal and driving the actuators, DC/stepper/servo motors or hydraulic/pneumatic cylinders to move the links, and transmission part to transfer data between robot manipulator subparts [1-3]. Control part is used to adjust the timing between the subparts of robot manipulator to reach the best trajectory. It provides four main abilities in robot manipulators [2-4]: controlling the manipulators movement in correct workspace, sensing the information from the environment, being able to intelligent control behavior and processing the data and information between all subparts.

Automatic control has played an important role in advance science and engineering and its extreme importance in many industrial applications, *i.e.*, aerospace, mechanical engineering and robotic systems. The first significant work in automatic control was James Watt's centrifugal governor for the speed control in motor engine in eighteenth century [5-7]. There are several methods for controlling a robot manipulator, which all of them follow two common goals, namely, hardware/software implementation and acceptable performance. However, the mechanical design of robot manipulator is very important to select the best

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controller but in general two types schemes can be presented, namely, a joint space control schemes and an operation space control schemes [1]. Joint space and operational space control are closed loop controllers which they have been used to provide robustness and rejection of disturbance effect. The main target in joint space controller is design a feedback controller that allows the actual motion ($q_a(t)$) tracking of the desired motion ($q_d(t)$). This control problem is classified into two main groups. Firstly, transformation the desired motion $X_d(t)$ to joint variable $q_d(t)$ by inverse kinematics of robot manipulators [8-10]. The main target in operational space controller is to design a feedback controller to allow the actual end-effector motion $X_a(t)$ to track the desired endeffector motion $X_d(t)$.

Some of robot manipulators are controlled by linear PID controllers, but the design of linear controller for robot manipulator is extremely difficult because this system is hardly nonlinear and uncertain [5-7]. To reduce the above challenges, the nonlinear fuzzy logic controller is used to control of nonlinear systems. Conventional controllers require accurate information of dynamic model of robot manipulator, but most of time these models are MIMO, nonlinear and partly uncertain therefore calculate accurate dynamic model is complicated [8]. One of the significant challenges in control algorithms is a linear behavior controller design for nonlinear systems (*e.g.*, robot manipulator). Some of robot manipulators which work in industrial processes are controlled by linear PID controllers, but the design of linear controller for robot manipulators is extremely difficult because they are hardly nonlinear and uncertain. To reduce the above challenges, the nonlinear robust controller is used to control of robot manipulator. Computed torque controller is a nonlinear controller [9-10]. To solve the uncertainties problem, fuzzy logic theory is used. The main reasons to use fuzzy logic methodology are able to give approximate recommended solution for uncertain and also certain complicated systems to easy understanding and flexible. Fuzzy logic provides a method to design a model-free controller for nonlinear plant with a set of IF-THEN rules [11-12]. The applications of artificial intelligence such as neural networks and fuzzy logic in modelling and control are significantly growing especially in recent years [13-14].

This paper is organized as follows: In section 2, main subject of modeling robot manipulator formulation, detail of PID controller, and fuzzy logic method are presented. Detail of proposed methodology is presented in section 3. In section 4, the simulation result is presented and finally in section 5, the conclusion is presented.

2. Theory

Dynamic Formulation of 2-DOF Robot Manipulator: Dynamic modeling of robot manipulators is used to describe the behavior of robot manipulator such as linear or nonlinear dynamic behavior, design of model based controller such as pure sliding mode controller which design this controller is based on nonlinear dynamic equations, and for simulation. The dynamic modeling describes the relationship between joint motion, velocity, and accelerations to force/torque or current/voltage and also it can be used to describe the particular dynamic effects (*e.g.*, inertia, coriolios, centrifugal, and the other parameters) to behavior of system[1]. The equation of an *n-DOF* robot manipulator governed by the following equation [3-5]:

$$\boldsymbol{M(q)\ddot{q} + N(q,\dot{q}) = \tau} \tag{1}$$

Where τ is actuation torque, M (q) is a symmetric and positive define inertia matrix, $N(q,\dot{q})$ is the vector of nonlinearity term. This robot manipulator dynamic equation can also be written in a following form [12-14]:

$$\boldsymbol{\tau} = \boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{B}(\boldsymbol{q})[\dot{\boldsymbol{q}}\,\dot{\boldsymbol{q}}] + \boldsymbol{C}(\boldsymbol{q})[\dot{\boldsymbol{q}}]^{2} + \boldsymbol{G}(\boldsymbol{q}) \quad \textbf{(2)}$$

Where B (q) is the matrix of coriolios torques, C(q) is the matrix of centrifugal torques, and G(q) is the vector of gravity force. The dynamic terms in equation (2) are only manipulator position. This is a decoupled system with simple second order linear differential dynamics. In other words, the component $\ddot{q}$ influences, with a double integrator relationship, only the joint variableq_i, independently of the motion of the other joints. Therefore, the angular acceleration is found as to be [12-14]:

$$\ddot{\boldsymbol{q}} = \boldsymbol{M}^{-1}(\boldsymbol{q}).\{\boldsymbol{\tau} - \boldsymbol{N}(\boldsymbol{q},\dot{\boldsymbol{q}})\} \quad \textbf{(3)}$$

This technique is very attractive from a control point of view.

Forward Kinematics of Robot: Calculate the relationship between rigid bodies and end-effector without any forces is called Robot manipulator Kinematics. Study of this part is pivotal to calculate accurate dynamic part, to design with an acceptable performance controller, and in real situations and practical applications. As expected the study of manipulator kinematics is divided into two main parts: forward and inverse kinematics. Forward kinematics has been used to find the position and orientation of task (end-effector) frame when angles and/or displacement of joints are known. Inverse kinematics has been used to find possible joints variable (displacements and angles) when all position and orientation of end-effector be active [1].
The main target in forward kinematics is calculating the following function:

$$\boldsymbol{\Psi}(\boldsymbol{X},\boldsymbol{q}) = \boldsymbol{0} \quad \textbf{(4)}$$

Where $\Psi(.) \in R^{n}$ is a nonlinear vector function, $X = [X_1, X_2, \dots\dots, X_l]^{T}$ is the vector of task space variables which generally endeffector has six task space variables, three position and three orientation, $q = [q_1, q_2, \dots., q_n]^{T}$ is a vector of angles or displacement, and finally n is the number of actuated joints. The Denavit-Hartenberg (D-H) convention is a method of drawing robot manipulators free body diagrams. Denvit-Hartenberg (D-H) convention study is necessary to calculate forward kinematics in serial robot manipulator. The first step to calculate the serial link robot manipulator forward kinematics is link description; the second step is finding the D-H convention after the frame attachment and finally finds the forward kinematics. Forward kinematics is a 4×4 matrix which 3×3 of them shows the rotation matrix, 3×1 of them is shown the position vector and last four cells are scaling factor[1, 6]. Singularity is a location in the robot manipulator's workspace which the robot manipulator loses one or more degrees of freedom in Cartesian space. Singularities are one of the most important challenges in inverse kinematics which Cheng *et al.*, have proposed a method to solve this problem [11]. A systematic Forward Kinematics of robot manipulator solution is the main target of this part. The first step to compute Forward Kinematics (F.K) of robot manipulator is finding the standard D-H parameters. The following steps show the systematic derivation of the standard D-H parameters.

1. Locate the robot arm
2. Label joints
3. Determine joint rotation or translation ($\theta\ or\ d$)
4. Setup base coordinate frames.
5. Setup joints coordinate frames.

6. Determineα_i, thatα_i, link twist, is the angle between Z_i and Z_{i+1} about an X_i.
7. Determine d_i and a_i , that a_i, link length, is the distance between Z_i and Z_{i+1} along X_i. d_i, offset, is the distance between X_{i-1} and X_i along Z_i axis.
8. Fill up the D-H parameters table.

The second step to compute Forward kinematics for robot manipulator is finding the rotation matrix (R_n^0). The rotation matrix from$\{F_i\}$ to $\{F_{i-1}\}$ is given by the following equation;

$$\boldsymbol{R_i^{i-1} = U_{i(\theta_i)} V_{i(\alpha_i)}} \tag{5}$$

Where $U_{i(\theta_i)}$ is given by the following equation [1];

$$\boldsymbol{U_{i(\theta_i)} = \begin{bmatrix} cos(\theta_i) & -sin(\theta_i) & 0 \\ sin(\theta_i) & cos(\theta_i) & 0 \\ 0 & 0 & 1 \end{bmatrix}} \tag{6}$$

and $V_{i(\alpha_i)}$ is given by the following equation [1];

$$\boldsymbol{V_{i(\theta_i)} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos(\alpha_i) & -sin(\alpha_i) \\ 0 & sin(\alpha_i) & cos(\alpha_i) \end{bmatrix}} \tag{7}$$

So (R_n^0) is given by [1]

$$\boldsymbol{R_n^0 = (U_1 V_1)(U_2 V_2) \dots \dots \dots (U_n V_n)} \tag{8}$$

The third step to compute the forward kinematics for robot manipulator is finding the displacement vector d_n^0, that it can be calculated by the following equation [1]

$$\boldsymbol{d_n^0 = (U_1 S_1) + (U_1 V_1)(U_2 S_2) + \dots + (U_1 V_1)(U_2 V_2) \dots . (U_{n-1} V_{n-1})(U_n S_n)} \tag{9}$$

The forth step to compute the forward kinematics for robot manipulator is calculate the transformation ${}_n^0T$ by the following formulation [1].

$$\boldsymbol{{}_n^0T = {}_1^0T . {}_2^1T . {}_3^2T \dots \dots . {}_n^{n-1}T = \begin{bmatrix} R_n^0 & d_n^0 \\ 0 & 1 \end{bmatrix}} \tag{10}$$

Figure 1 shows the block diagram of two degrees of freedom robot manipulator.

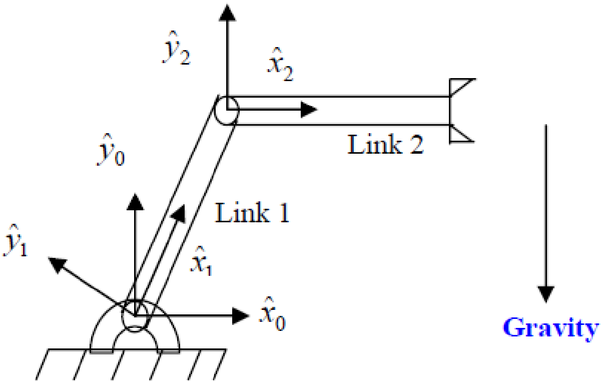

Figure 1. Manipulator Used for Simulations

Design PID Controller: Design of a linear methodology to control of continuum robot manipulator was very straight forward. Since there was an output from the torque model, this means that there would be two inputs into the PID controller. Similarly, the outputs of the controller result from the two control inputs of the torque signal. In a typical PID method, the controller corrects the error between the desired input value and the measured value. Since the actual position is the measured signal. Figure 2 is shown linear PID methodology, applied to continuum robot manipulator [5].

$$\boldsymbol{e(t) = \theta_a(t) - \theta_d(t)} \tag{11}$$

$$\boldsymbol{U_{PID} = K_{p_a} e + K_{V_a} \dot{e} + K_I \sum e} \tag{12}$$

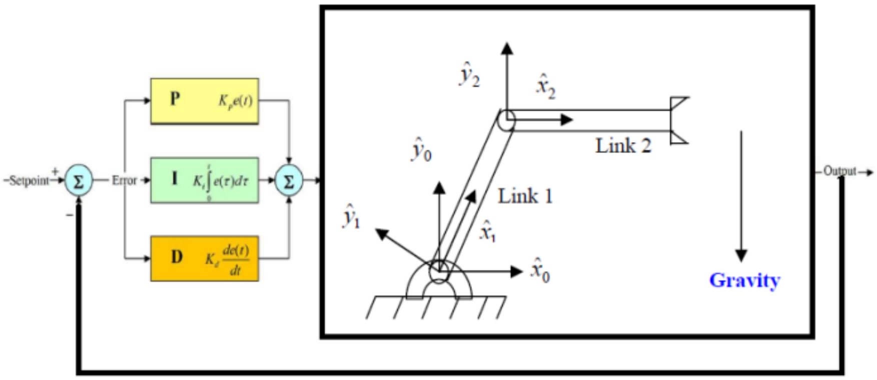

Figure 2. Block Diagram of Linear PID Method

The model-free control strategy is based on the assumption that the joints of the manipulators are all independent and the system can be decoupled into a group of single-axis control systems. Therefore, the kinematic control method always results in a group of individual controllers, each for an active joint of the manipulator. With the independent joint assumption, no a priori knowledge of robot manipulator dynamics is needed in the kinematic controller design, so the complex computation of its dynamics can be avoided and the controller design can be greatly simplified. This is suitable for real-time control applications when powerful processors, which can execute complex algorithms rapidly, are not accessible. However, since joints coupling is neglected, control performance degrades as operating speed increases and a manipulator controlled in this way is only appropriate for relatively slow motion [31-34]. The fast motion requirement results in even higher dynamic coupling between the various robot joints, which cannot be compensated for by a standard robot controller such as PID [33-34], and hence model-based control becomes the alternative.

Fuzzy Logic Methodology: Based on foundation of fuzzy logic methodology; fuzzy logic controller has played important rule to design nonlinear controller for nonlinear and uncertain systems [10-11]. However the application area for fuzzy control is really wide, the basic form for all command types of controllers consists of;

Input fuzzification (binary-to-fuzzy [B/F] conversion) Fuzzy rule base (knowledge base), Inference engine and Output defuzzification (fuzzy-to-binary [F/B] conversion). Figure 3 shows a fuzzy controller part.

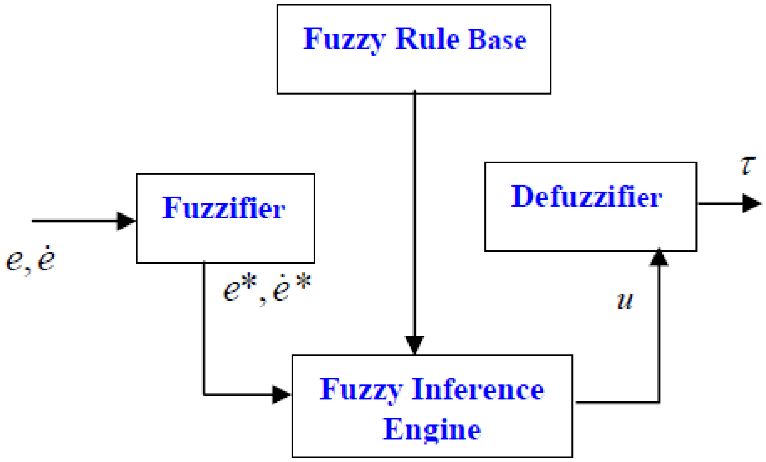

Figure 3. Fuzzy Controller Detail

Block diagram of fuzzy logic controller to control of 2 DOF robot manipulator shows in Figure 4.

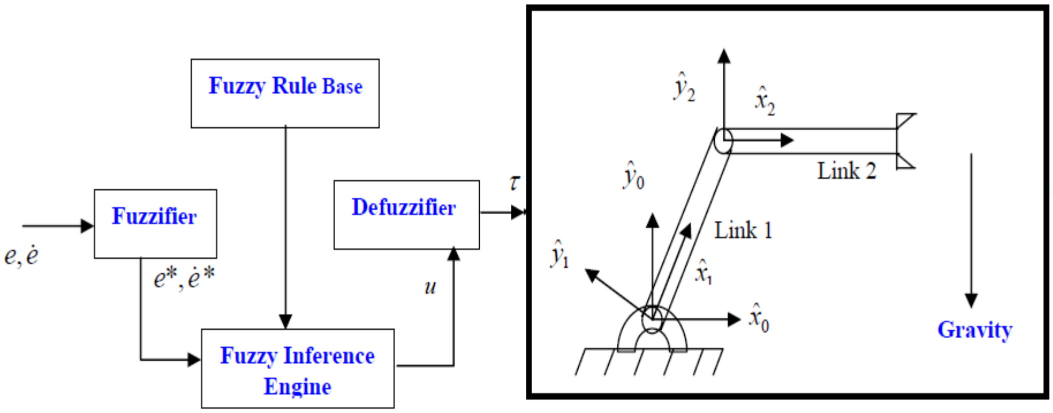

Figure 4. Block Diagram of Fuzzy Controller

The fuzzy inference engine offers a mechanism for transferring the rule base in fuzzy set which it is divided into two most important methods, namely, Mamdani method and Sugeno method. Mamdani method is one of the common fuzzy inference systems and he designed one of the first fuzzy controllers to control of system engine. Mamdani's fuzzy inference system is divided into four major steps: fuzzification, rule evaluation, aggregation of the rule outputs and defuzzification. Michio Sugeno use a singleton as a membership function of the rule consequent part. The following definition shows the Mamdani and Sugeno fuzzy rule base

$$\begin{array}{l} \boldsymbol{if\ x\ is\ A\ and\ y\ is\ B\ then\ z\ is\ C\ 'mamdani'} \\ \boldsymbol{if\ x\ is\ A\ and\ y\ is\ B\ then\ z\ is\ f(x,y)'sugeno'} \end{array} \tag{13}$$

When x and y have crisp values fuzzification calculates the membership degrees for antecedent part. The Figure of membership functions and linguistic variable shows in Figure 5.

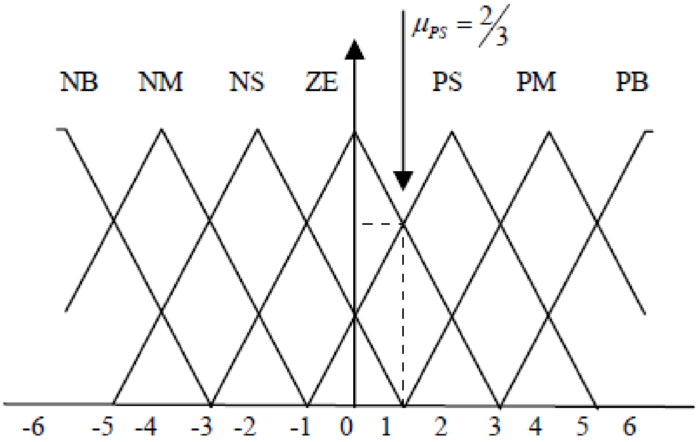

Figure 5. Membership Functions of Linguistic Variables

Rule evaluation focuses on fuzzy operation (AND/OR) in the antecedent of the fuzzy rules. The aggregation is used to calculate the output fuzzy set and several methodologies can be used in fuzzy logic controller aggregation, namely, Max-Min aggregation, Sum-Min aggregation, Max-bounded product, Max-drastic product, Max-bounded sum, Max-algebraic sum and Min-max. Two most common methods that used in fuzzy logic controllers are Max-min aggregation and Sum-min aggregation. Max-min aggregation defined as below;

$$\boldsymbol{\mu_U(x_k, y_k, U) = \mu_{\cup_{i=1}^{r} FR^i}(x_k, y_k, U) = \max\left\{\min_{i=1}^{r}\left[\mu_{R_{pq}}(x_k, y_k), \mu_{p_m}(U)\right]\right\}} \tag{14}$$

The Sum-min aggregation defined as below

$$\boldsymbol{\mu_U(x_k, y_k, U) = \mu_{\cup_{i=1}^{r} FR^i}(x_k, y_k, U) = \sum \min_{i=1}^{r}\left[\mu_{R_{pq}}(x_k, y_k), \mu_{p_m}(U)\right]} \tag{15}$$

where r is the number of fuzzy rules activated by x_k and y_k and also $\mu_{\cup_{i=1}^{r} FR^i}(x_k, y_k, U)$ is a fuzzy interpretation of $i-th$ rule. Defuzzification is the last step in the fuzzy inference system which it is used to transform fuzzy set to crisp set. Consequently defuzzification's input is the aggregate output and the defuzzification's output is a crisp number. Centre of gravity method (COG) and Centre of area method (COA) are two most common defuzzification methods, which COG method used the following equation to calculate the defuzzification

$$\boldsymbol{COG(x_k, y_k) = \frac{\sum_i U_i \sum_{j=1}^{r} . \mu_u(x_k, y_k, U_i)}{\sum_i \sum_{j=1}^{r} . \mu_u(x_k, y_k, U_i)}} \quad \textbf{(16)}$$

and COA method used the following equation to calculate the defuzzification

$$\boldsymbol{COA(x_k, y_k) = \frac{\sum_i U_i . \mu_u(x_k, y_k, U_i)}{\sum_i \mu_U . (x_k, y_k, U_i)}} \quad \textbf{(17)}$$

Where $COG(x_k, y_k)$ and $COA(x_k, y_k)$ illustrates the crisp value of defuzzification output, $U_i \in U$ is discrete element of an output of the fuzzy set, $\mu_U.(x_k, y_k, U_i)$ is the fuzzy set membership function, and r is the number of fuzzy rules.

3. Methodology

Linear PID controller works quite well in certain dynamic system but in practical application most of system works in uncertain condition and linear controllers have problem in this situation. At the same time, the dynamics of the robot can change during the process, and that can affect the result of the control, too. In this case the result of linear PID controller can decrease because the inquiry of dynamic model. To avoid of this situation fuzzy logic method is used to online adjustment of the PID parameters. In this case we can achieve the desired settling time and we can achieve very small steady state tracking errors. Based on fuzzy logic methodology

$$\boldsymbol{f(x) = U_{fuzzy} = \sum_{l=1}^{M} \theta^T \zeta(x)} \quad \textbf{(18)}$$

where $\boldsymbol{\theta^T}$ is adjustable parameter (gain updating factor) and $\boldsymbol{\zeta(x)}$ is defined by

$$\boldsymbol{\zeta(x) = \frac{\sum_i \mu(x_i) x_i}{\sum_i \mu(x_i)}} \quad \textbf{(19)}$$

Where $\boldsymbol{\mu(x_i)}$ is membership function.

This methodology has two main parts;

- Linear PID controller
- fuzzy tuning controller.

Based on this methodology;

$$\boldsymbol{\tau = \left(K_i \times U_{fuzzy}(\sum e) + K_v \times U_{fuzzy}(\dot{e}) + K_p \times U_{fuzzy}(e)\right)} \quad \textbf{(20)}$$

If the Lyapunov function in this method defined as follows;

$$\boldsymbol{V} = \left(\frac{1}{2}\right)\left(\dot{\boldsymbol{q}}^{\boldsymbol{T}} \times \dot{\boldsymbol{q}}\right) + \left(\boldsymbol{e}^{\boldsymbol{T}}\boldsymbol{K}_{\boldsymbol{p}}\boldsymbol{e}\right) + \frac{1}{2}\sum_{J=1}^{M}\frac{1}{\gamma_j}\boldsymbol{\phi}^{\boldsymbol{T}}.\boldsymbol{\phi}_{\boldsymbol{j}} \tag{21}$$

and the differentiate to obtain

$$\dot{\boldsymbol{V}} = \left(\dot{\boldsymbol{q}}^{\boldsymbol{T}}\right)\left(\ddot{\boldsymbol{q}} + \frac{1}{2}\dot{\boldsymbol{q}}\dot{\boldsymbol{e}} - \boldsymbol{K}_{\boldsymbol{p}}\boldsymbol{e}\right) + \sum_{J=1}^{M}\frac{1}{\gamma_j}\boldsymbol{\phi}^{\boldsymbol{T}}.\dot{\boldsymbol{\phi}}_{\boldsymbol{j}} \tag{22}$$

Based on (21) and (22);

$$\dot{\boldsymbol{V}} = \left(\dot{\boldsymbol{q}}^{\boldsymbol{T}}\right)(\frac{1}{2}\dot{\boldsymbol{e}} - \sum_{J=1}^{M}\frac{1}{\gamma_j}\boldsymbol{\phi}^{\boldsymbol{T}}.\dot{\boldsymbol{\phi}}_{\boldsymbol{j}} = \dot{\boldsymbol{q}}^{\boldsymbol{T}}\boldsymbol{K}_{\boldsymbol{v}}\dot{\boldsymbol{q}} + \sum_{J=1}^{M}\frac{1}{\gamma_j}\boldsymbol{\phi}^{\boldsymbol{T}}.\dot{\boldsymbol{\phi}}_{\boldsymbol{j}} \tag{23}$$

Therefore the skew symmetry of the first term is given by;

$$\dot{\boldsymbol{V}} = -\dot{\boldsymbol{q}}^{\boldsymbol{T}}\boldsymbol{K}_{\boldsymbol{v}}\dot{\boldsymbol{q}} - \sum_{J=1}^{M}\frac{1}{\gamma_j}\boldsymbol{\phi}^{\boldsymbol{T}}.\dot{\boldsymbol{\phi}}_{\boldsymbol{j}} \tag{24}$$

The proposed methodology shows in Figure 6.

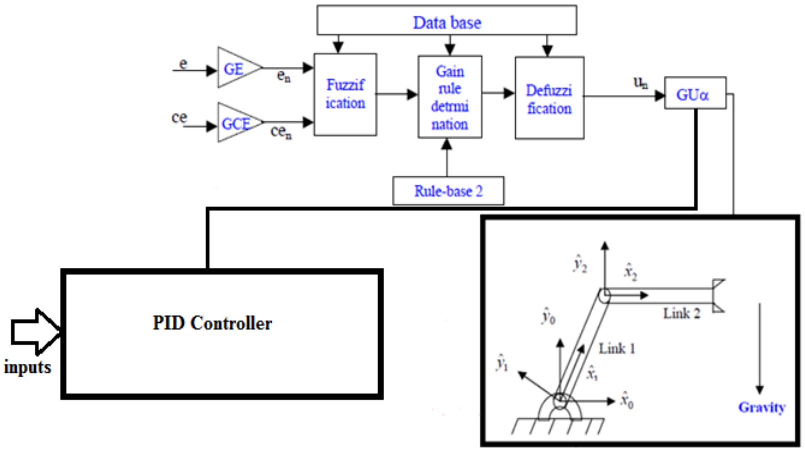

Figure 6. Adaptive Fuzzy Gain Scheduling Controller

4. Results and Discussion

Linear PID adaptive fuzzy gain scheduling controller was tested to Step response trajectory. In this simulation is used to control position of robot without and with external disturbance. The simulation was implemented in MATLAB/SIMULINK environment. These systems are tested by band limited white noise with a predefined 40% of relative to the input signal amplitude. This type of noise is used to external disturbance in continuous and hybrid systems and applied to nonlinear dynamic of these controllers.

Tracking Performances: Figure 7 shows tracking performance for PID and proposed method without disturbance. By comparing step response trajectory without disturbance in

CTC and AFGSC, it is found that the AFGSC's overshoot **(1.4%)** is lower than CTC's **(1.6%)**.

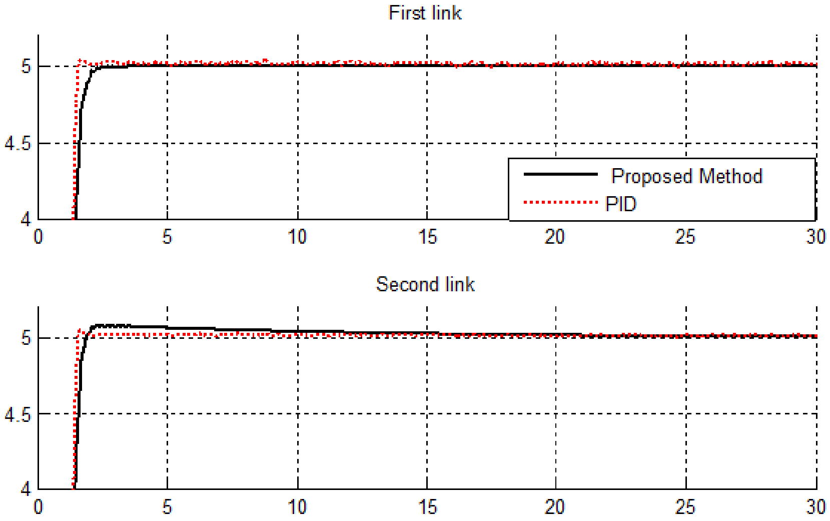

Figure 7. PID Controller and Proposed Method

Disturbance Rejection: Figure 8 shows the power disturbance elimination in PID and proposed method. The main target in this controller is disturbance rejection as well as the other responses. A band limited white noise with predefined of 40% the power of input signal is applied to PID and proposed method. It found fairly fluctuations in trajectory responses. As mentioned earlier, PID works very well when all parameters are known, or we have a limitation uncertainty in parameters. In this part conventional PID method has oscillation in presence of uncertainty and external disturbance.

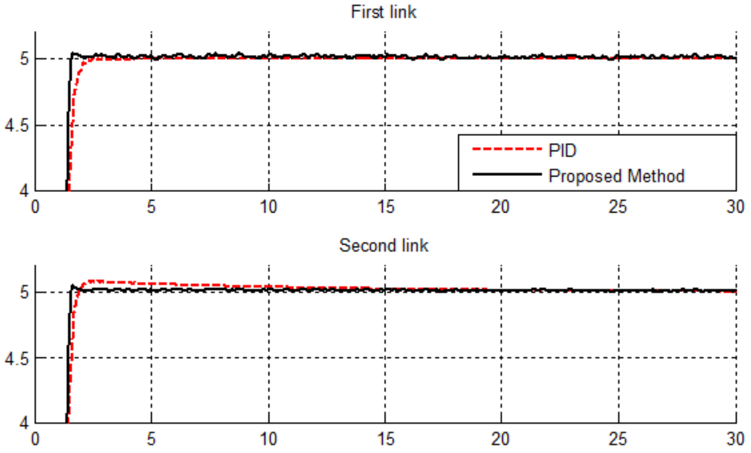

Figure 8. PID and Proposed Method with Disturbance

5. Conclusion

According to this research, adaptive gain scheduling controller is design and applied to robot manipulator. This method is used to resolve the uncertainty problem in conventional linear PID controller. Based on this method fuzzy tuning can solve the deviation on error, change of error and integral of error based on, online tuning the coefficients. According to this method, simulation and graphs; it can reduce the overshoot and oscillation in presence of uncertainty and external disturbance. In the worst case, the adaptive controller has the potential to perform as well as a PID controller. In adaptive methodology, the fuzzy controller action provides gross adjustments to attain the state of the system near to the set point.

References

[1] G. I. Vachtsevanos, K. Davey, and K. M. Lee, "Development of a Novel Intelligent Robotic Manipulator," IEEE Control System Magazine, (**1987**), pp. 9-15.

[2] K. Davey, G. I. Vachtsevanos, and R. Powers, "An analysis of Fields and Torques in Spherical Induction Motors," lEE Transactions on Magnetics, vol. MAG-23, (**1987**), pp. 273-282.

[3] A. Foggia, E. Oliver and F. Chappuis, "New Three Degrees of Freedom Electromagnetic Actuator," Conference Record -lAS Annual Meeting, New York, vol. 35, (**1988**).

[4] K. M. Lee, G. Vachtsevanos, and C-K. Kwan, "Development of a Spherical Wrist Stepper Motor," Proceedings of the 1988 IEEE lntemational Conference on Robotics and Automation, Philadelphia, PA. April 26-29.

[5] K. M. Lee and I. Pei, "Kinematic Analysis of a Three Degree-of-Freedom Spherical Wrist Actuator," The Fifth International Conference on Advanced Robotics, Italy, (**1991**).

[6] I. Wang, G. Jewel and D. Howe, "Modeling of a Novel Spherical Pennanent Magnet Actuator," Proceedings of IEEE International Conference on Robotics and Automation, Albuquerque, New Mexico, (**1997**), pp. 1190-1195.

[7] I. Wang, G. Jewel and D. Howe, "Analysis, Design and Control of a Novel Spherical Pennanent Magnet Actuator," lEE Proceedings on Electrical Power Applications, vol. 154, no. 1, (**1998**).

[8] G. S. Chirikjian and D. Stein, "Kinematic Design and Commutation of a Spherical Stepper Motor," IEEEIASME Transactions on Mechatronics, vol. 4, n 4, Piscataway, New Jersey, (**1999**) December, pp. 342-353.

[9] K. Kahlen, and R. W. De Doncker, "CW'l'ent Regulators for Multi-phase Pennanent Magnet Spherical Machines", Industry Applications Conference Record of the 2000 IEEE, vol. 3, (**2000**), pp. 2011-2016.

[10] K. M. Lee, I. Pei, and U. Gilboa, "On the Development of a Spherical Wrist Actuator", Proceedings of the 16th NSF Conference on Manufacturing Systems Research, Tempe AZ, (**1990**) January 8-12.

[11] C. Yang and Y. S. Back, "Design and Control of the 3-dcgn:es of freedom actuator by Controlling the Electromagnetic Force", IEEE Transactions on Magnetics, (**1999**) May, pp. 3607-3609.

[12] A. Shahcheraghi, F. Piltan, M. Mokhtar, O. Avatefipour and A. Khalilian, "Design a Novel SISO Off-line Tuning of Modified PID Fuzzy Sliding Mode Controller", IJITCS, vol. 6, no. 2, (**2014**), pp. 72-83. DOI: 10.5815/ijitcs.2014.02.10

[13] M. M. Ebrahimi, F. Piltan, M. Bazregar and A. Nabaee, "Artificial Chattering Free on-line Modified Sliding Mode Algorithm: Applied in Continuum Robot Manipulator", International Journal of Information Engineering and Electronic Business, vol. 5, no. 5, (**2013**), pp. 57-69. DOI: 10.5815/ijieeb.2013.05.08

[14] A. Jahed, F. Piltan, H. Rezaie and B. Boroomand, "Design Computed Torque Controller with Parallel Fuzzy Inference System Compensator to Control of Robot Manipulator", International Journal of Information Engineering and Electronic Business, vol. 5, no. 3, (**2013**), pp. 66-77. DOI: 10.5815/ijieeb.2013.03.08