Methodology of Robust Linear On-line High Speed Tuning for Stable Sliding Mode Controller: Applied to Nonlinear System

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Abstract

Refer to this research, a linear error-based tuning sliding mode controller (LTSMC) is proposed for robot manipulator. Sliding mode controller (SMC) is an important nonlinear controller in a partly uncertain dynamic system's parameters. Sliding mode controller has difficulty in handling unstructured model uncertainties. It is possible to solve this problem by combining sliding mode controller and adaption law which this method can helps improve the system's tracking performance by online tuning method. Since the sliding surface gain (λ) is adjusted by new linear tuning method, it is continuous. In this research new λ is obtained by the previous λ multiple sliding surface slopes updating factor (α) which is a coefficient varies between half to one. Linear error-based tuning sliding mode controller is stable model-based controller which eliminates the chattering phenomenon without to use the boundary layer saturation function. Lyapunov stability is proved in linear error-based tuning sliding mode controller based on switching (sign) function. This controller has acceptable performance in presence of uncertainty (e.g., overshoot=0%, rise time=0.4 second, steady state error = 1.8e-10 and RMS error=1.16e-12).

***Keywords**: a linear error-based tuning sliding mode controller, sliding mode controller, unstructured model uncertainties, adaptive method, sliding surface gain, sliding surface slopes updating factor, chattering phenomenon*

1. Introduction and Background

Introduction: Controller is a device which can sense information from linear or nonlinear system (e.g., robot manipulator) to improve the systems performance [3]. The main targets in designing control systems are stability, good disturbance rejection, and small tracking error[5]. Several industrial robot manipulators are controlled by linear methodologies (e.g., Proportional-Derivative (PD) controller, Proportional- Integral (PI) controller or Proportional-Integral-Derivative (PID) controller), but when robot manipulator works with various payloads and have uncertainty in dynamic models this technique has limitations. From the control point of view, uncertainty is divided into two main groups: uncertainty in unstructured inputs (e.g., noise, disturbance) and uncertainty in structure dynamics (e.g., payload, parameter variations). In some applications robot manipulators are used in an unknown and unstructured environment, therefore strong mathematical tools used in new control methodologies to design nonlinear robust controller with an acceptable performance (e.g., minimum error, good trajectory, disturbance rejection). Sliding mode controller is a powerful nonlinear robust controller under condition of partly uncertain dynamic parameters of system [7]. This controller is used to control of highly nonlinear systems especially for robot manipulators. Chattering phenomenon in uncertain dynamic parameter is the main drawback in pure sliding mode controller [20]. The chattering phenomenon problem in pure sliding mode controller is reduced by using linear saturation boundary layer function but prove the stability is very difficult. In various dynamic parameters systems that need to be training on-line adaptive control methodology is used. Adaptive control methodology can be classified into two main groups, namely, traditional adaptive method and fuzzy adaptive method [70]. Fuzzy adaptive method is used in systems which want to training parameters by expert knowledge. Traditional adaptive method is used in systems which some dynamic parameters are known. In this research in order to solve disturbance rejection and uncertainty dynamic parameter, adaptive method is applied to artificial sliding mode controller.

Robot manipulator is a collection of links that connect to each other by joints, these joints can be revolute and prismatic that revolute joint has rotary motion around an axis and prismatic joint has linear motion around an axis. Each joint provides one or more degrees of freedom (DOF). From the mechanical point of view, robot manipulator is divided into two main groups, which called; serial robot links and parallel robot links. In serial robot manipulator, links and joints is serially connected between base and final frame (end-effector). Parallel robot manipulators have many legs with some links and, where in these robot manipulators base frame has connected to the final frame. Most of industrial robots are serial links, which in n degrees of freedom serial link robot manipulator the axis of the first three joints has a known as major axis, these axes show the position of end-effector, the axis number four to six are the minor axes that use to calculate the orientation of end-effector and the axis number seven to n use to reach the avoid the difficult conditions (e.g., surgical robot and space robot manipulator). Kinematics is an important subject to find the relationship between rigid bodies (e.g., position and orientation) and end-effector in robot manipulator. The mentioned topic is very important to describe the three areas in robot manipulator: practical application such as trajectory planning, essential prerequisite for some dynamic description such as Newton's equation for motion of point mass, and control purposed therefore kinematics play important role to design accurate controller for robot manipulators. Robot manipulator kinematics is divided into two main groups: forward kinematics and inverse kinematics where forward kinematics is used to calculate the position and orientation of end-effector with given joint parameters (e.g., joint angles and joint displacement) and the activated position and orientation of end-effector calculate the joint variables in Inverse Kinematics [6]. 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 and pure computed torque controller which design these controller are 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].

Background: Chattering phenomenon can causes some problems such as saturation and heats the mechanical parts of robot arm or drivers. To reduce or eliminate the oscillation, various papers have been reported by many researchers which one of the best method is; boundary layer saturation method [1]. In boundary layer linear saturation method, the basic idea is the discontinuous method replacement by linear continuous saturation method with small neighborhood of the switching surface. This replacement caused to considerable chattering reduction. Slotine and Sastry have introduced boundary layer method instead of discontinuous method to reduce the chattering [21]. Slotine has presented sliding mode controller with boundary layer to improve the industry application [22]. Palm has presented a fuzzy method to nonlinear approximation instead of linear approximation inside the boundary layer to improve the chattering and control the result performance [23]. Moreover, Weng and Yu improved the previous method by using a new method in fuzzy nonlinear approximation inside the boundary layer and adaptive method [24]. In various dynamic parameters systems that need to be training on-line, adaptive control methodology is used. Mathematical model free adaptive method is used in systems which want to training parameters by performance knowledge. In this research in order to solve disturbance rejection and uncertainty dynamic parameter, adaptive method is applied to sliding mode controller. Mohan and Bhanot [40] have addressed comparative study between some adaptive fuzzy, and a new hybrid fuzzy control algorithm for robot arm control. They found that self-organizing fuzzy logic controller and proposed hybrid integrator fuzzy give the best performance as well as simple structure. Temeltas [46] has proposed fuzzy adaption techniques for VSC to achieve robust tracking of nonlinear systems and solves the chattering problem. Conversely system's performance is better than sliding mode controller; it is depended on nonlinear dynamic equqation. Hwang *et al.* [47]have proposed a Tagaki-Sugeno (TS) fuzzy model based sliding mode controller based on *N* fuzzy based linear state-space to estimate the uncertainties. A MIMO FVSC reduces the chattering phenomenon and reconstructs the approximate the unknown system has been presented for a nonlinear system [42]. Yoo and Ham [58]have proposed a MIMO fuzzy system to help the compensation and estimation the torque coupling. This method can only tune the consequence part of the fuzzy rules. Medhafer et al. [59] have proposed an indirect adaptive fuzzy sliding mode controller to control nonlinear system. This MIMO algorithm, applies to estimate the nonlinear dynamic parameters. Compared with the previous algorithm the numbers of fuzzy rules have reduced by introducing the sliding surface as inputs of fuzzy systems. Guo and Woo [60] have proposed a SISO fuzzy system compensate and reduce the chattering. Lin and Hsu [61] can tune both systems by fuzzy rules. Eksin et. al [70] have designed mathematical model-free sliding surface slope in fuzzy sliding mode controller.

This paper is organized as follows. In section 2, main subject of sliding mode controller, proof of stability and dynamic formulation of robot manipulator are presented. This section covered the following details, classical sliding mode control, classical sliding for robotic manipulators, proof of stability in pure sliding mode controller, chatter free sliding controller and nonlinear dynamic formulation of system. A methodology of proposed method is presented in section 3, which covered the linear tuning error-based tuning sliding mode controller and proofs the stability in this method and applied to robot manipulator. In section 4, the sliding mode controller and proposed methodology are compared and discussed. In section 5, the conclusion is presented.

2. Theorem: Dynamic Formulation of Robotic Manipulator, Sliding Mode Formulation Applied to Robot Arm, Proof of Stability

Dynamic of robot arm: The equation of an *n-DOF* robot manipulator governed by the following equation [1, 4, 15-29, 63-70]:

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

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]:

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

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]:

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

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]:

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

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

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

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

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

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

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

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].

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

where ζ is positive constant.

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

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

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

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

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

and

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

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

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

suppose S is defined as

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

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

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

suppose the second order system is defined as;

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$\tau = \tau_{eq} + \tau_{dis} \tag{23}$$

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]:

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

and τ_{dis} is computed as [1];

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

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

$$\boldsymbol{\tau} = \boldsymbol{\tau}_{eq} + \boldsymbol{K}.\,\mathbf{sgn}(\boldsymbol{S}) \tag{26}$$

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

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

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,

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

the derivation of V can be determined as,

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

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

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

it is assumed that

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

by substituting (30) in (29)

$$\dot{\boldsymbol{V}} = \frac{\mathbf{1}}{\mathbf{2}}\boldsymbol{S}^{\boldsymbol{T}}\dot{\boldsymbol{M}}\boldsymbol{S} - \boldsymbol{S}^{\boldsymbol{T}}\boldsymbol{B} + \boldsymbol{C}\boldsymbol{S} + \boldsymbol{S}^{\boldsymbol{T}}\left(\boldsymbol{M}\dot{\boldsymbol{S}} + \boldsymbol{B} + \boldsymbol{C}\boldsymbol{S} + \boldsymbol{G}\right) \tag{32}$$

$$= \boldsymbol{S}^{\boldsymbol{T}}\left(\boldsymbol{M}\dot{\boldsymbol{S}} + \boldsymbol{B} + \boldsymbol{C}\boldsymbol{S} + \boldsymbol{G}\right)$$

suppose the control input is written as follows

$$\widehat{\boldsymbol{U}} = \boldsymbol{U}_{\widehat{\boldsymbol{Nonlinear}}} + \widehat{\boldsymbol{U}_{\boldsymbol{dis}}} \tag{33}$$

$$= \left[\widehat{\boldsymbol{M}^{-1}}(\boldsymbol{B} + \boldsymbol{C} + \boldsymbol{G}) + \dot{\boldsymbol{S}}\right]\widehat{\boldsymbol{M}} + \boldsymbol{K}.\boldsymbol{sgn}(\boldsymbol{S}) + \boldsymbol{B} + \boldsymbol{C}\boldsymbol{S} + \boldsymbol{G}$$

by replacing the equation (33) in (32)

$$\dot{\boldsymbol{V}} = \boldsymbol{S}^{\boldsymbol{T}}(\boldsymbol{M}\dot{\boldsymbol{S}} + \boldsymbol{B} + \boldsymbol{C} + \boldsymbol{G} - \widehat{\boldsymbol{M}}\dot{\boldsymbol{S}} - \widehat{\boldsymbol{B} + \boldsymbol{C}}\boldsymbol{S} + \boldsymbol{G} - \boldsymbol{K}\boldsymbol{sgn}(\boldsymbol{S}) = \boldsymbol{S}^{\boldsymbol{T}}\Big(\widetilde{\boldsymbol{M}}\dot{\boldsymbol{S}} + \boldsymbol{B}+\boldsymbol{C}\boldsymbol{S}+\boldsymbol{G}-\boldsymbol{K}\boldsymbol{sgn}\boldsymbol{S} \tag{34}$$

it is obvious that

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

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

$$\boldsymbol{K}_{\boldsymbol{u}} = \left[\left|\widetilde{\boldsymbol{M}}\dot{\boldsymbol{S}}\right| + |\boldsymbol{B} + \boldsymbol{C}\boldsymbol{S} + \boldsymbol{G}| + \boldsymbol{\eta}\right]_{\boldsymbol{i}}, \boldsymbol{i} = \mathbf{1}, \mathbf{2}, \mathbf{3}, \mathbf{4}, \ldots \tag{36}$$

the equation (11) can be written as

$$\boldsymbol{K}_{\boldsymbol{u}} \ge \left|\left[\widetilde{\boldsymbol{M}}\dot{\boldsymbol{S}} + \boldsymbol{B} + \boldsymbol{C}\boldsymbol{S} + \boldsymbol{G}\right]_{\boldsymbol{i}}\right| + \boldsymbol{\eta}_{\boldsymbol{i}} \tag{37}$$

therefore, it can be shown that

$$\dot{\boldsymbol{V}} \le -\sum_{\boldsymbol{i}=\mathbf{1}}^{\boldsymbol{n}} \boldsymbol{\eta}_{\boldsymbol{i}}\,|\boldsymbol{S}_{\boldsymbol{i}}| \tag{38}$$

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

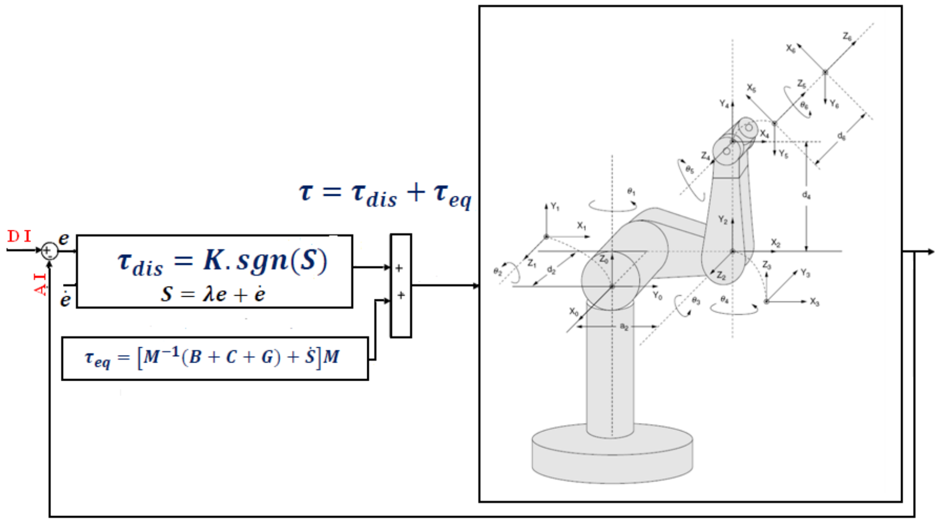

Figure 1. Block Diagram of a Sliding Mode Controller: Applied to Robot Arm

3. Methodology: Robust Linear On-Line High Speed Tuning for Stable SMC

Sliding mode controller has difficulty in handling unstructured model uncertainties [71-77]. It is possible to solve this problem by combining sliding mode controller and linear error-based tuning method which this method can helps to eliminate the chattering in presence of switching function method and improves the system's tracking performance by online tuning method. In this research the nonlinear equivalent dynamic (equivalent part) formulation problem in uncertain system is solved by using on-line linear error-based tuning theorem. In this method linear error-based theorem is applied to sliding mode controller to adjust the sliding surface slope. Sliding mode controller has difficulty in handling unstructured model uncertainties and this controller's performance is sensitive to sliding surface slope coefficient. It is possible to solve above challenge by combining linear error-based tuning method and sliding mode controller which this methodology can help to improve system's tracking performance by on-line tuning (linear error-based tuning) method. Based on above discussion, compute the best value of sliding surface slope coefficient has played important role to improve system's tracking performance especially when the system parameters are unknown or uncertain. This problem is solved by tuning the surface slope coefficient ($\boldsymbol{\lambda}$) of the sliding mode controller continuously in real-time. In this methodology, the system's performance is improved with respect to the pure sliding mode controller. Figure 2 shows the linear error-based tuning sliding mode controller. Based on (23) and (27) to adjust the sliding surface slope coefficient we define $\hat{f}(x|\lambda)$ as the fuzzy based tuning.

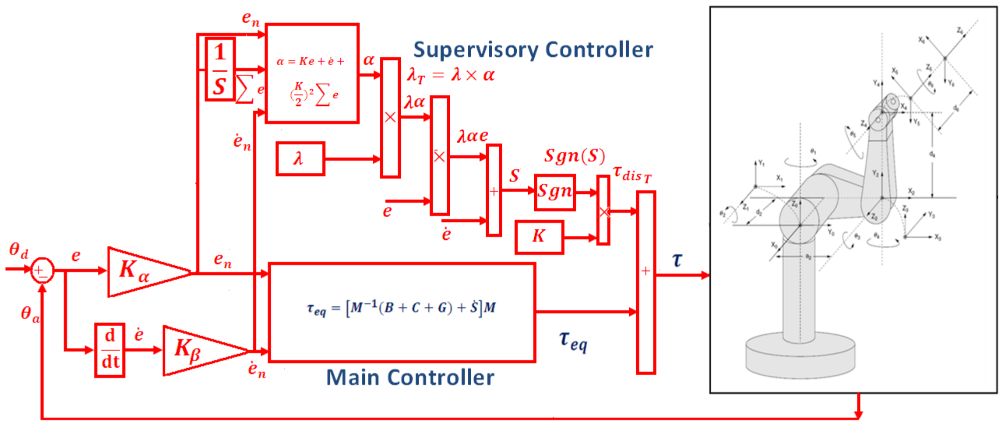

Figure 2. Block Diagram of a Linear Error-based Sliding Mode Controller: Applied to Robot Arm

$$\hat{f}(x|\lambda) = \lambda^T \alpha \tag{39}$$

If minimum error (λ^*) is defined by;

$$\lambda^* = \arg\min \left[\left(Sup\left|\hat{f}(x|\lambda) - f(x)\right)\right]\right. \tag{40}$$

Where λ^T is adjusted by an adaption law and this law is designed to minimize the error's parameters of $\lambda - \lambda^*$. adaption law in linear error-based tuning sliding mode controller is used to adjust the sliding surface slope coefficient. Linear error-based tuning part is a supervisory controller based on the following formulation methodology. This controller has three inputs namely; error (e), change of error ($\dot{e}$) and the integral of error ($\sum e$) and an output namely; gain updating factor(α). As a summary design a linear error-based tuning is based on the following formulation:

$$\alpha = K.e + \dot{e} + \frac{(K)^2}{2}\sum e \tag{41}$$

$$S_{on-line} = \alpha.\lambda e + \dot{e} \Rightarrow S_{on-line} = (K.e + \dot{e} + \frac{(K)^2}{2}\sum e)\lambda e + \dot{e}$$

$$\lambda_{Tune} = \lambda.\alpha \Rightarrow \lambda_{Tune} = \lambda(K.e + \dot{e} + \frac{(K)^2}{2}\sum e)$$

Where (α) is gain updating factor, ($\sum e$) is the integral of error, ($\dot{e}$) is change of error, (e) is error and K is a coefficient.

Proof of Stability: The Lyapunov function in this design is defined as

$$V = \frac{1}{2}S^T M S + \frac{1}{2}\sum_{J=1}^{M}\frac{1}{\gamma_{sj}}\phi^T.\phi_j \tag{42}$$

where γ_{sj} is a positive coefficient, $\phi = \lambda^* - \lambda, \theta^*$ is minimum error and λ is adjustable parameter. Since $\dot{M} - 2V$ is skew-symetric matrix;

$$S^T M\dot{S} + \frac{1}{2}S^T \dot{M} S = S^T(M\dot{S} + VS) \tag{43}$$

If the dynamic formulation of robot manipulator defined by

$$\boldsymbol{\tau} = \boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{V}(\boldsymbol{q}, \dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{G}(\boldsymbol{q}) \quad \textbf{(44)}$$

the controller formulation is defined by

$$\boldsymbol{\tau} = \widehat{\boldsymbol{M}}\ddot{\boldsymbol{q}}_{\boldsymbol{r}} + \widehat{\boldsymbol{V}}\dot{\boldsymbol{q}}_{\boldsymbol{r}} + \widehat{\boldsymbol{G}} - \boldsymbol{\lambda}\boldsymbol{S} - \boldsymbol{K} \quad \textbf{(45)}$$

According to (43) and (44)

$$\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{V}(\boldsymbol{q}, \dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{G}(\boldsymbol{q}) = \widehat{\boldsymbol{M}}\ddot{\boldsymbol{q}}_{\boldsymbol{r}} + \widehat{\boldsymbol{V}}\dot{\boldsymbol{q}}_{\boldsymbol{r}} + \widehat{\boldsymbol{G}} - \boldsymbol{\lambda}\boldsymbol{S} - \boldsymbol{K} \quad \textbf{(46)}$$

Since $\dot{\boldsymbol{q}}_{\boldsymbol{r}} = \dot{\boldsymbol{q}} - \boldsymbol{S}$ and $\ddot{\boldsymbol{q}}_{\boldsymbol{r}} = \ddot{\boldsymbol{q}} - \dot{\boldsymbol{S}}$

$$\boldsymbol{M}\dot{\boldsymbol{S}} + (\boldsymbol{V} + \boldsymbol{\lambda})\boldsymbol{S} = \Delta\boldsymbol{f} - \boldsymbol{K} \quad \textbf{(47)}$$

$$\boldsymbol{M}\dot{\boldsymbol{S}} = \boldsymbol{\Delta f} - \boldsymbol{K} - \boldsymbol{V}\boldsymbol{S} - \boldsymbol{\lambda}\boldsymbol{S}$$

The derivation of V is defined

$$\dot{\boldsymbol{V}} = \boldsymbol{S}^{\boldsymbol{T}}\boldsymbol{M}\dot{\boldsymbol{S}} + \frac{\boldsymbol{1}}{\boldsymbol{2}}\boldsymbol{S}^{\boldsymbol{T}}\dot{\boldsymbol{M}}\boldsymbol{S} + \sum_{\boldsymbol{J}=\boldsymbol{1}}^{\boldsymbol{M}} \frac{\boldsymbol{1}}{\boldsymbol{\gamma}_{\boldsymbol{sj}}} \boldsymbol{\phi}^{\boldsymbol{T}}.\dot{\boldsymbol{\phi}}_{\boldsymbol{j}} \quad \textbf{(48)}$$

$$\dot{\boldsymbol{V}} = \boldsymbol{S}^{\boldsymbol{T}}(\boldsymbol{M}\dot{\boldsymbol{S}} + \boldsymbol{V}\boldsymbol{S}) + \sum_{\boldsymbol{J}=\boldsymbol{1}}^{\boldsymbol{M}} \frac{\boldsymbol{1}}{\boldsymbol{\gamma}_{\boldsymbol{sj}}} \boldsymbol{\phi}^{\boldsymbol{T}}.\dot{\boldsymbol{\phi}}_{\boldsymbol{j}}$$

Based on (46) and (47)

$$\dot{\boldsymbol{V}} = \boldsymbol{S}^{\boldsymbol{T}}(\boldsymbol{\Delta f} - \boldsymbol{K} - \boldsymbol{V}\boldsymbol{S} - \boldsymbol{\lambda}\boldsymbol{S} + \boldsymbol{V}\boldsymbol{S}) + \sum_{\boldsymbol{J}=\boldsymbol{1}}^{\boldsymbol{M}} \frac{\boldsymbol{1}}{\boldsymbol{\gamma}_{\boldsymbol{sj}}} \boldsymbol{\phi}^{\boldsymbol{T}}.\dot{\boldsymbol{\phi}}_{\boldsymbol{j}} \quad \textbf{(49)}$$

where $\Delta f = [M(q)\ddot{q} + V(q, \dot{q})\dot{q} + G(q)] - \sum_{l=1}^{M} \boldsymbol{\lambda}^{\boldsymbol{T}}\, \boldsymbol{\alpha}$

$$\dot{\boldsymbol{V}} = \sum_{\boldsymbol{J}=\boldsymbol{1}}^{\boldsymbol{M}} \left[\boldsymbol{S}_{\boldsymbol{j}}(\boldsymbol{\Delta f}_{\mathbf{j}} - \boldsymbol{K}_{\boldsymbol{j}})\right] - \boldsymbol{S}^{\boldsymbol{T}}\boldsymbol{\lambda}\boldsymbol{S} + \sum_{\boldsymbol{J}=\boldsymbol{1}}^{\boldsymbol{M}} \frac{\boldsymbol{1}}{\boldsymbol{\gamma}_{\boldsymbol{sj}}} \boldsymbol{\phi}^{\boldsymbol{T}}.\dot{\boldsymbol{\phi}}_{\boldsymbol{j}}$$

suppose α is defined as follows

$$\boldsymbol{\alpha}_{\boldsymbol{j}} = \boldsymbol{K}.\boldsymbol{e} + \dot{\boldsymbol{e}} + \frac{(\boldsymbol{K})^{\boldsymbol{2}}}{\boldsymbol{2}} \sum \boldsymbol{e} \quad \textbf{(50)}$$

according to 48 and 49;

$$\dot{\boldsymbol{V}} = \sum_{\boldsymbol{J}=\boldsymbol{1}}^{\boldsymbol{M}} \left[\boldsymbol{S}_{\boldsymbol{j}}(\boldsymbol{\Delta f}_{\mathbf{j}} - \boldsymbol{\lambda}^{\boldsymbol{T}}\boldsymbol{K}.\boldsymbol{e} + \dot{\boldsymbol{e}} + \frac{(\boldsymbol{K})^{\boldsymbol{2}}}{\boldsymbol{2}} \sum \boldsymbol{e}]\right] - \boldsymbol{S}^{\boldsymbol{T}}\boldsymbol{\lambda}\boldsymbol{S} + \sum_{\boldsymbol{J}=\boldsymbol{1}}^{\boldsymbol{M}} \frac{\boldsymbol{1}}{\boldsymbol{\gamma}_{\boldsymbol{sj}}} \boldsymbol{\phi}^{\boldsymbol{T}}.\dot{\boldsymbol{\phi}}_{\boldsymbol{j}} \quad \textbf{(51)}$$

Based on $\boldsymbol{\phi} = \boldsymbol{\theta}^* - \boldsymbol{\theta} \rightarrow \boldsymbol{\theta} = \boldsymbol{\theta}^* - \boldsymbol{\phi}$

$$\dot{\boldsymbol{V}} = \sum_{\boldsymbol{J}=\boldsymbol{1}}^{\boldsymbol{M}} \left[\boldsymbol{S}_{\boldsymbol{j}}(\boldsymbol{\Delta f}_{\mathbf{j}} - \boldsymbol{\theta}^{*\boldsymbol{T}}[\boldsymbol{K}.\boldsymbol{e} + \dot{\boldsymbol{e}} + \frac{(\boldsymbol{K})^{\boldsymbol{2}}}{\boldsymbol{2}} \sum \boldsymbol{e}] + \boldsymbol{\phi}^{\boldsymbol{T}}[\boldsymbol{\alpha} \right. \quad \textbf{(52)}$$

$$\left. = \boldsymbol{K}.\boldsymbol{e} + \dot{\boldsymbol{e}} + \frac{(\boldsymbol{K})^{\boldsymbol{2}}}{\boldsymbol{2}} \sum \boldsymbol{e}]\right] - \boldsymbol{S}^{\boldsymbol{T}}\boldsymbol{\lambda}\boldsymbol{S} + \sum_{\boldsymbol{J}=\boldsymbol{1}}^{\boldsymbol{M}} \frac{\boldsymbol{1}}{\boldsymbol{\gamma}_{\boldsymbol{sj}}} \boldsymbol{\phi}^{\boldsymbol{T}}.\dot{\boldsymbol{\phi}}_{\boldsymbol{j}}$$

$$\dot{V} = \sum_{J=1}^{M}\left[S_j(\Delta f_j - (\lambda^*)^T K.e + \dot{e} + \frac{(K)^2}{2}\sum e]\right] - S^T\lambda S + \sum_{J=1}^{M}\frac{1}{\gamma_{sj}}\phi_j^T[K.e + \dot{e} + \frac{(K)^2}{2}\sum e + \dot{\phi}_j])$$

where $\dot{\theta}_j = K.e + \dot{e} + \frac{(K)^2}{2}\sum e$ is adaption law, $\dot{\emptyset}_J = -\dot{\theta}_j = [K.e + \dot{e} + \frac{(K)^2}{2}\sum e]$

$\dot{V}$ is considered by

$$\dot{V} = \sum_{j=1}^{m}[S_j\,\Delta f_j - \left((\lambda_j^*)^T K.e + \dot{e} + \frac{(K)^2}{2}\sum e\right)] - S^T\lambda S \tag{53}$$

The minimum error is defined by

$$e_{mj} = \Delta f_j - \left((\lambda_j^*)^T\alpha = K.e + \dot{e} + \frac{(K)^2}{2}\sum e\right) \tag{54}$$

Therefore $\dot{V}$ is computed as

$$\dot{V} = \sum_{j=1}^{m}[S_j\, e_{mj}] - S^T\lambda S \tag{55}$$

$$\le \sum_{j=1}^{m} |S_j\,||e_{mj}| - S^T\lambda S$$

$$= \sum_{j=1}^{m} |S_j\,||e_{mj}| - \lambda_j {S_j}^2$$

$$= \sum_{j=1}^{m} |S_j\,|\left(|e_{mj}| - \lambda_j S_j\right) \tag{56}$$

4. Results

This part is focused on compare between Sliding Mode Controller (SMC) and linear error-based tuning Sliding Mode Controller (LTSMC). These controllers were tested by step responses. In this simulation, to control position of PUMA 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. **Trajectory performance, torque performance, disturbance rejection, steady state error and RMS error** are compared in these controllers. 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: In sliding mode 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 SMC. 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 linear error-based tuning sliding mode controller the sliding surface gain is adjusted online depending on the last values of error (e), change of error $(\dot{e})$ and the integral of error $(\sum e)$ by sliding surface slope updating factor (α). Figure 3 shows tracking performance in linear error-based tuning sliding mode controller (LTSMC) and sliding mode controller (SMC) without disturbance for step trajectory.

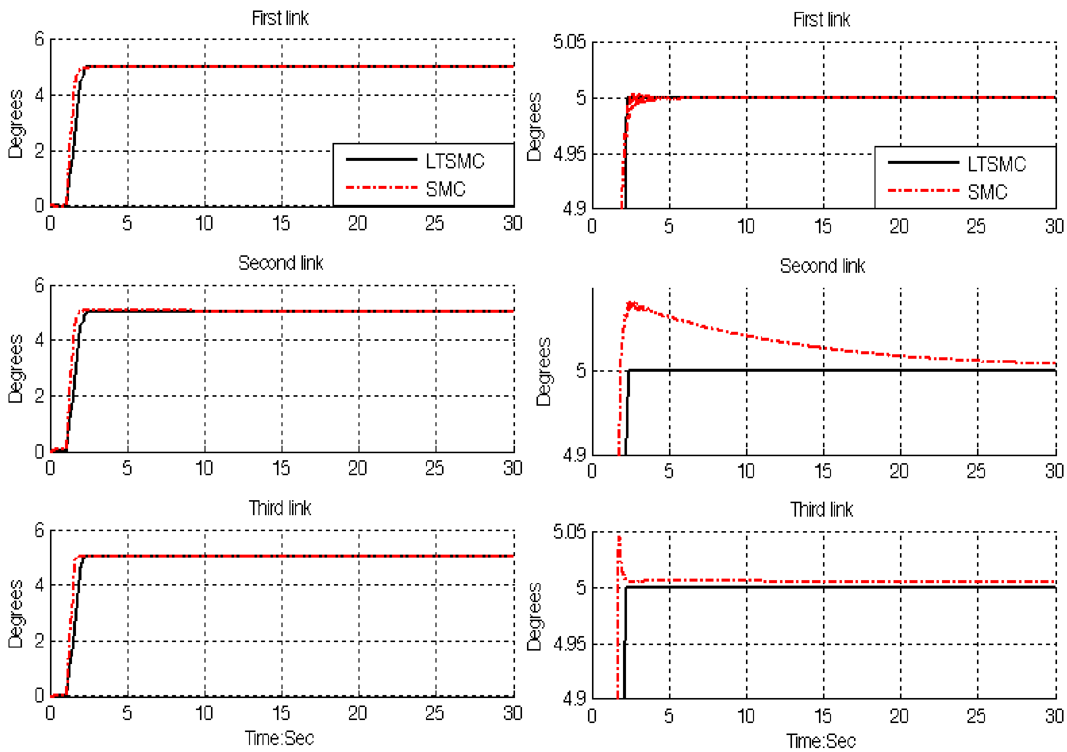

Figure 3. LTSMC and SMC for First, Second and Third Link Step Trajectory Performance without Disturbance

Based on Figure 3 it is observed that, the overshoot in LTSMC is 0% and in SMC's is 1%, and the rise time in LTSMC's is 0.48 seconds and in SMC's is 0.4 second. From the trajectory MATLAB simulation for LTSMC and SMC in certain system, it was seen that all of two controllers have acceptable performance.

Disturbance rejection: Figure 4 shows the power disturbance elimination in LTSMC and SMC with disturbance for step trajectory. The disturbance rejection is used to test the robustness comparisons in these two controllers for step trajectory. A band limited white noise with predefined of 40% the power of input signal value is applied to the step trajectory. It found fairly fluctuations in SMC trajectory responses.

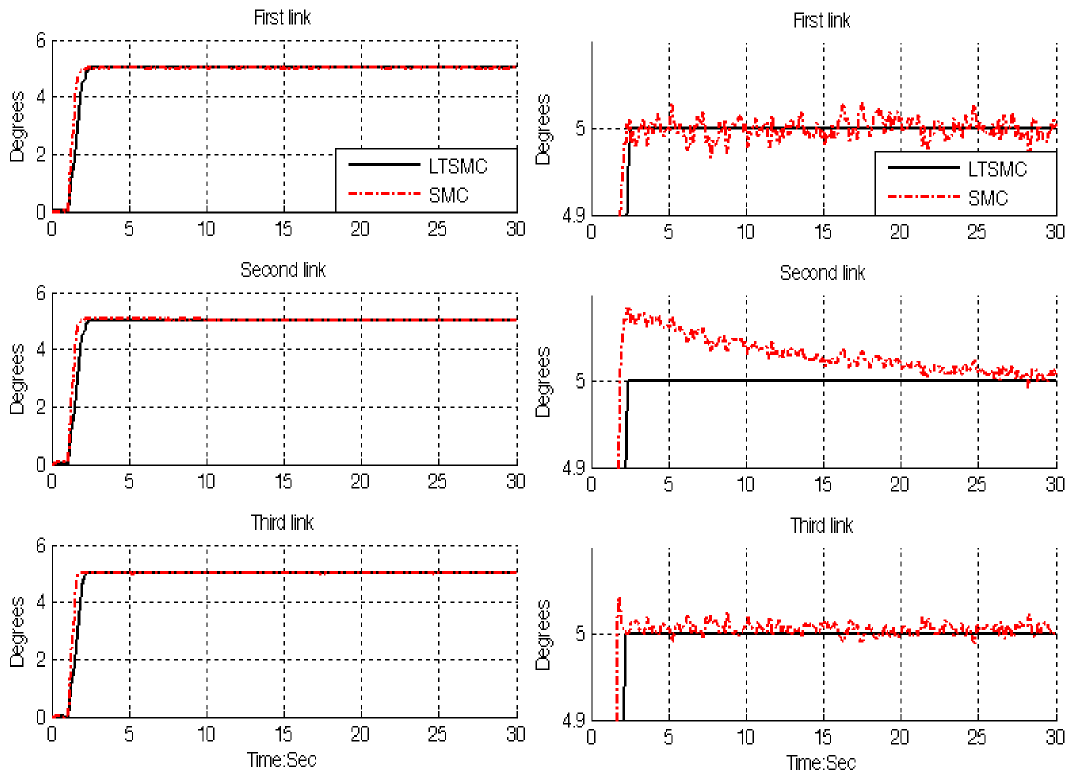

Figure 4. LTSMC and SMC for First, Second and Third Link Trajectory with 40% External Disturbance: Step Trajectory

Based on Figure 4; by comparing step response trajectory with 40% disturbance of relative to the input signal amplitude in LTSMC and SMC, LTSMC's overshoot about **(0%)** is lower than SMC's (**8%**). SMC's rise time **(0.5 seconds)** is lower than LTSMC's **(0.8 second).** Besides the Steady State and RMS error in LTSMC and SMC it is observed that, error performances in LTSMC **(Steady State error =1.3e-12 and RMS error=1.8e-12)** are about lower than SMC's **(Steady State error=10e-4 and RMS error=11e-4).** Based on Figure 4, SMC has moderately oscillation in trajectory response with regard to 40% of the input signal amplitude disturbance but LTSMC has stability in trajectory responses in presence of uncertainty and external disturbance. Based on Figure 4 in presence of 40% unstructured disturbance, LTSMC's is more robust than SMC because LTSMC can auto-tune the sliding surface slope coefficient as the dynamic manipulator parameter's change and in presence of external disturbance whereas SMC cannot.

Torque performance: Figure 5 and 6 have indicated the power of chattering rejection in LTSMC and SMC with 40% disturbance and without disturbance.

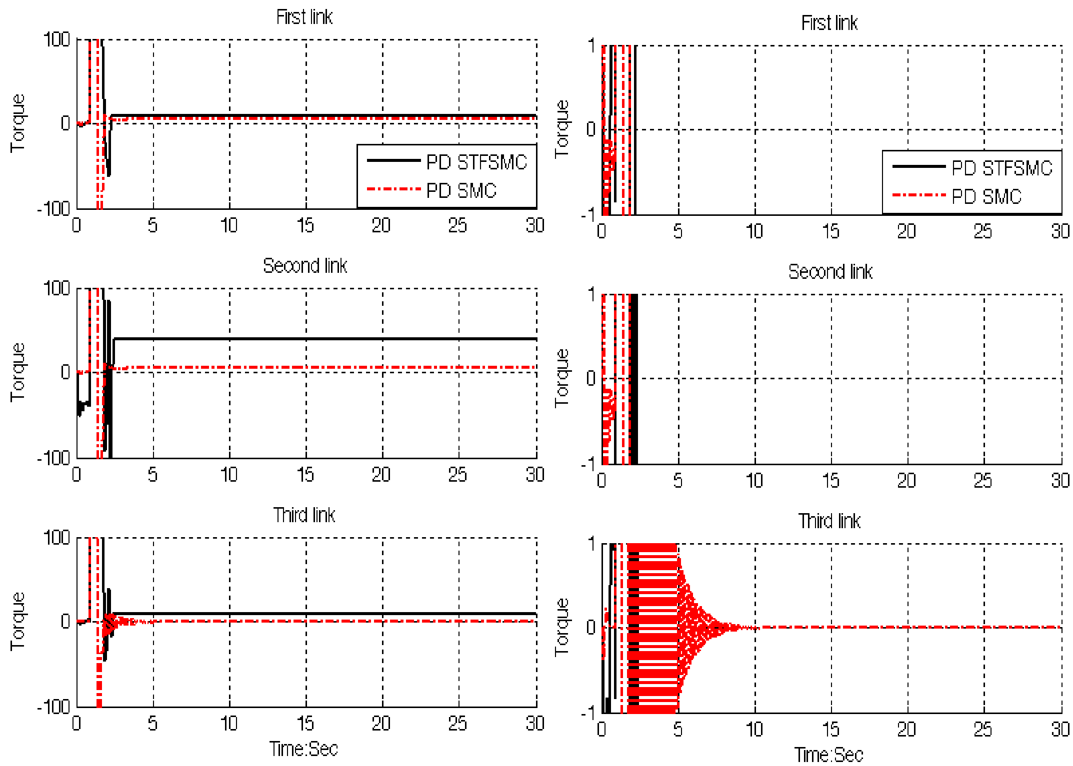

Figure 5. LTSMC and SMC for First, Second and Third Link Torque Performance without Disturbance

Figure 5 shows torque performance for first three links robot manipulator in LTSMC and SMC without disturbance. Based on Figure 5, LTSMC and SMC give considerable torque performance in certain system and all two controllers eliminate the chattering phenomenon in certain system. Figure 6 has indicated the robustness in torque performance for three links robot manipulator in LTSMC and SMC in presence of 40% disturbance. Based on Figure 6, it is observed that SMC controller has oscillation but LTSMC has steady in torque performance. This is mainly because pure SMC are robust but they have limitation in presence of external disturbance. The LTSMC gives significant chattering elimination when compared to SMC. This elimination of chattering phenomenon is very significant in presence of 40% disturbance. This challenge is one of the most important objectives in this research.

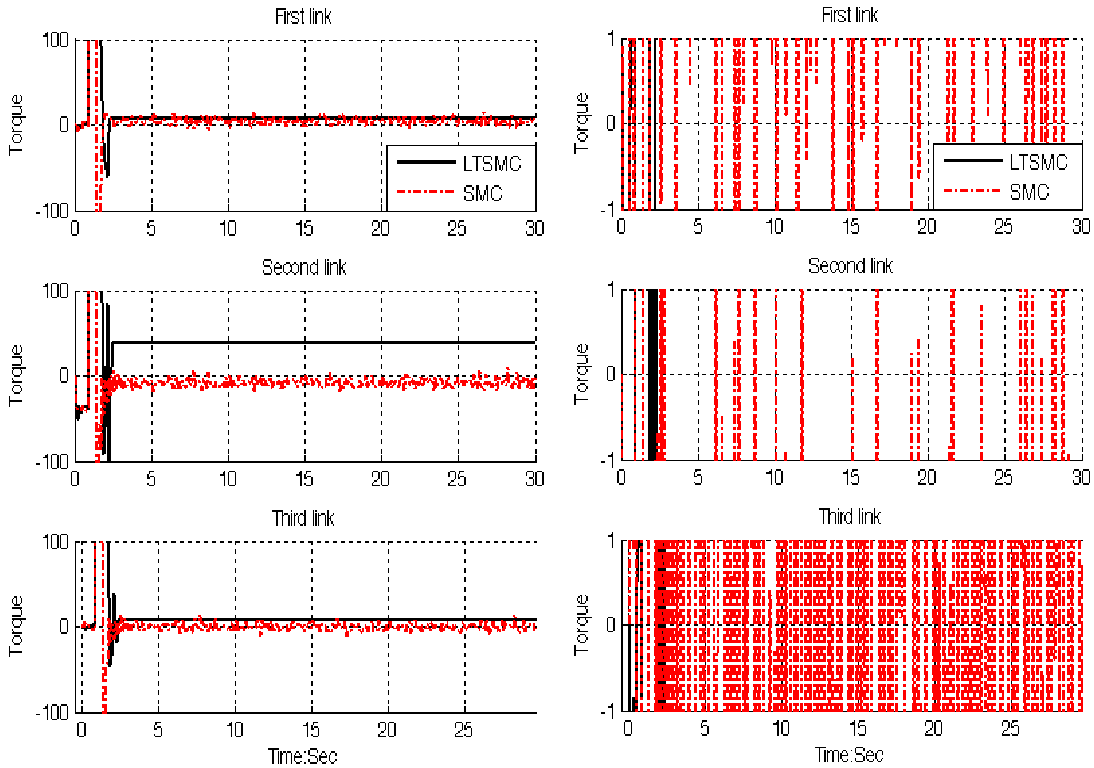

Figure 6. LTSMC and SMC for First, Second and Third Link Torque Performance with 40% Disturbance

SMC has limitation to eliminate the chattering in presence of highly external disturbance (e.g., 40% disturbance) but LTSMC is a robust against to highly external disturbance.

Steady state error: Figure 7 is shown the error performance in LTSMC and SMC for three links robot manipulator**.** The error performance is used to test the disturbance effect comparisons of these controllers for step trajectory. All three joint's inputs are step function with the same step time (step time= 1 second), the same initial value (initial value=0) and the same final value (final value=5). Based on Figure 3, LTSMC's rise time is about 0.48 second and SMC's rise time is about 0.4 second which caused to create a needle wave in the range of 5 (amplitude=5) and the different width. In this system this time is transient time and this part of error introduced as a transient error. Besides the Steady State and RMS error in LTSMC and SMC it is observed that, error performances in LTSMC **(Steady State error =1.8e-10 and RMS error=1.16e-12)** are about lower than SMC's **(Steady State error=1e-8 and RMS error=1.2e-6)**.

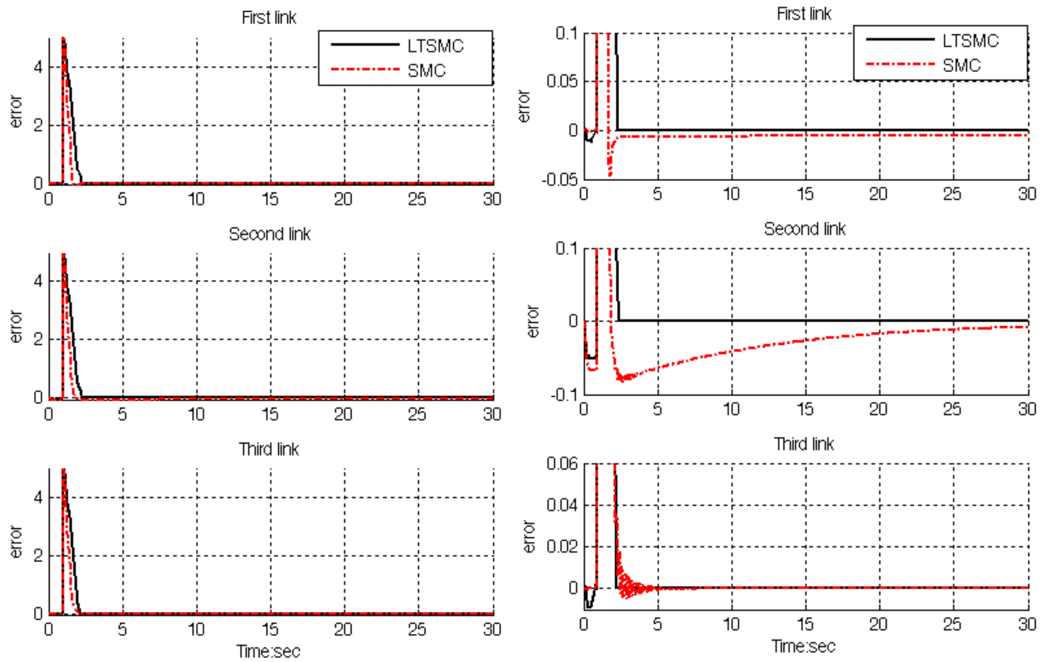

Figure 7. LTSMC and SMC for First, Second and Third Link Steady State Error without Disturbance: Step Trajectory

The LTSMC gives significant steady state error performance when compared to SMC. When applied 40% disturbances in LTSMC the RMS error increased approximately 0.0164% (percent of increase the LTSMC RMS error= $\frac{(40\%\ disturbance\ RMS\ error}{no\ disturbanceRMS\ error} = \frac{1.16e-12}{1.1e-12} =$ 0.0122%) and in SMC the RMS error increased approximately 9.17% (percent of increase the PD-SMC RMS error= $\frac{(40\%\ disturbance\ RMS\ error}{no\ disturbance\ RMS\ error} = \frac{11e-4}{1.2e-6} =$ 9.17%). In this part LTSMC and SMC have been comparatively evaluation through MATLAB simulation, for 3DOF robot manipulator control. It is observed that however LTSMC is dependent of nonlinear dynamic equation of robot manipulator but it can guarantee the trajectory following and eliminate the chattering phenomenon in certain systems, structure uncertain systems and unstructured model uncertainties by online tuning method.

5. Conclusion

In this research, a linear error-based tuning sliding mode controller (LTSMC) is design and applied to robot manipulator. Pure sliding mode controller has difficulty in handling unstructured model uncertainties. It is possible to solve this problem by combining sliding mode controller and linear error-based tuning. The sliding surface gain (λ) is adjusted by linear error-based tuning method. The sliding surface slope updating factor (α) of linear error-based tuning part can be changed with the changes in error, change of error and the integral (summation) of error. Sliding surface gain is adapted on-line by sliding surface slope updating factor. In pure sliding mode controller the sliding surface gain is chosen by trial and error, which means pure sliding mode controller had to have a prior knowledge of the system uncertainty. If the knowledge is not available error performance and chattering phenomenon are go up. In linear error-based tuning sliding mode controller the sliding surface gain are updated on-line to compensate the system unstructured uncertainty. The simulation results exhibit that the linear error-based tuning sliding mode controller works well in various situations.

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