Design New Control Methodology of Industrial Robot Manipulator: Sliding Mode Baseline Methodology

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Abstract

Design a nonlinear controller for second order nonlinear uncertain dynamical systems is one of the most important challenging works. This paper focuses on the design of a chattering free mathematical baseline sliding mode controller (BSMC) for highly nonlinear dynamic robot manipulator, in presence of uncertainties and external disturbance. In order to provide high performance nonlinear methodology, sliding mode controller and baseline methodology are selected. Conversely, pure sliding mode controller is used in many applications; it has an important drawback namely; chattering phenomenon which it can causes some problems such as saturation and heat the mechanical parts of robot manipulators or drivers so baseline sliding mode controller is used to eliminate this important challenge. In order to reduce the chattering this research is used the switching function in presence of baseline method instead of switching function method in pure sliding mode controller. The results demonstrate that baseline sliding mode controller with switching function is a model-based controllers which works well in certain and partly uncertain system and have a better performance compare to pure sliding mode controller. Chattering free baseline sliding mode controller is stable controller which eliminates the chattering phenomenon without to use the boundary layer saturation function.

Keywords*: nonlinear controller, chattering free baseline sliding mode controller, uncertainties, chattering phenomenon, industrial robot arm, sliding mode controller, baseline methodology*

1. Introduction

Industrial Robot Manipulator (Robot Arm): 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) [11-20]. 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 [1-10].

Nonlinear Controller: A nonlinear robust controller design is major subject in this work. 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. 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) [21-45].

Sliding Mode Controller: Sliding mode controller (SMC) is a significant nonlinear controller under condition of partly uncertain dynamic parameters of system. This controller is used to control of highly nonlinear systems especially for robot manipulators, because this controller is a robust and stable [11-30]. 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 [31-50]. It is possible to solve this problem by combining sliding mode controller and baseline law which this method can helps improve the system's tracking performance by adjusting controller's coefficient [51-97].

This paper is organized as follows: Section 2, is served as an introduction to the sliding mode controller formulation algorithm and its application to control of robot manipulator. Part 3, introduces and describes the methodology (design baseline sliding mode controller) algorithms. 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 of Robotic Manipulator, Sliding Mode Formulation Applied to Robot Arm and Proof of Stability

Dynamic of robot arm: The equation of an *n-DOF* robot manipulator governed by the following equation [1, 4, 15-29, 63-80]:

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

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, 70-97]:

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

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]:

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

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]:

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

Where u is the vector of control input, $\boldsymbol{x}^{(\boldsymbol{n})}$ is the $\boldsymbol{n^{th}}$ derivation of $\boldsymbol{x}$, $\boldsymbol{x} = [\boldsymbol{x}, \dot{\boldsymbol{x}}, \ddot{\boldsymbol{x}}, \dots, \boldsymbol{x}^{(\boldsymbol{n}-\boldsymbol{1})}]^{\boldsymbol{T}}$ 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; $\boldsymbol{x_d} = [\boldsymbol{x_d}, \dot{\boldsymbol{x}}_{\boldsymbol{d}}, \ddot{\boldsymbol{x}}_{\boldsymbol{d}}, \dots, \boldsymbol{x_d}^{(\boldsymbol{n}-\boldsymbol{1})}]^{\boldsymbol{T}}$, and trucking error vector is defined by [6]:

$$\widetilde{\boldsymbol{x}} = \boldsymbol{x} - \boldsymbol{x_d} = [\widetilde{\boldsymbol{x}}, \dots, \widetilde{\boldsymbol{x}}^{(\boldsymbol{n}-\boldsymbol{1})}]^{\boldsymbol{T}} \tag{5}$$

A time-varying sliding surface $\boldsymbol{s}(\boldsymbol{x}, \boldsymbol{t})$ in the state space $\boldsymbol{R^n}$ is given by [6, 81-97]:

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

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

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

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

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

where ζ is positive constant.

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

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

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

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

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

and

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

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

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

suppose S is defined as

$$\boldsymbol{s}(\boldsymbol{x}, \boldsymbol{t}) = \left(\frac{\boldsymbol{d}}{\boldsymbol{dt}} + \boldsymbol{\lambda}\right) \quad \widetilde{\boldsymbol{x}} = (\dot{\mathbf{x}} - \dot{\mathbf{x}}_{\mathbf{d}}) + \boldsymbol{\lambda}(\mathbf{x} - \mathbf{x_d}) \tag{14}$$

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

$$\dot{\boldsymbol{S}} = (\ddot{\mathbf{x}} - \ddot{\mathbf{x}}_{\mathbf{d}}) + \boldsymbol{\lambda}(\dot{\mathbf{x}} - \dot{\mathbf{x}}_{\mathbf{d}}) \tag{15}$$

suppose the second order system is defined as;

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

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

$$\boldsymbol{\widehat{U}} = -\boldsymbol{\hat{f}} + \boldsymbol{\ddot{x}_d} - \boldsymbol{\lambda}(\dot{\mathrm{x}} - \dot{\mathbf{x}}_{\mathbf{d}}) \quad \textbf{(17)}$$

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

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

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

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

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

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

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

$$\boldsymbol{s}(\boldsymbol{x}, \boldsymbol{t}) = (\frac{\boldsymbol{d}}{\boldsymbol{dt}} + \boldsymbol{\lambda})^2 \left(\int_{\mathbf{0}}^{\boldsymbol{t}} \tilde{\boldsymbol{x}}\, \boldsymbol{dt}\right) = (\dot{\mathrm{x}} - \dot{\mathbf{x}}_{\mathbf{d}}) + \mathbf{2}\boldsymbol{\lambda}(\dot{\mathrm{x}} - \dot{\mathbf{x}}_{\mathbf{d}}) - \boldsymbol{\lambda}^{\mathbf{2}}(\mathbf{x} - \mathbf{x}_{\mathbf{d}}) \quad \textbf{(21)}$$

in this method the approximation of $\boldsymbol{U}$ is computed as [6]

$$\boldsymbol{\widehat{U}} = -\boldsymbol{\hat{f}} + \boldsymbol{\ddot{x}_d} - \mathbf{2}\boldsymbol{\lambda}(\dot{\mathrm{x}} - \dot{\mathbf{x}}_{\mathbf{d}}) + \boldsymbol{\lambda}^{\mathbf{2}}(\mathbf{x} - \mathbf{x}_{\mathbf{d}}) \quad \textbf{(22)}$$

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

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

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

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

and $\boldsymbol{\tau_{dis}}$ is computed as [1];

$$\boldsymbol{\tau_{dis}} = \boldsymbol{K} \cdot \mathbf{sgn}(\boldsymbol{S}) \quad \textbf{(25)}$$

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

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

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

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

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

Pure Sliding Mode Controller's Proof of Stability: the lyapunov formulation can be written as follows,

$$\boldsymbol{V} = \frac{\mathbf{1}}{\mathbf{2}}\boldsymbol{S}^{\boldsymbol{T}}.\boldsymbol{M}.\boldsymbol{S} \quad \textbf{(28)}$$

the derivation of V can be determined as,

$$\dot{\boldsymbol{V}} = \frac{1}{2}\boldsymbol{S}^{\boldsymbol{T}}.\dot{\boldsymbol{M}}.\boldsymbol{S} + \boldsymbol{S}^{\boldsymbol{T}}\, \boldsymbol{M}\dot{\boldsymbol{S}} \quad \textbf{(29)}$$

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

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

it is assumed that

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

by substituting (30) in (29)

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

suppose the control input is written as follows

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

by replacing the equation (33) in (32)

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

it is obvious that

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

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

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

the equation (11) can be written as

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

therefore, it can be shown that

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

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

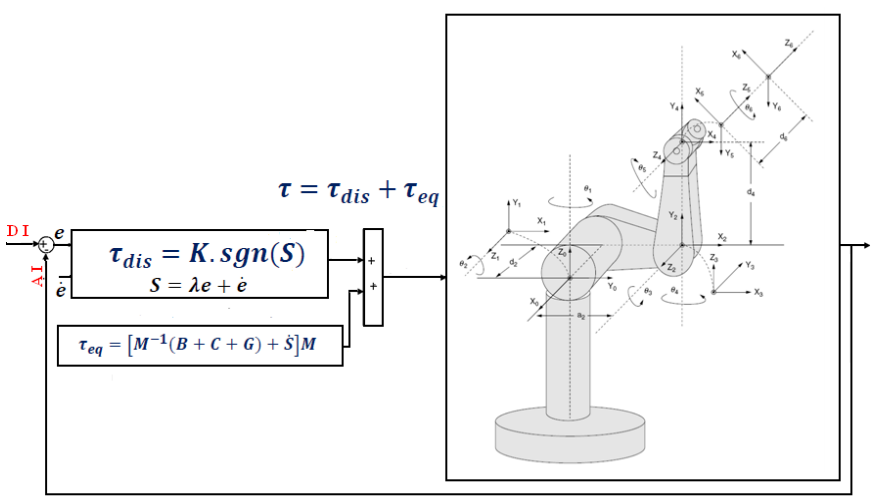

Figure 1. Block Diagram of a Sliding Mode Controller: Applied to Robot Arm

3. Methodology: Design Baseline Sliding Mode Controller with Switching Function

Baseline Sliding Mode Controller Design: The design of a baseline controller to control the sliding surface slope was very straight forward. Since there was an output from the sliding surface slope model, this means that there would be two inputs into the baseline controller. Similarly, the output of the controller result from the control input of the sliding surface slope. In a typical PID controller, the controller corrects the error between the desired output value and the measured value. Since the sliding surface slope is the measured signal, two controllers were cascaded together to control the sliding surface slope. The first was a PID controller that corrected the error between the desired joint variable and the measured joint variable; while the second was only a proportional integral (PI) controller that corrected the sliding surface, error and integral of error. Figure 2 shows the baseline based sliding mode controller.

$$\boldsymbol{e(t) = q_{actual}(t) - q_{desired}(t)} \tag{39}$$

$$\boldsymbol{S_{\alpha} = \lambda_a e + \dot{e} + \left(\frac{\lambda_a}{2}\right)^2 \sum e} \tag{40}$$

$$\boldsymbol{S_T = \left(\lambda_a e + \left(\frac{\lambda_a}{2}\right)^2 \sum e\right) \times S_{\alpha}} \tag{41}$$

$$\boldsymbol{S_T = \left(\lambda_a e + \left(\frac{\lambda_a}{2}\right)^2 \sum e\right) \times \left(\lambda_a e + \dot{e} + \left(\frac{\lambda_a}{2}\right)^2 \sum e\right)} \tag{42}$$

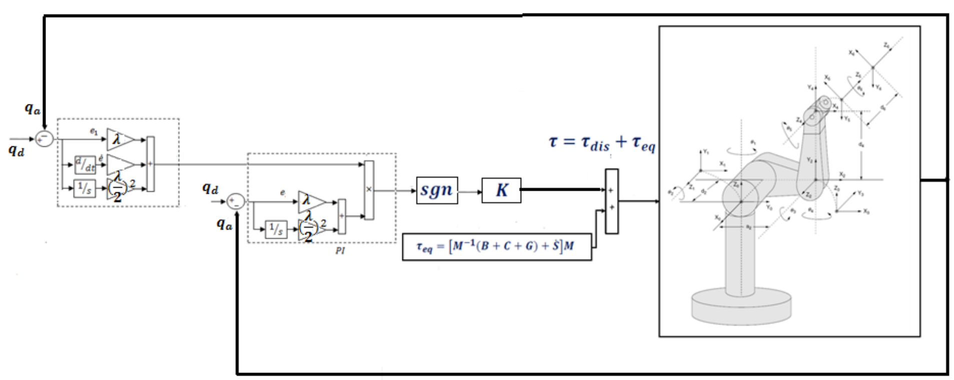

Figure 2. Block Diagram of BASELINE based SM Controller

4. Results

This section is focused on compare between Sliding Mode Controller (SMC) and baseline Sliding Mode Controller (BSMC). These controllers were tested by step responses. The simulation was implemented in Matlab/Simulink environment.

Tracking Performances: Based on (27) 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 BSMC are; $K_p = K_v = K_i = 12,\ \emptyset_1 = \emptyset_2 = \emptyset_3 = 0.1, and\ \lambda_1 = 2, \lambda_2 = 6, \lambda_3 = 8$ and the best possible coefficients in step SMC are; $\lambda_1 = 1, \lambda_2 = 6, \lambda_3 = 8$; $K_p = K_v = K_i = 10$; $\emptyset_1 = \emptyset_2 = \emptyset_3 = 0.1$. Figure 3 shows tracking performance in SMC and BSMC without disturbance for step trajectory.

Based on Figure 3 it is observed that, SMC has chattering in presence of switching mode function but BSMC has steady in response. SMC's overshoot is 1.3% but BSMC's overshoot is 0%. First and second links rise time in SMC is better than BSMC.

Disturbance Rejection: Figures 4 to 6 show the power disturbance elimination in SMC and BSMC with disturbance for step trajectory. The disturbance rejection is used to test the robustness comparisons of these two controllers for step trajectory. A band limited white noise with predefined of 10% and 20% the power of input signal value is applied to the step trajectory.

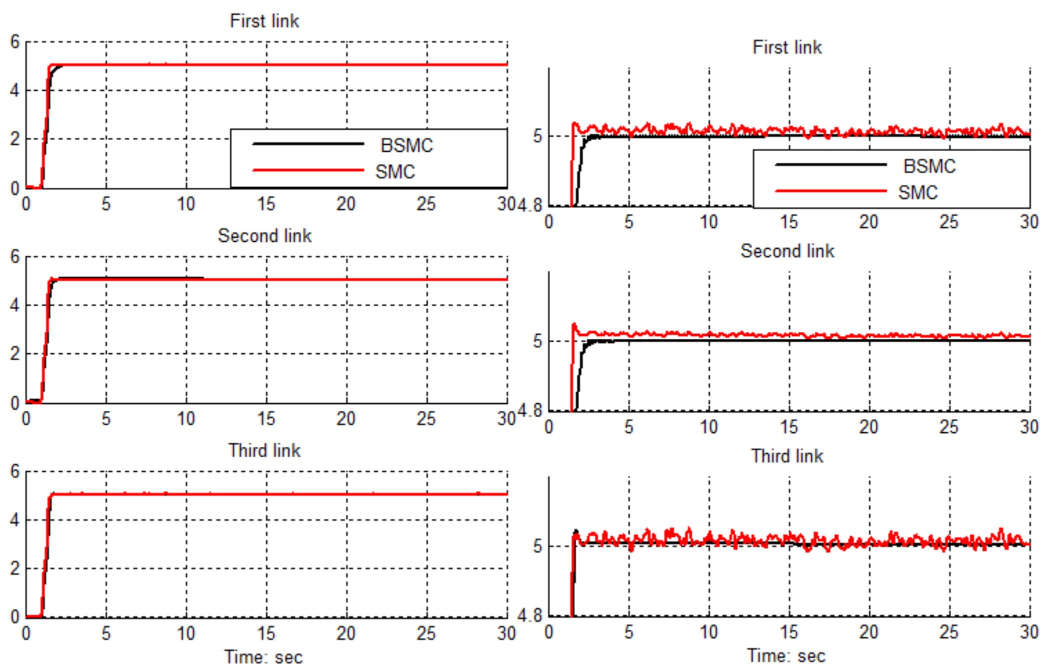

Figure 3. BSMC and SMC for First, Second and Third Link Step Trajectory Performance without Disturbance

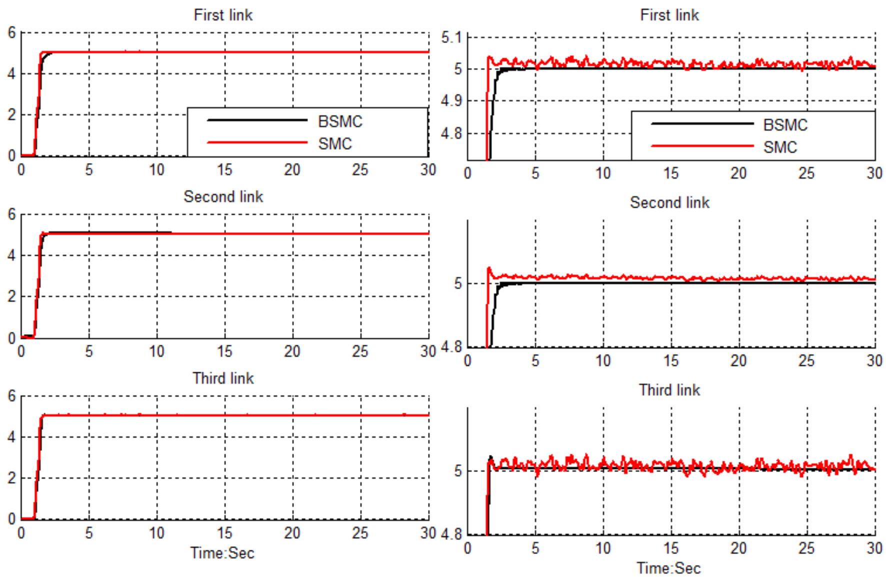

Figure 4. BSMC and SMC for First, Second and Third Link Trajectory with 10% External Disturbance: Step Trajectory

Based on Figure 4; by comparing step response trajectory with 10% disturbance of relative to the input signal amplitude in BSMC and SMC, BSMC's overshoot about (0%) is lower than SMC's **(1%)** . Besides the Steady State and RMS error in BSMC and SMC it is observed that, error performances in BSMC **(Steady State error =0.8e-6 and RMS error=1e-6)** are bout lower than SMC's **(Steady State error=1.6e-6 and RMS error=1.9e-6)**. Based on Figure 4, it is observed that BSMC's performances are better than SMC and it also can eliminate the chattering in presence of 10% disturbance.

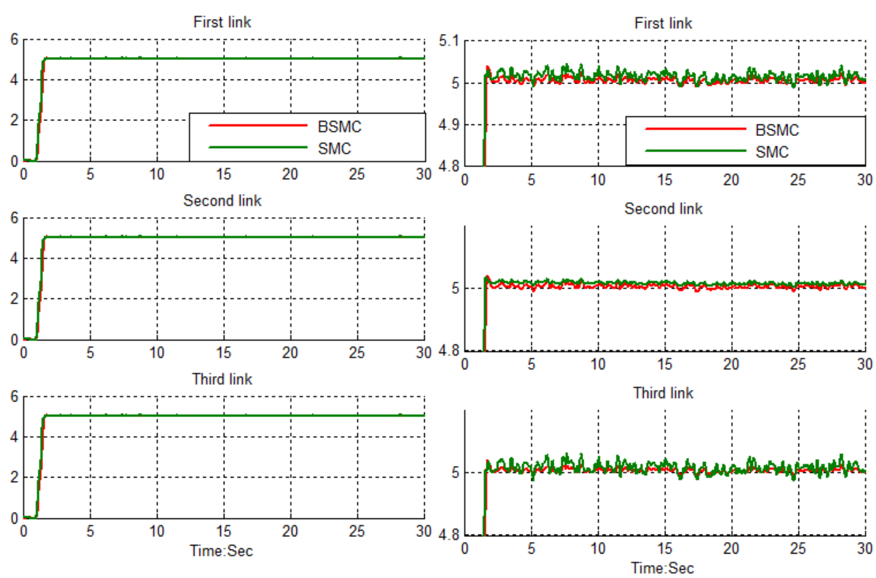

Figure 5. Desired Input, MTSMC, FSMC and SMC for First, Second and Third Link Trajectory with 20% External Disturbance: Step Trajectory

Based on Figure 5; by comparing step response trajectory with 20% disturbance of relative to the input signal amplitude in BSMC and SMC, BSMC's overshoot about **(1.8%)** is lower than SMC's (**2.1%). ** Besides the Steady State and RMS error in BSMC and PD-SMC it is observed that, error performances in MTSMC **(Steady State error =0.3e-5 and RMS error=1e-5)** are about lower than SMC's **(Steady State error=1.8e-5 and RMS error=2e-5)**. Based on Figure 5 it is observed that, these two controllers have oscillation in presence of uncertainty but BSMC is more stable and more robust than SMC.

Torque performance: Figure 6 has indicated the torque performance in presence of 20% disturbance.

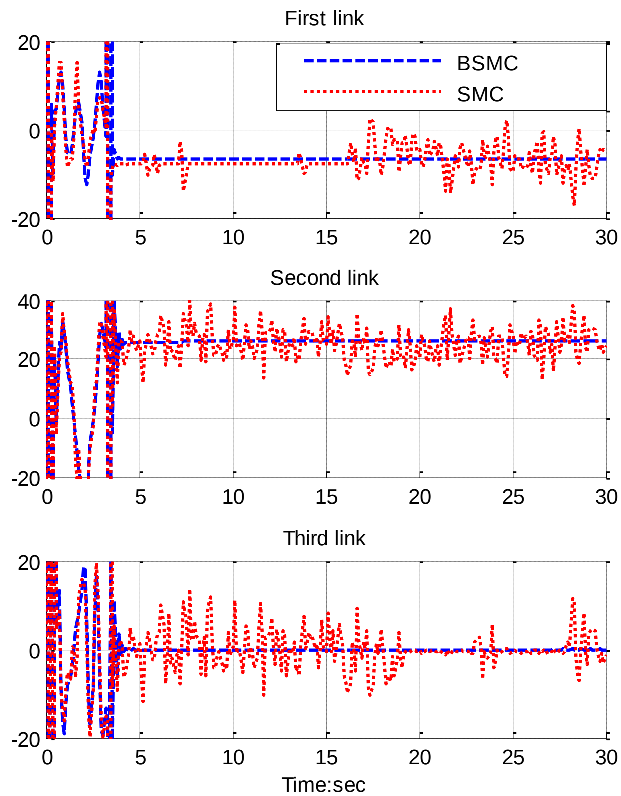

Figure 6. BSMC and SMC for First, Second and Third Link Torque Performance with Disturbance

Figure 6 shows torque performance for first three links industrial robot manipulator in BSMC and SMC with disturbance. The BSMC gives significant chattering elimination when compared to SMC. This elimination of chattering phenomenon is very significant in presence of 20% disturbance. This challenge is the main important objectives in this research.

5. Conclusion

Refer to this research, a baseline based sliding mode controller (BSMC) is proposed for industrial robot manipulator. The stability and convergence of the baseline based sliding mode controller based on switching function is guarantee and proved by the Lyapunov method. The simulation results exhibit that the baseline-based sliding mode controller works well in various situations. The BSMC gives significant steady state error performance when compared to SMC. When applied 20% disturbances in BSMC the RMS error increased approximately 0.0164% (percent of increase the MTSMC RMS error= $\frac{(20\%\ disturbance\ RMS\ error}{no\ disturbanceRMS\ error} = \frac{1e-5}{1e-6} = 0.1\%$), SMC the RMS error increased approximately 1.3% (percent of increase the PD-SMC RMS error= $\frac{(20\%\ disturbance\ RMS\ error}{no\ disturbance\ RMS\ error} = \frac{2e-5}{1.6e-6} = 1.3\%$).

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