Gradient Descent Optimal Chattering Free Sliding Mode Fuzzy Control Design: Lyapunov Approach

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Abstract

This paper expands a sliding mode fuzzy controller which sliding surface gain is optimized by Gradient Descent Optimization Algorithm (GDOA). The main goal is to guarantee acceptable trajectories tracking between the second order nonlinear system (robot manipulator) actual and the desired trajectory. The fuzzy controller in proposed sliding mode fuzzy controller is based on Mamdani's fuzzy inference system (FIS) and it has one input and one output. The input represents the function between sliding function, error and the rate of error. The outputs represent torque, respectively. The GDOA is the most prominent iterative method for solving sparse systems of nonlinear equations. The GDOA is a composite of simple, elegant ideas that almost anyone can understand. Pure sliding mode fuzzy controller has difficulty in handling unstructured model uncertainties. To solve this problem applied GDOA to sliding mode fuzzy controller for adjusting the sliding surface gain (λ). Since the sliding surface gain (λ) is adjusted by GDOA, it is nonlinear and continuous. GDOA sliding mode fuzzy controller is stable model-free controller which eliminates the chattering phenomenon without to use the boundary layer saturation function. Lyapunov stability is proved in GDOA sliding mode fuzzy controller based on switching (sign) function. This controller has acceptable performance in presence of uncertainty (e.g., overshoot=0.1%, rise time=0.6 second, steady state error = 1.1e-9 and RMS error=1.8e-9).

Keywords*:* *robot manipulator, sliding mode controller, sliding mode fuzzy controller, gradient descent optimization algorithm, Lyapunov- based, fuzzy inference system*

1. Introduction

Industrial robot manipulator which used in this paper is a 6 DOF serial robot manipulator. From the control point of view, robot manipulator divides into two main parts i.e. kinematics and dynamic parts. The dynamic parameters of this system are highly nonlinear [1-10]. Sliding mode controller (SMC) is a significant nonlinear controller under condition of partly uncertain dynamic parameters of system [1, 6-30]. This controller is used to control of highly nonlinear systems especially for robot manipulators, because this controller is a robust and stable [41-51]. Conversely, pure sliding mode controller is used in many applications; it has two important drawbacks namely; chattering phenomenon, and nonlinear equivalent dynamic formulation in uncertain dynamic parameter [52-60]. The chattering phenomenon problem can be reduced by linear saturation boundary layer. Lyapunov stability is proved in pure sliding mode controller based on switching (sign) function [59-60]. To eliminate the equivalent part in pure sliding mode controller fuzzy inference system is applied to the main controller. Fuzzy logic theory is used to estimate the system dynamic [31-40]. However fuzzy logic controller is used to control complicated nonlinear dynamic systems, but it cannot guarantee stability and robustness [31-40]. The main drawback in sliding mode fuzzy controller is calculation the value of sliding surface slope coefficient pri-defined very carefully. To estimate the system dynamics, fuzzy inference system is introduced. Most of researcher is applied fuzzy logic theorem in sliding mode controller to design a model free controller. Pure sliding mode controller and sliding mode fuzzy controller have difficulty in handling unstructured model uncertainties. It is possible to solve this problem by combining fuzzy sliding mode controller or sliding mode fuzzy controller and GDOA which this method can helps improve the system's tracking performance by optimization method [61-82].

Gradient descent is a first-order optimization algorithm. To find a local minimum of a function using gradient descent, one takes steps proportional to the negative of the gradient (or of the approximate gradient) of the function at the current point. If instead one takes steps proportional to the *positive* of the gradient, one approaches a local maximum of that function; the procedure is then known as gradient ascent. Gradient descent is also known as steepest descent, or the method of steepest descent. When known as the latter, gradient descent should not be confused with the method of steepest descent for approximating integrals [61-80]. Gradient descent works in spaces of any number of dimensions, even in infinite-dimensional ones. In the latter case the search space is typically a function space, and one calculates the Gâteaux derivative of the functional to be minimized to determine the descent direction. The gradient descent can take much iteration to compute a local minimum with a required accuracy, if the curvature in different directions is very different for the given function. For such functions, preconditioning, which changes the geometry of the space to shape the function level sets like concentric circles, cures the slow convergence. Constructing and applying preconditioning can be computationally expensive, however. The gradient descent can be combined with a line search, finding the locally optimal step size γ on each iteration. Performing the line search can be time-consuming. Conversely, using a fixed small γ can yield poor convergence. Methods based on Newton's method and inversion of the Hessian using conjugate gradient techniques can be better alternatives. Generally, such methods converge in less iteration, but the cost of each iteration is higher [61-80].

This method is based on resolve the sliding surface slope as well as improve the output performance by GDOA tuning the sliding surface slope coefficient. The sliding surface gain ($\boldsymbol{\lambda}$) of this controller is adjusted off line depending on the iterations. GDOA tuning sliding mode fuzzy controller is stable model-free controller which does not need to limits the dynamic model of robot manipulator and eliminate the chattering phenomenon without to use the boundary layer saturation function. Lyapunov stability is proved in fuzzy-based tuning sliding mode fuzzy controller based on switching (sign) function.

Sliding mode controller is used to control of highly nonlinear systems especially for robot manipulators. The first problem of the pure sliding mode controller with switching function was chattering phenomenon in certain and uncertain systems. The nonlinear equivalent dynamic problem in uncertain system is the second challenge in pure sliding mode controller. To eliminate the robot manipulator's dynamic of system, 7 rules Mamdani inference system is design and applied to sliding mode methodology with switching function. This methodology is worked based on applied fuzzy logic in equivalent nonlinear dynamic part to eliminate unknown dynamic parameters. Pure sliding mode controller has difficulty in handling unstructured model uncertainties. This research is solved this problem by combining sliding mode fuzzy controller and GDOA tuning. It is based on resolve the off line sliding surface gain ($\boldsymbol{\lambda}$) as well as improve the output performance. The sliding surface gain ($\boldsymbol{\lambda}$) of this controller is adjusted off line depending on the iterations of last value of error. GDOA sliding mode fuzzy controller is stable model-free controller which does not need to limits the dynamic model of robot manipulator and eliminate the chattering phenomenon without to use the boundary layer saturation function.

Section 2, is served as an introduction to the sliding mode controller formulation algorithm and its application to control of robot manipulator, dynamic of robot manipulator and proof of stability. Part 3, introduces and describes the methodology (design fuzzy-based tuning error-based sliding mode fuzzy controller) algorithms and proves Lyapunov stability. Section 4 presents the simulation results and discussion of this algorithm applied to a robot arm and the final section is describing the conclusion.

2. Theorem

Dynamic formulation: The equation of an *n-DOF* robot manipulator governed by the following equation [1, 4, 15-29, 63-74]:

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

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 [1-29]:

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

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 [3, 41-62]:

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

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

Sliding mode methodology: Consider a nonlinear single input dynamic system is defined by [6]:

$$\boldsymbol{x}^{(\boldsymbol{n})} = \boldsymbol{f}(\vec{\boldsymbol{x}}) + \boldsymbol{b}(\vec{\boldsymbol{x}})\boldsymbol{u} \quad \textbf{(4)}$$

Where u is the vector of control input, $\boldsymbol{x}^{(\boldsymbol{n})}$ is the $\boldsymbol{n^{th}}$ derivation of $\boldsymbol{x}$, $\boldsymbol{x} = [\boldsymbol{x}, \dot{\boldsymbol{x}}, \ddot{\boldsymbol{x}}, \dots, \boldsymbol{x}^{(\boldsymbol{n-1})}]^{\boldsymbol{T}}$ is the state vector, $\boldsymbol{f}(\boldsymbol{x})$ is unknown or uncertainty, and $\boldsymbol{b}(\boldsymbol{x})$ is of known *sign* function. The main goal to design this controller is train to the desired state; $\boldsymbol{x_d} = [\boldsymbol{x_d}, \dot{\boldsymbol{x}}_{\boldsymbol{d}}, \ddot{\boldsymbol{x}}_{\boldsymbol{d}}, \dots, \boldsymbol{x_d}^{(\boldsymbol{n-1})}]^{\boldsymbol{T}}$, and trucking error vector is defined by [6]:

$$\tilde{x} = x - x_d = [\tilde{x}, \dots, \tilde{x}^{(n-1)}]^T \quad (5)$$

A time-varying sliding surface $s(x,t)$ in the state space R^n is given by [6]:

$$s(x,t) = (\frac{d}{dt} + \lambda)^{n-1}\,\tilde{x} = 0 \quad (6)$$

where λ is the positive constant. To further penalize tracking error, integral part can be used in sliding surface part as follows [6]:

$$s(x,t) = (\frac{d}{dt} + \lambda)^{n-1}\left(\int_0^t \tilde{x}\,dt\right) = 0 \quad (7)$$

The main target in this methodology is kept the sliding surface slope $s(x,t)$ near to the zero. Therefore, one of the common strategies is to find input U outside of $s(x,t)$ [6].

$$\frac{1}{2}\frac{d}{dt}s^2(x,t) \le -\zeta|s(x,t)| \quad (8)$$

where ζ is positive constant.

If $\mathbf{S(0)>0} \rightarrow \frac{d}{dt}S(t) \le -\zeta$ (9)

To eliminate the derivative term, it is used an integral term from t=0 to t=t_{reach}

$$\int_{t=0}^{t=t_{reach}} \frac{d}{dt}S(t) \le -\int_{t=0}^{t=t_{reach}} \eta \rightarrow S(t_{reach}) - S(0) \le -\zeta(t_{reach} - 0) \quad (10)$$

Where t_{reach} is the time that trajectories reach to the sliding surface so, suppose S(t_{reach} = 0) defined as

$$0 - S(0) \le -\eta(t_{reach}) \rightarrow t_{reach} \le \frac{S(0)}{\zeta} \quad (11)$$

and

$$if\ S(0) < 0 \rightarrow 0 - S(0) \le -\eta(t_{reach}) \rightarrow S(0) \le -\zeta(t_{reach}) \rightarrow t_{reach} \le \frac{|S(0)|}{\eta} \quad (12)$$

Equation (12) guarantees time to reach the sliding surface is smaller than $\frac{|S(0)|}{\zeta}$ since the trajectories are outside of $S(t)$.

$$if\ S_{t_{reach}} = S(0) \rightarrow error(x - x_d) = 0 \quad (13)$$

suppose S is defined as

$$s(x,t) = (\frac{d}{dt} + \lambda)\quad \tilde{x} = (\dot{x} - \dot{x}_d) + \lambda(x - x_d) \quad (14)$$

The derivation of S, namely, $\dot{S}$ can be calculated as the following;

$$\dot{S} = (\ddot{x} - \ddot{x}_d) + \lambda(\dot{x} - \dot{x}_d) \quad (15)$$

suppose the second order system is defined as;

$$\ddot{x} = f + u \rightarrow \dot{S} = f + U - \ddot{x}_d + \lambda(\dot{x} - \dot{x}_d) \quad (16)$$

Where f is the dynamic uncertain, and also since $S = 0$ *and* $\dot{S} = 0$, to have the best approximation ,$\widehat{U}$ is defined as

$$\widehat{U} = -\hat{f} + \ddot{x}_d - \lambda(\dot{x} - \dot{x}_d) \quad (17)$$

A simple solution to get the sliding condition when the dynamic parameters have uncertainty is the switching control law:

$$U_{dis} = \widehat{U} - K(\vec{x}, t) \cdot \mathrm{sgn}(s) \quad (18)$$

where the switching function $\mathbf{sgn}(S)$ is defined as [1, 6]

$$sgn(s) = \begin{cases} 1 & s > 0 \\ -1 & s < 0 \\ 0 & s = 0 \end{cases} \quad (19)$$

and the $K(\vec{x}, t)$ is the positive constant. Suppose by (8) the following equation can be written as,

$$\frac{1}{2}\frac{d}{dt}s^2(x,t) = \dot{S} \cdot S = \left[f - \hat{f} - K\mathrm{sgn}(s)\right] \cdot S = \left(f - \hat{f}\right) \cdot S - K|S| \quad (20)$$

and if the equation (12) instead of (11) the sliding surface can be calculated as

$$s(x,t) = \left(\frac{d}{dt} + \lambda\right)^2 \left(\int_0^t \tilde{x}\, dt\right) = (\dot{x} - \dot{x}_d) + 2\lambda(\dot{x} - \dot{x}_d) - \lambda^2(x - x_d) \quad (21)$$

in this method the approximation of U is computed as [6]

$$\widehat{U} = -\hat{f} + \ddot{x}_d - 2\lambda(\dot{x} - \dot{x}_d) + \lambda^2(x - x_d) \quad (22)$$

Based on above discussion, the sliding mode control law for a multi degrees of freedom robot manipulator is written as [1, 6]:

$$\tau = \tau_{eq} + \tau_{dis} \quad (23)$$

Where, the model-based component τ_{eq} is the nominal dynamics of systems and τ_{eq} for first 3 DOF PUMA robot manipulator can be calculate as follows [1]:

$$\tau_{eq} = \left[M^{-1}(B + C + G) + \dot{S}\right]M \quad (24)$$

and τ_{dis} is computed as [1];

$$\tau_{dis} = K \cdot \mathrm{sgn}(S) \quad (25)$$

by replace the formulation (25) in (23) the control output can be written as;

$$\tau = \tau_{eq} + K.\mathrm{sgn}(S) \quad (26)$$

By (26) and (24) the sliding mode control of PUMA 560 robot manipulator is calculated as;

$$\tau = \left[M^{-1}(B + C + G) + \dot{S}\right]M + K \cdot \mathrm{sgn}(S) \quad (27)$$

where $S = \lambda e + \dot{e}$ in PD-SMC and $S = \lambda e + \dot{e} + (\frac{\lambda}{2})^2 \sum e$ in PID-SMC.

Proof of Stability: the lyapunov formulation can be written as follows,

$$V = \frac{1}{2} S^T . M . S \tag{28}$$

the derivation of V can be determined as,

$$\dot{V} = \frac{1}{2} S^T . \dot{M} . S + S^T M \dot{S} \tag{29}$$

the dynamic equation of IC engine can be written based on the sliding surface as

$$M\dot{S} = -VS + M\dot{S} + B + C + G \tag{30}$$

it is assumed that

$$S^T(\dot{M} - 2B + C + G)S = 0 \tag{31}$$

by substituting (30) in (29)

$$\dot{V} = \frac{1}{2} S^T \dot{M} S - S^T B + CS + S^T(M\dot{S} + B + CS + G) \\ = S^T(M\dot{S} + B + CS + G) \tag{32}$$

suppose the control input is written as follows

$$\hat{U} = \widehat{U_{Nonlinear}} + \widehat{U_{dis}} = \left[\widehat{M^{-1}}(B + C + G) + \dot{S}\right]\widehat{M} + K.sgn(S) + B + CS + G \tag{33}$$

by replacing the equation (33) in (32)

$$\dot{V} = S^T(M\dot{S} + B + C + G - \widehat{M}\dot{S} - \widehat{B + C}S + G - Ksgn(S) = S^T\left(\widetilde{M}\dot{S} + \widetilde{B + C}S + G - Ksgn(S)\right) \tag{34}$$

it is obvious that

$$\left|\widetilde{M}\dot{S} + \widetilde{B + C}S + G\right| \le \left|\widetilde{M}\dot{S}\right| + \left|\widetilde{B + C}S + G\right| \tag{35}$$

the Lemma equation in robot arm system can be written as follows

$$K_u = \left[\left|\widetilde{M}\dot{S}\right| + |B + CS + G| + \eta\right]_i, i = 1, 2, 3, 4, \ldots \tag{36}$$

the equation (11) can be written as

$$K_u \ge \left|\left[\widetilde{M}\dot{S} + B + CS + G\right]_i\right| + \eta_i \tag{37}$$

therefore, it can be shown that

$$\dot{V} \le -\sum_{i=1}^{n} \eta_i |S_i| \tag{38}$$

Consequently the equation (38) guaranties the stability of the Lyapunov equation. Figure 1 is shown pure sliding mode controller, applied to robot arm.

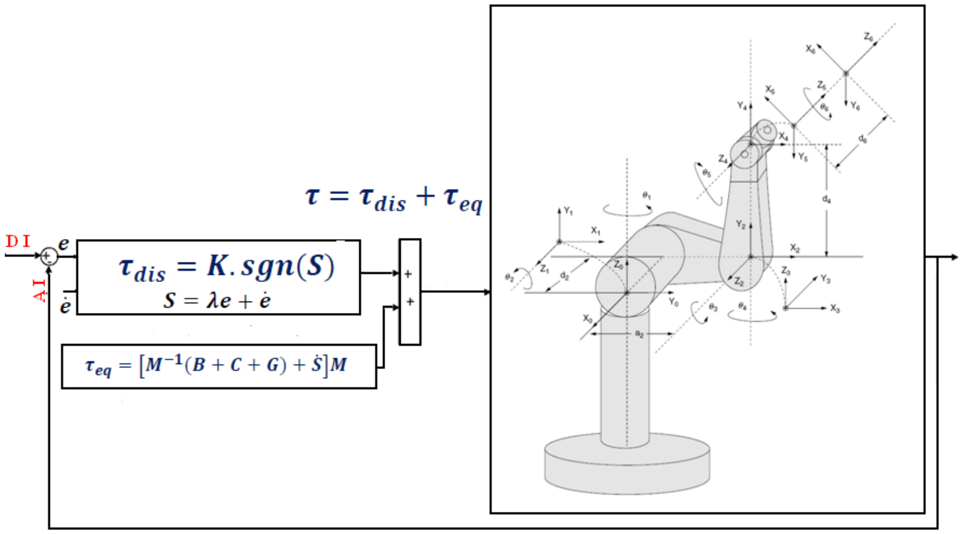

Figure 1. Block Diagram of a Sliding Mode Controller: Applied to Robot Arm

As shown in Figure 1, sliding mode controller is divided into two main parts: discontinuous part and equivalent part. Discontinuous part is based on switching function which this method is used to good following trajectory. Equivalent part is based on robot manipulator's dynamic formulation which these formulations are nonlinear; MIMO and some of them are unknown. Equivalent part of sliding mode controller is based on nonlinear dynamic formulations of robot manipulator. Robot manipulator's dynamic formulations are highly nonlinear and some of parameters are unknown therefore design a controller based on dynamic formulation is complicated. To solve this challenge fuzzy logic methodology is applied to sliding mode controller. Based on literature [43-44, 58-61], most of researchers are designed fuzzy model-based sliding mode controller and model-based sliding mode fuzzy controller. In this research fuzzy logic method is applied to SMC to reduce the fuzzy rule base, improve the stability and robustness. Figure 2 shows sliding mode fuzzy controller.

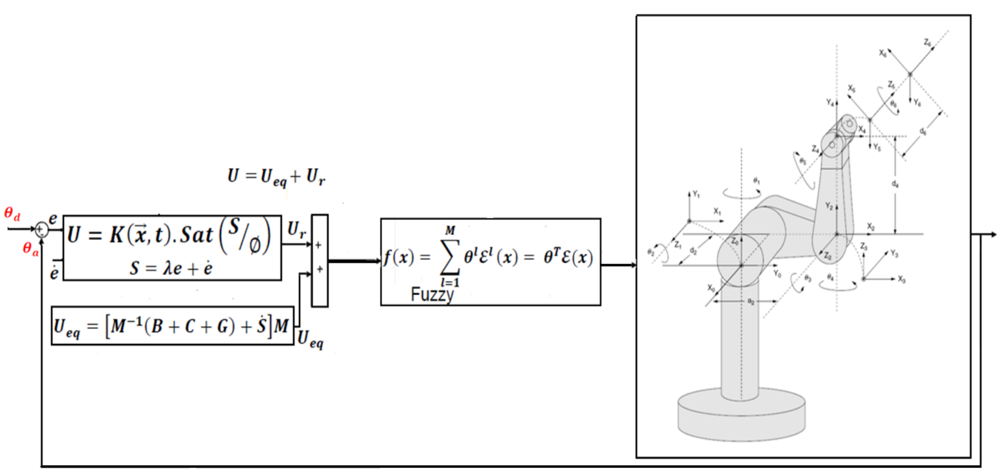

Figure 2. Sliding Mode Fuzzy Controller

To solve the challenge of sliding mode controller based on nonlinear dynamic formulation this research is focused on estimate the nonlinear equivalent formulation based on fuzzy logic methodology in feed forward way in this system. In this method; dynamic nonlinear equivalent part is estimated by performance/error-based fuzzy logic controller. In sliding mode fuzzy controller; error based Mamdani's fuzzy inference system has considered with one input, one output and totally 7 rules to estimate the dynamic equivalent part. In this method a model free Mamdani's fuzzy inference system has considered based on error-based fuzzy logic controller to estimate the nonlinear equivalent part.

Based on [80-81] to compute dynamic parameters of PUMA;

$$\tau_{fuzzy} = \begin{bmatrix} \tau_{1fuzzy} \\ \tau_{2fuzzy} \\ \tau_{3fuzzy} \end{bmatrix} , M^{-1} = \begin{bmatrix} M_{11} & M_{12} & M_{13} & 0 & 0 & 0 \\ M_{21} & M_{22} & M_{23} & 0 & 0 & 0 \\ M_{31} & M_{32} & M_{33} & 0 & M_{35} & 0 \\ 0 & 0 & 0 & M_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & M_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & M_{66} \end{bmatrix}^{-1}$$

$$B + C + G = \begin{bmatrix} b_{112}\dot{q}_1\dot{q}_2 + b_{113}\dot{q}_1\dot{q}_3 + 0 + b_{123}\dot{q}_2\dot{q}_3 \\ 0 + b_{223}\dot{q}_2\dot{q}_3 + 0 + 0 \\ 0 \\ b_{412}\dot{q}_1\dot{q}_2 + b_{413}\dot{q}_1\dot{q}_3 + 0 + 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} C_{12}\dot{q}_2^{\,2} + C_{13}\dot{q}_3^{\,2} \\ C_{21}\dot{q}_1^{\,2} + C_{23}\dot{q}_3^{\,2} \\ C_{31}\dot{q}_1^{\,2} + C_{32}\dot{q}_2^{\,2} \\ 0 \\ C_{51}\dot{q}_1^{\,2} + C_{52}\dot{q}_2^{\,2} \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ g_2 \\ g_3 \\ 0 \\ g_5 \\ 0 \end{bmatrix}$$

$$\dot{S} = \begin{bmatrix} \dot{S}_1 \\ \dot{S}_2 \\ \dot{S}_3 \\ \dot{S}_4 \\ \dot{S}_5 \\ \dot{S}_6 \end{bmatrix} \text{ and } M = \begin{bmatrix} M_{11} & M_{12} & M_{13} & 0 & 0 & 0 \\ M_{21} & M_{22} & M_{23} & 0 & 0 & 0 \\ M_{31} & M_{32} & M_{33} & 0 & M_{35} & 0 \\ 0 & 0 & 0 & M_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & M_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & M_{66} \end{bmatrix}$$

Therefore, the error-based fuzzy sliding mode controller for PUMA robot manipulator is calculated by the following equation;

$$\begin{bmatrix} \widehat{\tau_1} \\ \widehat{\tau_2} \\ \widehat{\tau_3} \end{bmatrix} = \left(\begin{bmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \end{bmatrix} + \begin{bmatrix} K_1 \\ K_2 \\ K_3 \end{bmatrix} \ \mathrm{sgn} \begin{bmatrix} s_1 \\ s_2 \\ s_3 \end{bmatrix} \right)_{fuzzy\ estimate} \quad \textbf{(39)}$$

3. Methodology

For both sliding mode controller and sliding mode fuzzy controller the system performances are sensitive to the sliding surface slope coefficient(λ). For instance, if large value of λ is chosen the response is very fast the system is unstable and conversely, if small value of λ is considered the response of system is very slow but system is stable. Therefore to have a good response, compute the best value sliding surface slope coefficient is very important. Gradient descent is based on the observation that if the multivariable function $F(x)$ is defined and differentiable in a neighborhood of a point a, then $F(x)$ decreases *fastest* if one goes from a in the direction of the negative gradient of F at , $a - \nabla F(a)$. It follows that, if

$$\boldsymbol{b} = a - \gamma \nabla F(a) \quad \textbf{(40)}$$

for $\gamma \rightarrow 0$ a small enough number, then $F(a) < F(b)$. With this observation in mind, one starts with a guess x_0 for a local minimum of F , and considers the sequence $x_0, x_1, x_2, \ldots ..$ such that

$$\boldsymbol{X_{n+1}} = \boldsymbol{X_n} - \gamma_n \nabla F(X_n), \qquad n \geq 0 \quad \textbf{(41)}$$

We have

$$\boldsymbol{F}(\boldsymbol{X_0}) \geq \boldsymbol{F}(\boldsymbol{X_1}) \geq \boldsymbol{F}(\boldsymbol{X_2}), \geq \cdots \quad \textbf{(42)}$$

So hopefully the sequence (X_n) converges to the desired local minimum. Note that the value of the *step size* γ is allowed to change at every iteration. With certain assumptions on the function F(for example, F convex and ∇F Lipschitz) and particular choices of γ(e.g., chosen via a line search that satisfies the Wolfe conditions), convergence to a local minimum can be guaranteed. When the function F is convex, all local minima are also global minima, so in this case gradient descent can converge to the global solution.

4. Results and Discussion

Sliding mode controller (SMC), sliding mode fuzzy controller (SMFC) and GDOA sliding mode fuzzy controller (GDOASMFC) were tested to Step response trajectory. In this simulation, to control position of 6DOF robot manipulator the first, second, and third joints are moved from home to final position without and with external disturbance. The simulation was implemented in MATLAB/SIMULINK environment. These controllers 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.

GDOA Sliding Mode Fuzzy Controller Optimization: Based on (41) in GDOA sliding mode fuzzy controller; controllers performance are depended on the gain updating factor (K) and sliding surface slope coefficient (λ). These two coefficients are computed by GDOA optimization; Figure 3.

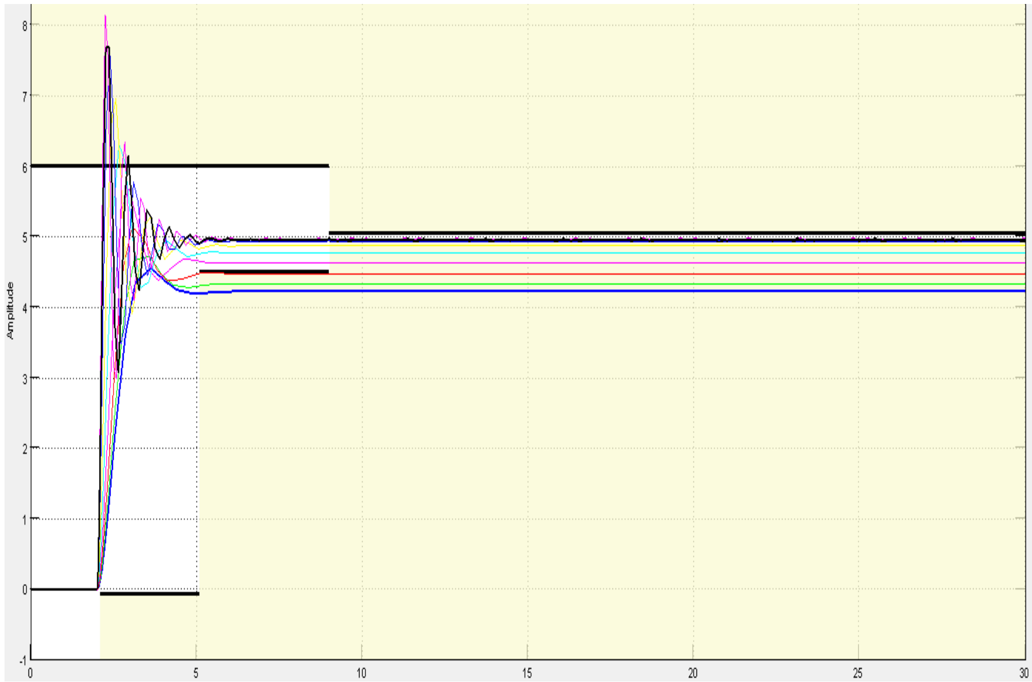

Figure 3. GDOA Sliding Mode Fuzzy Controller Optimization

The best possible coefficients in step GDOASMFC are; $K_p = K_v = K_i = 12,\ \emptyset_1 = \emptyset_2 = \emptyset_3 = 0.1, and\ \lambda_1 = 100.1, \lambda_2 = \lambda_3 = 100.9915$.

Tracking performances: Based on (30) in sliding mode fuzzy controller and based on (10) in sliding mode fuzzy controller; controllers performance are depended on the gain updating factor (K) and sliding surface slope coefficient (λ). These two coefficients are computed by trial and error in PD-SMC and FSMC. The best possible coefficients in step SMFC are; $K_p = K_v = K_i = 18,\ \emptyset_1 = \emptyset_2 = \emptyset_3 = 0.1, and\ \lambda_1 = 3, \lambda_2 = 6, \lambda_3 = 6$ and the best possible coefficients in step SMC are; $\lambda_1 = 1\ , \lambda_2 = 6, \lambda_3 = 8$; $K_p = K_v = K_i = 10$; $\emptyset_1 = \emptyset_2 = \emptyset_3 = 0.1$. In GDOA tuning sliding mode fuzzy controller the sliding surface gain is adjusted off-line depending on the last values of error (e). Figure 4 shows tracking performance in GDOA sliding mode fuzzy controller (GDOASMFC), sliding mode fuzzy controller (SMFC) and SMC without disturbance for step trajectory.

Based on Figure 4 it is observed that, the overshoot in FTSMFC is 0%, in SMC's is 1% and in SMFC's is 0%, and rise time in FTSMFC's is 0.6 seconds, in SMC's is 0.483 second and in SMFC's is about 0.6 seconds. From the trajectory MATLAB simulation for FTSMFC, SMC and SMFC in certain system, it was seen that all of three controllers have acceptable performance.

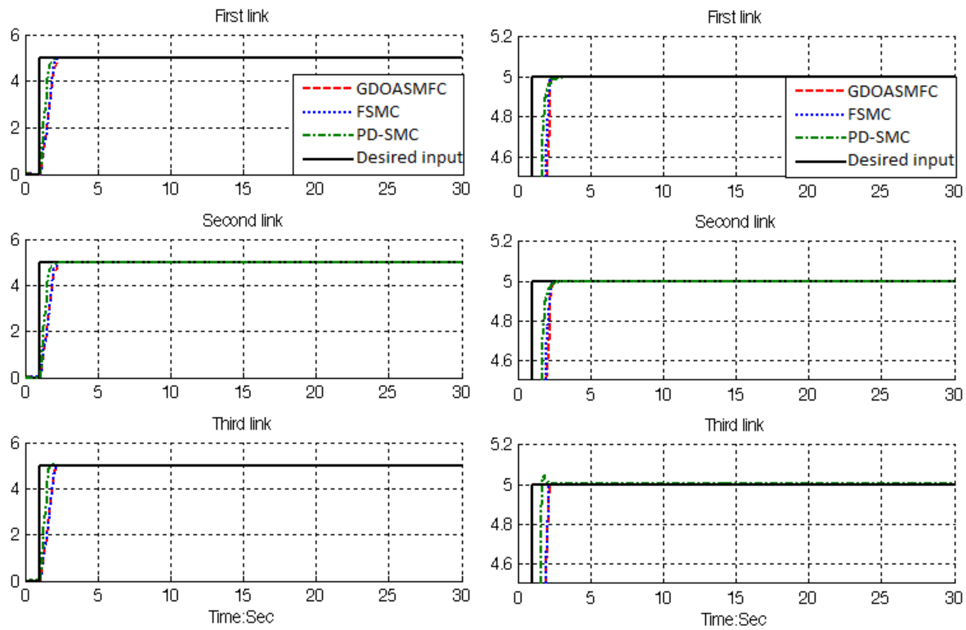

Figure 4. Desired Input, FTSMFC, SMFC and SMC for First, Second and Third Link Trajectory: Step Trajectory

Disturbance rejection: Figure 5 shows the power disturbance elimination in GDOASMFC, SMC and SMFC with 40% disturbance for step trajectory. The power of disturbance rejection is used to test the power of robustness. A band limited white noise with predefined of 40% the power of input signal value is applied to the step trajectory. Based on Figure 5, it was seen that, GDOASMFC's performance is more better than SMFC and SMC.

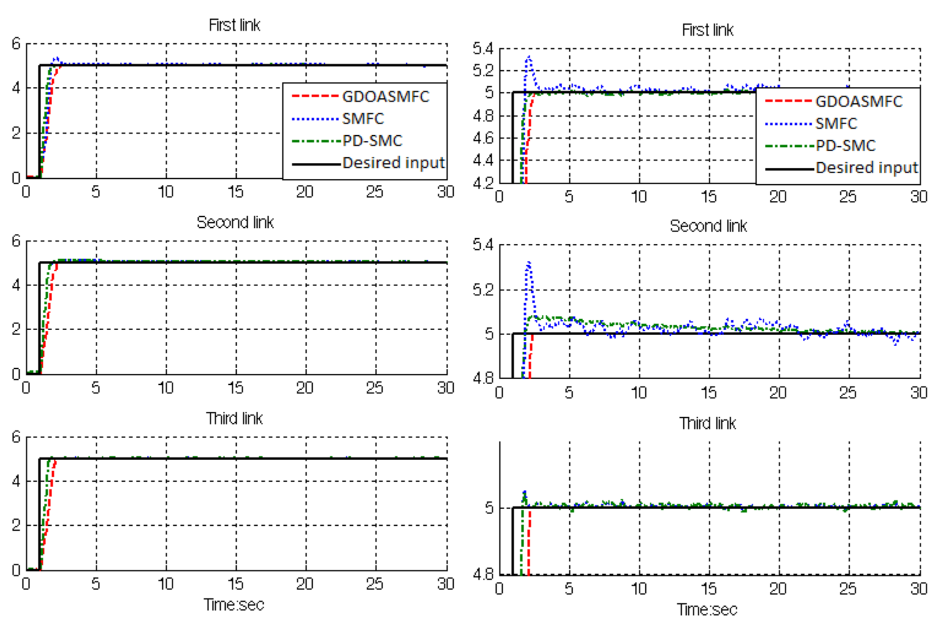

Figure 5. Desired Input, FTSMFC, SMFC and SMC for First, Second and Third Link Trajectory with 40% External Disturbance: Step Trajectory

Based on Figure 5; by comparing between above three controllers, GDOASMFC's overshoot about **(0.1%)** is lower than FTSMFC's **(6%)** and SMC's (**8%). SMC's rise time (0.5 seconds)** is lower than SMFC's **(0.57 second)** and GDOASMFC's **(0.6 second).** Besides the Steady State and RMS error in GDOASMFC, SMFC and SMC it is observed that, error performances in GDOASMFC **(Steady State error =1.1e-9 and RMS error=1.8e-9)** are about lower than SMFC **(Steady State error =10e-4 and RMS error=0.69e-4)** and SMC's **(Steady State error=10e-4 and RMS error=11e-4).**

Torque performance: Figures 6 and 7 have indicated the power of chattering rejection in GDOASMFC, SMC and SMFC with 40% disturbance and without disturbance.

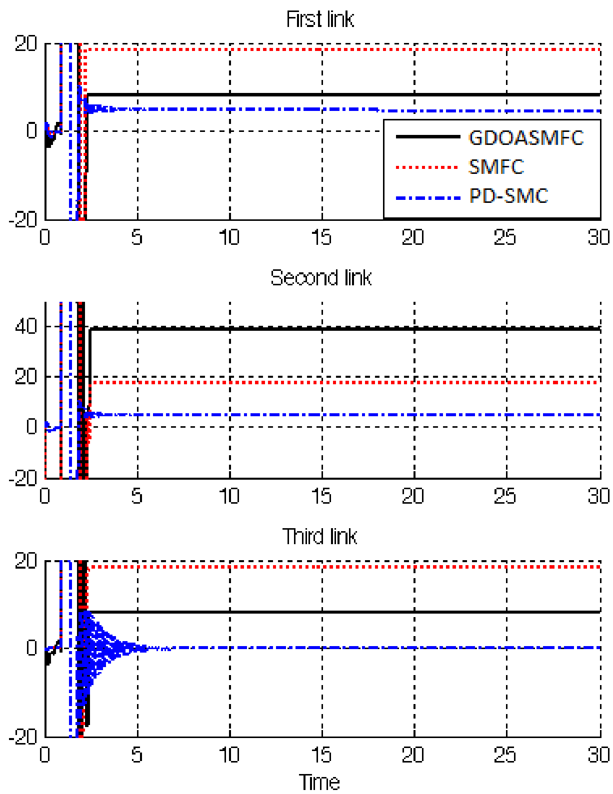

Figure 6. GDOASMFC, SMC and SMFC for First, Second and Third Link Torque Performance without Disturbance

Figure 6 shows torque performance for first three links industrial robot manipulator in GDOASMFC, SMC and SMFC without disturbance. Based on Figure 6, GDOASMFC, SMC and SMFC give considerable torque performance in certain system and all three of controllers eliminate the chattering phenomenon in certain system. Figure 7 has indicated the robustness in torque performance for first three links industrial robot manipulator in GDOASMFC, SMC and SMFC in presence of 40% disturbance. Based on Figure 7, it is observed that SMC and SMFC controllers have highly oscillation but GDOASMFC has steady in torque performance.

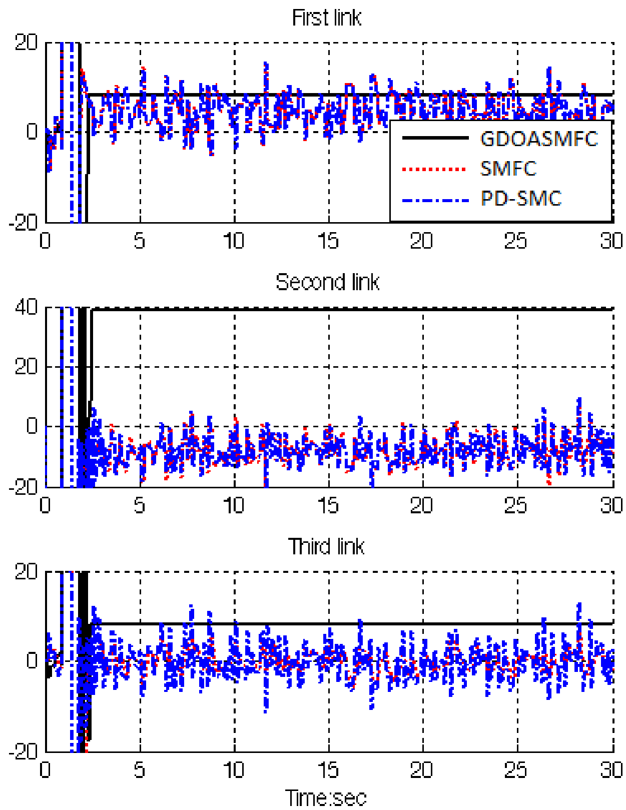

Figure 7. GDOASMFC, SMC and SMFC for First, Second and Third Link Torque Performance with 40% Disturbance

5. Conclusion

Refer to this research, a position Gradient descent optimal sliding mode fuzzy controller (GDOASMFC) is proposed for 6DOF industrial robot manipulator. The nonlinear equivalent dynamic problem in uncertain system is estimated by using fuzzy logic theory. To estimate the robot manipulator system's dynamic, 7 rules Mamdani inference system is design and applied to sliding mode methodology. The results demonstrate that the sliding mode fuzzy controller is a model-based controllers which works well in certain and partly uncertain system. Pure sliding mode controller and sliding mode fuzzy controller have difficulty to tune sliding surface slope coefficient. It is possible to solve this problem by combining sliding mode fuzzy controller and Gradient descent theory. Since the sliding surface gain (λ) is adjusted by GDOA tuning method. In pure sliding mode controller and sliding mode fuzzy controller the sliding surface gain is chosen by trial and error, which means pure sliding mode controller and sliding mode fuzzy controller have to have a prior knowledge of the system uncertainty. If the knowledge is not available error performance and chattering phenomenon are go up. The simulation results exhibit that the GDOA sliding mode fuzzy controller works well in various situations.

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