Design On-Line Tunable Gain Artificial Nonlinear Controller

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Abstract

One of the most important challenges in nonlinear, multi-input multi-output (MIMO) and time variant systems (e.g., robot manipulator) is designing a controller with acceptable performance. This paper focused on design a new artificial non linear controller with on line tunable gain applied in the robot manipulator. The sliding mode fuzzy controller (SMFC) was designed as 7 rules Mamdani's inference system because it has one input as sliding function and one output as fuzzy sliding function (U_{fs}) *which the integral part was added to the sliding function in the presence of uncertainties and external disturbance to reduce the limitations. Sliding mode controller (SMC) has two most important challenges in uncertain systems: chattering phenomenon and nonlinear dynamic equivalent part. Applying the sliding mode methodology to Mamdani's fuzzy logic controller with minimum rules was the first goal that caused the stability development. Second target focused on the elimination of chattering phenomenon with regard to the variety of uncertainty and external disturbance in fuzzy sliding mode controller by on-line optimization the tunable gain.*

Keywords: *robot manipulator, artificial nonlinear controller, on-line tunable gain, sliding mode controller, sliding mode fuzzy controller, chattering phenomenon, dynamic equivalent part, on-line optimization*

1. Introduction

Most of robot manipulators which work in industry are usually controlled by linear controllers. The robot manipulator dynamic functions are, being nonlinear with strong coupling between joints (low gear ratio), structure and unstructured uncertainty, and multi- inputs multi-outputs (MIMO). The design of linear controller is very difficult especially when the velocity and acceleration of robot manipulator is high and also when the ratio between joints gear is small [2]. To eliminate above problems in physical systems most of control researchers tend toward selecting nonlinear robust controller.

Sliding mode controller (SMC) is an influential nonlinear robust controller which was first proposed in the 1950 [3-4]. However this controller has an acceptable control performance, is wide range and solves some main challenging topics in control such as resistivity of the external disturbance and uncertainty but pure sliding mode controller has some disadvantages. The first challenge in classical SMC is chattering phenomenon, chattering problem can caused high frequency oscillation of the controllers output. The second one is equivalent dynamic formulation where calculation of equivalent control formulation is difficult since it depends on the nonlinear dynamic equation [5]. To solve this challenge artificial intelligence (e.g., fuzzy logic) is applied into SMC which compensate the equivalent nonlinear dynamic formulation. In this research fuzzy logic methodology was applied in to SMC in order to reduce the chattering and solve the nonlinear dynamic equivalent problems [7-11]. The result of applying fuzzy concept was fuzzy sliding mode controller (FSMC).

This paper is organized as follows: In section 2, the main subject of sliding mode controller and formulation were presented. The reason of designing sliding mode fuzzy controller with tuneable gain was presented in section 3. This section covers the self tuning proposed sliding mode fuzzy controller. This method was used to reduce the chattering and estimate the equivalent (nonlinear) part in SMFC. In section 4, the main concepts of modelling robot manipulator formulation were presented. In section 5 and 6, the simulation result and conclusion were presented respectively.

2. Classical Sliding Mode Control

CSMC has been applied to control nonlinear, MIMO and uncertain system. Robot manipulator has nonlinear dynamic formulation which opts the best performance controller which is a challenging work. Basically formulation of a sliding mode controller is shown as [3] in equation 1:

$$U = U_{eq} + U_r \tag{1}$$

Where, the model-based component $\boldsymbol{U_{eq}}$ compensate for the nominal dynamics of the systems. So $\boldsymbol{U_{eq}}$ can be calculated as follows [1, 3] in equation 2:

$$U_{eq} = \left[M^{-1}(B + C + G) + \dot{S}\right]M \tag{2}$$

Assuming $\boldsymbol{S = \lambda e + \dot{e}}$ yields $\boldsymbol{\dot{S} = \lambda \dot{e} + \ddot{q}_d}$. A simple solution to get the sliding condition when the dynamic parameters have uncertainty is the switching control law [14] as in equation 3:

$$\mathrm{U_r} = \mathrm{K}(\vec{\mathrm{x}}, \mathrm{t}).\operatorname{sgn}(\mathrm{s}) \qquad \operatorname{sgn}(\mathrm{s}) = \begin{cases} 1 & \mathrm{s} > 0 \\ -1 & \mathrm{s} < 0 \\ 0 & \mathrm{s} = 0 \end{cases} \tag{3}$$

Where the $\boldsymbol{K(\vec{x}, t)}$ is the positive constant. To reduce or eliminate the chattering this research focused on the boundary layer methods in which the basic idea is to replace the discontinuous method by saturation (linear) method. The saturation function $\mathbf{Sat}(\mathbf{S}/_{\emptyset})$ is added to the control law small neighbourhood as in equation 4:

$$U_r = K(\vec{x}, t).\operatorname{Sat}\left(\mathrm{S}/_{\emptyset}\right) \qquad \operatorname{sat}\left(\mathrm{S}/_{\emptyset}\right) = \begin{cases} 1 & (S/_{\emptyset} > 1) \\ -1 & (S/_{\emptyset} < 1) \\ S/_{\emptyset} & (-1 < S/_{\emptyset} < 1) \end{cases} \tag{4}$$

where $\emptyset$ is the width of the boundary layer, therefore the control output can be written as [13] in equation 5:

$$U = U_{eq} + K.\mathrm{sat}\left({}^{S}\!/_{\emptyset}\right) = \begin{cases} U_{eq} + K.\mathrm{sgn}(S) & , |S| \geq \emptyset \\ U_{eq} + K.{}^{S}\!/_{\emptyset} & , |S| < \emptyset \end{cases} \tag{5}$$

Figure 1 shows the block diagram of classical sliding mode controller.

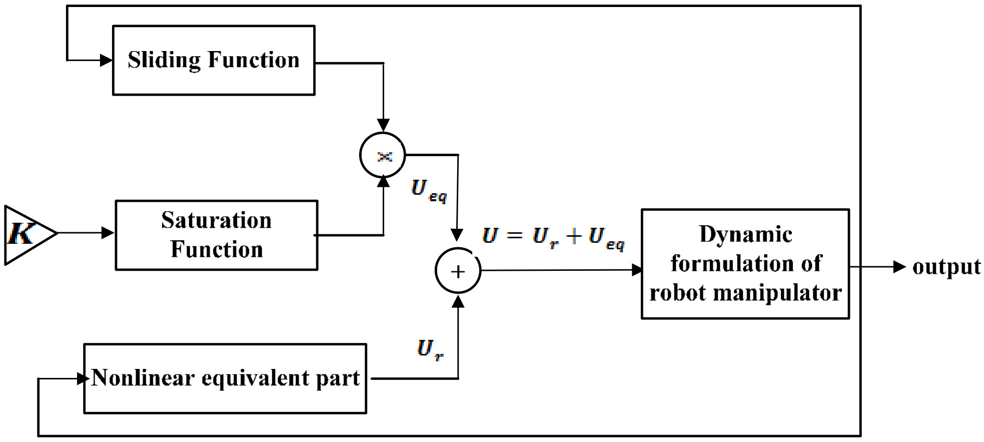

Figure 1. Block diagram of classical sliding mode controller

3. Proposed Methodology

To compensate the nonlinearity for dynamic equivalent control several researchers used model base fuzzy controller instead of classical equivalent controller that was employed to obtain the desired control behaviour and a fuzzy switching control was applied to reinforce system performance [10-14]. In the proposed sliding mode fuzzy controller, sliding mode controller was applied to fuzzy logic controller to improve the stability and reduce the fuzzy rule base; the first fuzzy inference system was designed to reduce the uncertainty challenge. A block diagram for proposed fuzzy sliding mode controller was shown in Figure 2. In this method the fuzzy like equivalent part was designed to reduce or eliminate the equivalent part challenge. Systems with uncertainty in nonlinear dynamic parameter equivalent part need to have estimator that fuzzy like equivalent part is estimated nonlinear equivalent part. The main fuzzy logic controller has one input as sliding function (S) and one output as fuzzy logic saturation part $(\boldsymbol{U_r})$. In this method gain updating factor $(\boldsymbol{\alpha\ and\ \beta})$ plays an important role to tune the controllers response which optimization of these coefficients are difficult. Mamdani's fuzzy inference system was used. The Fuzzy logic controller was written as equation 6:

$$\begin{aligned} &1 > if\ S\ is\ NB\ then\ \ U_{r\,fuzzy}\ \ is\ NB \\ &2 > if\ S\ is\ Z\ then\ U_{r\,fuzzy}\ is\ Z \end{aligned} \tag{6}$$

Fuzzy like equivalent part has two inputs; error (e) and change of error $(\dot{\boldsymbol{e}})$ and one output as fuzzy like output $(\boldsymbol{U_{fuzzy\ like}})$. This controller plays an important role to filtering uncertain part in nonlinear equivalent part.

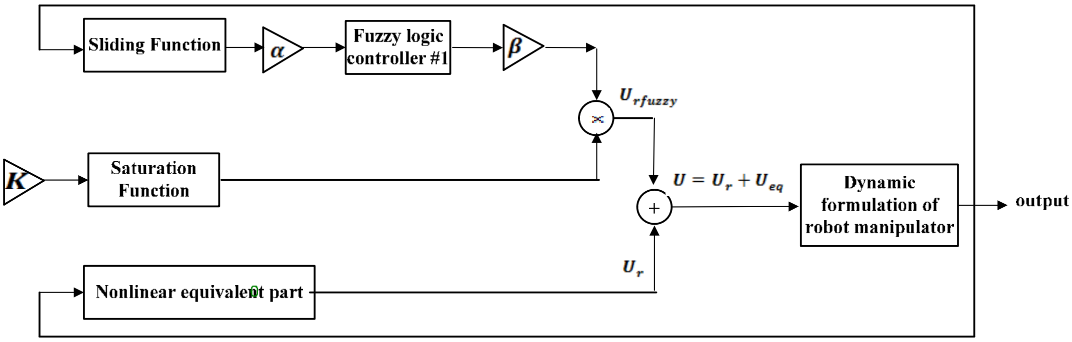

Figure 2. Block diagram of proposed SMFC with minimum rule base

In fuzzy like equivalent part the tracking error was defined as equation 7:

$$e = q_d - q_a \tag{7}$$

where $\boldsymbol{q_d} = [\boldsymbol{q_{1d}}, \boldsymbol{q_{2d}}, \boldsymbol{q_{3d}}]^T$ is the desired output and $\boldsymbol{q_a} = [\boldsymbol{q_{1a}}, \boldsymbol{q_{2a}}, \boldsymbol{q_{3a}}]^T$ is an actual output. The sliding surface was defined as follows in equation 8:

$$\mathrm{S} = \dot{\mathrm{e}} + \lambda \mathrm{e} \tag{8}$$

where $\boldsymbol{\lambda} = \boldsymbol{diag}[\boldsymbol{\lambda_1}, \boldsymbol{\lambda_2}, \boldsymbol{\lambda_3}]$ is chosen as the bandwidth of the robot manipulator controller. The time derivative of S can be calculated by the equation 9:

$$\dot{S} = \ddot{q}_d + \lambda_1 \dot{e} \tag{9}$$

Based on classical SMC the SMFC was calculated as equation 10:

$$\mathrm{U} = \mathrm{U}_{\mathrm{r\ fuzzy}} + \mathrm{U}_{\mathrm{eq}} + \mathrm{U}_{\mathrm{fuzzy\ like}} \tag{10}$$

Where, the model-based component U_{eq} can be calculated as (2); and $U_{fuzzy\ like}$ was used to filter the uncertainty in nonlinear equivalent part, the $U_{fuzzy\ like}$ fuzzy system can be defined as equation 11:

$$f(x) = U_{fuzzy\ like} = \sum_{l=1}^{M} \theta^T \zeta(x) = \psi(e, \dot{e}) \tag{11}$$

where $\theta = (\theta^1, \theta^2, \theta^3, \dots \dots, \theta^M)^T, \zeta(x) = (\zeta^1(x), \zeta^2(x), \zeta^3(x), \dots \dots, \zeta^M(x))^T$ as in equation 12:

$$\zeta^1(x) = \frac{\sum_i \mu_{(xi)x_i}}{\sum_i \mu_{(xi)}} \tag{12}$$

where $\theta = (\theta^1, \theta^2, \theta^3, \dots \dots, \theta^M)$ is adjustable parameter in (11) and $\mu_{(xi)}$ is membership function. Error base fuzzy controller was defined as equation 13:

$$U_{fuzzy\ like} = \psi(e, \dot{e}) \tag{13}$$

and $\boldsymbol{U_{r\ fuzzy}}$ is in equation 14:

$$U_{r\ fuzzy} = K.sat(S) \tag{14}$$

As a summary the design of fuzzy logic controller for SMFC had five steps:

1. ***Determining inputs and outputs:*** This controller has one input as sliding surface (S) and one output ($\boldsymbol{U_{r\,fuzzy}}$).
2. ***Finding membership function and linguistic variable:*** The linguistic variables for sliding surface (S) were; Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM), Positive Big (PB), and it was quantized into thirteen levels represented by: -1, -0.83, -0.66, -0.5, -0.33, -0.16, 0, 0.16, 0.33, 0.5, 0.66, 0.83, 1, and the linguistic variables to find the output $\left(\boldsymbol{U_{r\,fuzzy}}\right)$ were; Large Left (LL), Medium Left (ML), Small Left (SL), Zero (Z), Small Right (SR), Medium Right (MR), Large Right (LR) and it was quantized in to thirteen levels represented by: -85, -70.8, -56.7, -42.5, -28.3, -14.2, 0, 14.2, 28.3, 42.5, 56.7, 70.8, 85.
3. ***Selecting the shape of membership function:*** In this work triangular membership function was selected.
4. ***Designing fuzzy rule table:*** designing the rule base fuzzy logic controller play an important role in designing the best performance SMFC, the complete rule base for this controller was shown in Table 1.

Table 1. Rule table for proposed FSMC

S	NB	NM	NS	Z	PS	PM	PB
τ	LL	ML	SL	Z	SR	MR	LR

5. ***Defuzzification:*** The final step to design fuzzy logic controller is deffuzification , there are many deffuzzification methods in the literature, in this controller the COG method was used, as in equation 15:

$$COG(x_k, y_k) = \frac{\sum_i U_i \sum_{j=1}^{r} \cdot \mu_u(x_k, y_k, U_i)}{\sum_i \sum_{j=1}^{r} \cdot \mu_u(x_k, y_k, U_i)} \tag{15}$$

Fuzzy like equivalent part had two inputs, error (e) and change of error ($\dot{\boldsymbol{e}}$) and one output as fuzzy like output ($\boldsymbol{U_{fuzzy\,like}}$). It had 9 rule base because error and change of error has 3 linguistic variables: negative (N), zero (ZE) and positive (P). All membership functions were triangular because it was simpler than the nonlinear membership function and the output response was suitable. The other steps to design this controller were the same as SMFC which discussed previously. The main drawback of this controller was the value of gain updating factor $\boldsymbol{\alpha, \beta, \lambda}$ ***and*** $\boldsymbol{K}$ must be pre-defined very carefully and the most important advantage of this proposed method compare to pure SMC was a nonlinearity dynamic parameter. It is basic that the system performance is sensitive to the gain updating factors for both SMC and proposed SMFC application. For instance, if large value of $\boldsymbol{K}$ is chosen the response is very fast but the system is very unstable and conversely, if small value of $\boldsymbol{K}$ considered the response of system is very slow but the system is very stable. Therefore, calculation of the optimum value of gain updating factors for a system is one of the most important challenging works. However most of time the control performance for FLC and SMFC is similar to each other, but SMFC has two most important advantages:

- The number of rule base is smaller
- Increase the robustness and stability

The most important target in proposed methodology was designing the fuzzy logic controller combined with sliding mode methodology and fuzzy like equivalent part to solve the problems in classical sliding mode controller and fuzzy logic controller.

This part focused on self tuning gain updating factor in proposed SMFC: sliding surface slope ($\boldsymbol{\lambda}$) and fuzzy gain updating factors ($\boldsymbol{\alpha}$ **and** $\boldsymbol{\beta}$). The block diagram for this method was shown in Figure 6. In this controller the actual sliding surface gain ($\boldsymbol{\lambda}$) and fuzzy gain updating factors ($\boldsymbol{\alpha}$ **and** $\boldsymbol{\beta}$) were obtained by multiplying the sliding surface with tuning gain updating factor($\boldsymbol{\alpha_{tune}}$). The tuning gain updating factor($\boldsymbol{\alpha_{tune}}$) was calculated on-line by fuzzy dynamic model independent which had sliding surface (S) as its inputs. The tune gain updating factor was independent of any dynamic model of robotic manipulator parameters.

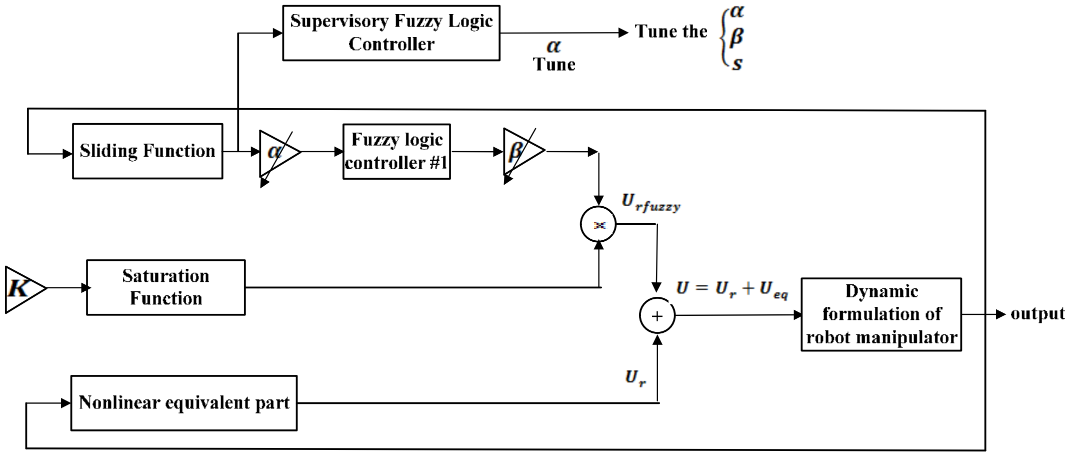

Figure 3. Block diagram of proposed gain tuning sliding mode fuzzy controller with minimum rule base in fuzzy equivalent part and fuzzy supervisory

4. Applications

Dynamic modelling of robot manipulators was used to describe the behaviour of robot manipulator, design of model based controller, and simulation results. The dynamic modelling described the relationship between joint motion, velocity, and accelerations to force/torque or current/voltage and also it was used to describe the particular dynamic effects (e.g., inertia, coriolios, centrifugal, and the other parameters) of the behaviour of the system. It is well known that the equation of an *n-DOF* robot manipulator governed by equation 16 [1,3]:

$$M(q)\ddot{q} + N(q,\dot{q}) = \tau \tag{16}$$

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 equation 17:

$$\tau = M(q)\ddot{q} + B(q)[\dot{q}\,\dot{q}] + C(q)[\dot{q}]^2 + G(q) \tag{17}$$

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 variable q_i, independently of the motion of the other joints. Therefore, the angular acceleration was found as equation 18 [1, 13-14]:

$$\ddot{q} = M^{-1}(q).\{\tau - N(q,\dot{q})\} \qquad (18)$$

5. Simulation Result

Classical sliding mode control (SMC), proposed sliding mode fuzzy control (SMFC) and gain tuning sliding mode fuzzy controller (GTSMFC) were implemented in Matlab/Simulink environment for 6 DOF's robot manipulator. Tracking performance and robustness were compared.

Tracking performances: Figure 4 showed tracking performance for first, second and third link of robot manipulator. By comparing step response trajectory without disturbance, all of controller's overshoot were about the same but SMC's rise time was fairly lower than SMFC and GTSMFC.

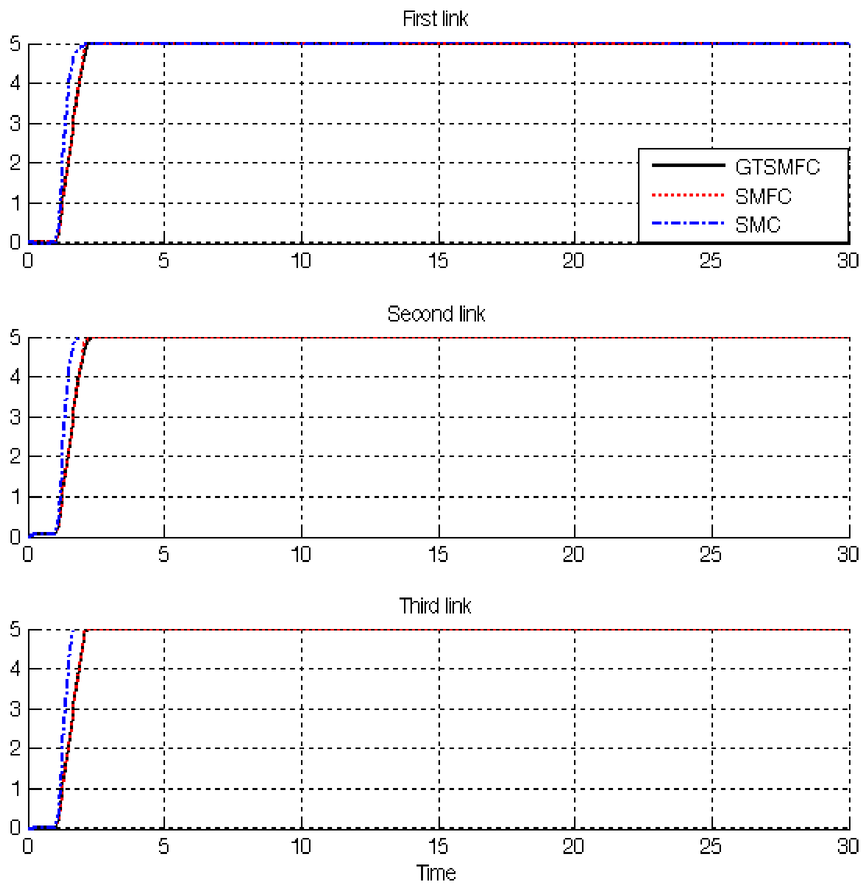

Figure 4. step trajectory without disterbance

Disturbance rejection: Figure 5 showed the power disturbance elimination in these three controllers. The main targets in these controllers were disturbance rejection as well as the other responses. A band limited white noise with predefined of 40% the power of input signal was applied to the step response. It found fairly fluctuations in SMC and SMFC trajectory responses. SMC worked very well when all parameters were known, this challenge plays an important role to select the GTSMFC as a based robust controller in this research.

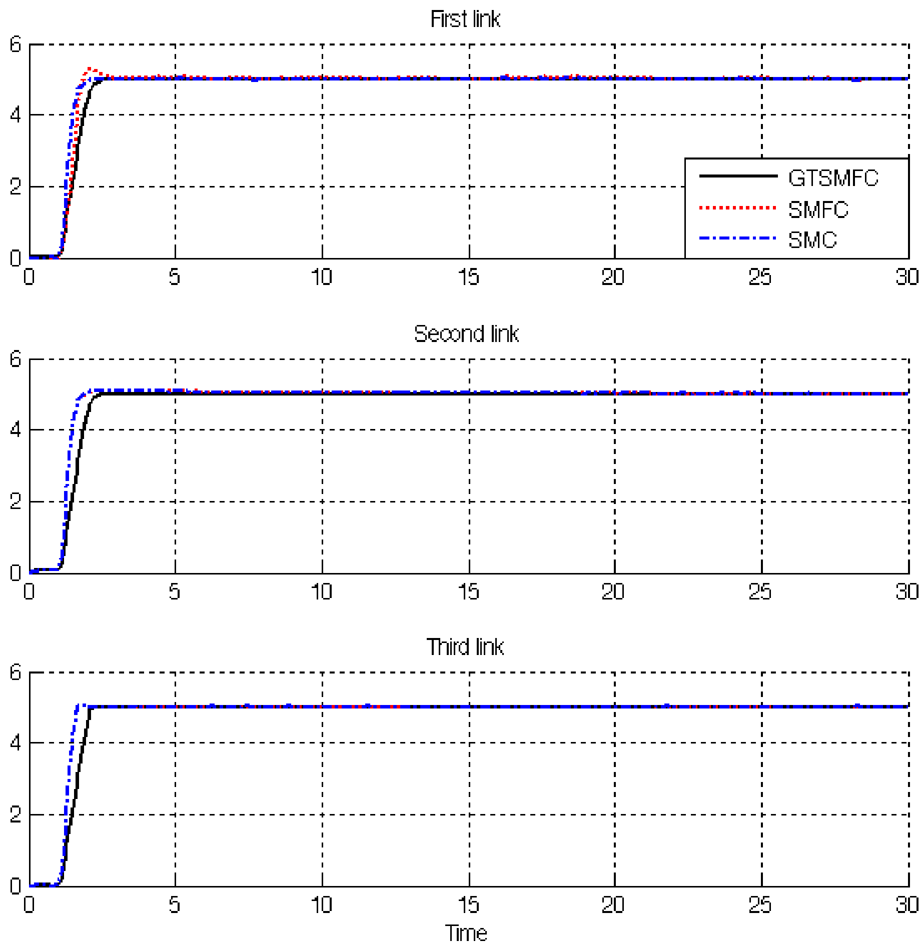

Figure 5. Step trajectory with 40% disturbance

6. Conclusions:

Refer to this research, a position artificial intelligence controller with on-line tunable gain (GTSMFC) design and application to robot manipulator was proposed in order to design high performance nonlinear controller in the presence of uncertainties. Regarding to the positive points in fuzzy logic controller, sliding mode controller and on-line tunable method, the performance improved. Each method by adding to the previous methods covered negative points. The system performance in sliding mode controller and proposed sliding mode fuzzy controller were sensitive to the gain updating factors and sliding surface slope. Therefore, computation of the optimum value of gain updating factor and sliding surface slope for this system was more important. In order to solve this problem, on-line tuneable gain was introduced and applied to proposed sliding mode fuzzy controller. In this technique, the overall system performance improved with respect to the pure sliding mode controller. This method solved chattering phenomenon as well as filtering mathematical nonlinear equivalent part by applying fuzzy logic method.

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