

# Terminal Sliding Mode Control of an Anthropomorphic Manipulator with Friction Based Observer

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**Abstract**—The role of modern control techniques has been instrumental in today’s robotic applications because of their increasing requirements for reliability, accuracy, productivity and repeatability. Robotic manipulators are highly non-linear systems with coupled dynamics and thus are vulnerable to a lot of disturbances such as unknown payloads, dynamics that the model and joint friction do not predict. To achieve superior performance and reliability in the presence of friction, this research proposes a robust control algorithm for a five-degree-of-freedom (DoF) robotic manipulator. The dynamic LuGre friction model is used to develop the robot’s dynamic model. A sliding mode observer (SMO) is proposed for the estimation of the internal friction state of the LuGre model. The friction and load torque are based on an estimated state to compensate for unidentified friction. A Lyapunov candidate function is used to check the stability of the controller with the SMO. The proposed control methodology has been designed and implemented in MATLAB/Simulink environment to illustrate the tracking of various trajectories. This study’s outcomes proved that the proposed control law with model-based friction compensation is effective and efficient.

**Index Terms**—Robotic Manipulator, Degree of Freedom, Terminal Sliding Mode Control, Sliding Mode Friction observer

## I. INTRODUCTION

With the rapid advancement of automation in the industrial era, robotic manipulators are becoming highly significant in medical, renewable energy, textile and agriculture etc., applications [1]. The manipulator tasks must be controlled safely, efficiently and consistently to achieve high production or efficient exploration [2]. As a result, improved robotic manipulators controllers are required to deliver high accuracy under various diverse situations affected by the operating environment, including external noise, measurement mistakes, or unknown uncertain components [3]. However, a robotic manipulator is

a complex nonlinear system whose dynamic properties are difficult to anticipate. In fact, due to uncertainties such as non-linear frictions and the flexibility of joints of the robotic manipulator, obtaining correct dynamic models is incredibly difficult [4]. One of the most significant constraints to achieve good performance of control technique in mechanical systems is friction, which is a non-linear phenomenon that is difficult to characterise analytically. Numerous methods have been offered in the literature to deal with parameter uncertainty, such as PID Control [5], Sliding Mode Control (SMC) [6], Optimal Control [7], Model Predictive Control (MPC) [8], Adaptive control [9], and Terminal sliding mode control (TSMC) [10], etc.

Friction is one of the primary factors that impedes the quick tracking behaviour of robotic manipulator actuators. It might lead to steady-state tracking inaccuracies as well it could limit cycle oscillation. As a result, friction is an inherently unpredictable non-linear phenomenon that should be modelled. Several friction models approaches have been presented in the literature that describes the improved behavior of friction as well as predict friction. However, it appears that classical models are unable to represent some of the empirically observed behaviour in systems with high friction effects. They are divided into static and dynamic friction models [11]. One of the dynamic models that caters to most non-linear phenomena is the LuGre friction model. In the first category, the friction force is a static function of velocity. The most well-known models in this perspective are the Coulomb friction model, which assumes the friction force is independent of velocity, and the viscous friction model, which presumes that the force is proportional to velocity. The Dahl model and its extensions, the generalised Maxwell-slip model, and the

more contemporary LuGre model, which has been modified and applied in many forms [12], are all pertinent examples of dynamic models. Friction is one of the most significant factor affecting the precision with which an actuator system positions itself. To compensate for known non-linearities, the feedback linearisation technique can be used. Furthermore, adaptive-based control laws and robust control techniques for improving mechanical system control performance have been extensively researched. Recent studies have considered friction models for compensation of friction to get rid of non-linear effects. In [13], an observer-based friction compensation technique is addressed to estimate its internal state. In [14], an author has recommended an adaptive control with SMO for actuators of mechanical system, which differs from the methods for friction compensation debated above. SMC has been described in the literature to be effective in controlling non-linear systems and MIMO systems, thereby reducing variation sensitivity due to various types of uncertainties [15].

In this study, we propose a robust control algorithm with compensation of friction using dynamic LuGre friction model to accomplish high-level precision torque tracking control of robotic manipulator. TSMC based law [16], [17] is developed for five DoF robotic manipulator with sliding mode friction observer. The friction observer is devised for the estimation of friction state. Implementation of the controller has been formed to compensate friction behaviours (static and dynamic), that is based on the predicted internal friction state  $z_F(t)$  along with controlling the speed and position so that the required trajectories are tracked asymptotically.

This article is organized into five Sections. Section II presents a concise state-space model of the robotic manipulator, including the LuGre friction model, and a SMO is developed to estimate the unmeasurable state of friction. Section III starts with the preliminary dynamics of a terminal sliding mode based control law and it is designed using an LuGre model to achieve the position objectives. Simulation and discussion is included in Section IV. Finally, the paper is concluded in the section V.

## II. MODELLING

The system's mathematical model is required for the application of control algorithms. Autonomous Articulated Robotic Educational Platform (AUTAREP) ED-7220C robotic manipulator that is being used to conduct the research and analysis in this current study as shown in Fig. 1. It is an articulated robot with five degrees of freedom which are controlled by DC servo motors. Each joint is moved by a single motor, with the exception of the wrist joint, which is moved by two motors that control both pitch and roll motions. The robotic manipulator has optical encoders mounted on each joint servo motor axis, which provide information about the joint's position in order to receive feedback from the joints. The kinematics and dynamics of a robot are included in the model. kinematics is the study of the relationship between robot joint angles and the position and orientation of the end-effector. The kinematic representation of the AUTAREP manipulator is depicted in the Fig. 2. The

kinematic model of the manipulator established on Denavit-Hartenberg (D-H) parameters is reported in [18].

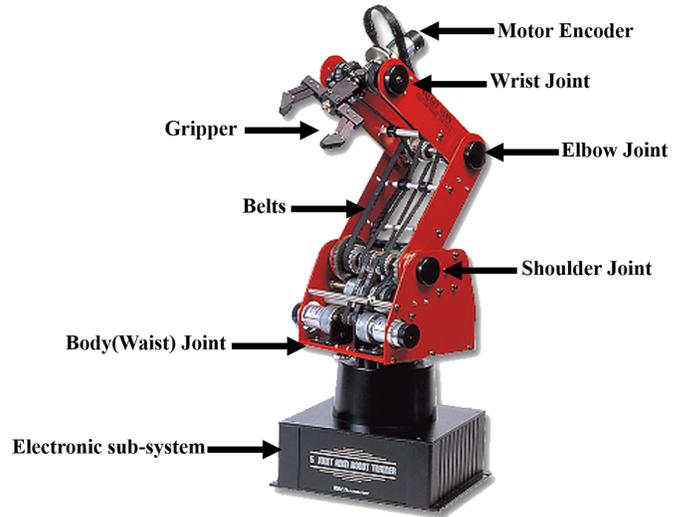


Fig. 1. AUTAREP Manipulator ED-7220C

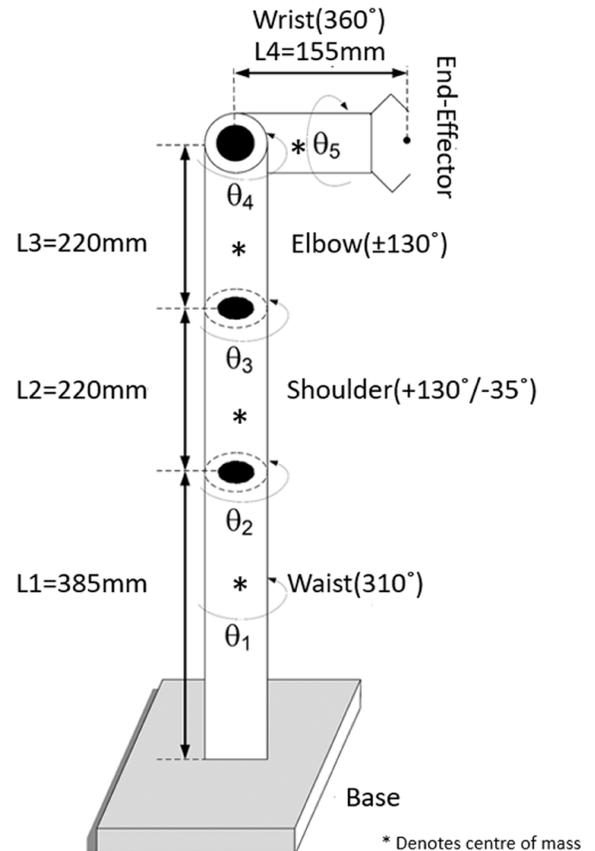


Fig. 2. Kinematic representation of the robotic arm

### A. Dynamic Model

The study of dynamics is concerned with the torques and forces that cause robot motion. The Euler-Lagrange method [19], is used to model a platform in the current research. The dynamic equation of the n-link robotic manipulator is given by an equation (1).

$$\tau_r = M(h_i)\ddot{h}_i + C_F(h_i, \dot{h}_i)\dot{h}_i + G(h_i) + T_F(\dot{h}_i) \quad (1)$$

where for  $n$  joints,  $M(h_i) \in R^{n \times n}$  is the mass matrix,  $C_F(h_i) \in R^n$  represents the centripetal and coriolis forces,  $G(h_i) \in R^n$  describe the gravitational matrix,  $T_F(\dot{h}_i) \in R^n$  represents friction torques and total torque of robotic manipulator joints is denoted by  $\tau_r$ .

### B. LuGre Friction Model

Friction is also a significant factor in the performance of control systems. Friction reduces the precision of positioning and pointing systems, and it can also cause instabilities in the system. Friction compensation can help to mitigate the negative impact of friction to a certain extent. It is beneficial to have simple models of friction that capture the essential properties of friction for use in control applications. The LuGre friction model [20], a non-linear dynamic friction model widely used in mechanical and servo systems, will be used to formulate the dynamic friction  $T_F$  in this subsection. The LuGre model is defined as in (2)

$$\frac{dz_F}{dt} = \nu - \sigma_0 \frac{|\nu|}{g(\nu)} z_F \quad (2)$$

$$T_F = \sigma_0 z_F + \sigma_1 \dot{z}_F + f(\nu) \quad (3)$$

$$T_F = \sigma_0 z_F + \sigma_1 \dot{z}_F + \sigma_2 \nu \quad (4)$$

where the internal friction state is presented by  $z_F$ , the velocity between the two surfaces in contact is represented by the  $\nu$ ,  $g(\nu)$  is the function which describes the stiction phenomena of the surfaces in contact and it is defined in (5), the predicted friction torque is  $T_F$ ,  $\sigma_0$  and  $\sigma_1$  are coefficients for bristles. and  $f(\nu) = \sigma_2 \nu$ .

$$g(\nu) = F_c + (F_s - F_c) \exp^{-(|\nu|/\nu_s)} \quad (5)$$

where Coulomb friction is  $F_c$  and  $F_s$  relates to the stiction force. The factor  $\nu_s$ , decides exactly how instantly  $g(\nu)$  approaches  $F_c$ .

The AUTAREP robotic manipulator system is presented in equation set (6) as a state space model, where  $h_1$ ,  $h_2$  and  $z_F$  are state variables for the position of the robotic manipulator, its velocity and the bristle length, respectively.

$$\begin{aligned} \dot{h}_1 &= h_2 \\ \dot{h}_2 &= M^{-1}(\tau_r - (C_F h_2 + G h_1 + \sigma_0 z_F + \sigma_2 h_2 + \sigma_1 \dot{z}_F)) \\ \dot{z}_F &= h_2 - \sigma_0 \frac{|h_2|}{g(h_2)} z_F \end{aligned} \quad (6)$$

TABLE I  
PARAMETERS OF LUGRE FRICTION MODEL

Parameter	Value	Unit	Description
$\nu_s$	$6.109 \cdot 10^{-2}$	rad/sec	Velocity
$\sigma_2$	1.819	Nm.sec/rad	Viscous friction coefficients
$\sigma_1$	45.2	Nm.sec/rad	Damping coefficient
$\sigma_0$	2750	Nm/rad	Stiffness coefficient
$F_s$	8.875	Nm	Static friction torque
$F_c$	6.975275	Nm	Coulomb friction torque

### C. Friction Observer

The friction state  $z_F$  is not measurable in the dynamic model of robotic manipulator, as a result it must be monitored to quantify the applied friction force. To determine the internal state of the system  $z_F$ , a SM based friction observer is developed to do so [9]. The SM observer equation is defined by (7), which is given as follow

$$\dot{\hat{z}}_F = h_2 - \sigma_0 \frac{|h_2|}{g(h_2)} z_F - \mu_0 \text{sign}(S_T(t)) \quad (7)$$

where  $\mu_0$  is described as a constant with positive value. For the friction state, the error dynamics are defined by (8)

$$\begin{aligned} \tilde{z}_F &= \hat{z}_F - z_F \\ \dot{\tilde{z}}_F &= \dot{\hat{z}}_F - \dot{z}_F \end{aligned} \quad (8)$$

For solving  $\dot{\tilde{z}}_F$ , the error dynamics are given in (9)

$$\dot{\tilde{z}}_F = -\sigma_0 \frac{|h_2|}{g(h_2)} \tilde{z}_F - \mu_0 \text{sign}(S_T(t)) \quad (9)$$

It will be demonstrated that there is a constant variable  $\mu_0$  such that that the estimation error approaches zero and the sliding mode occurs on the sliding surface  $S_T(t) = 0$ . The estimated friction state derivative  $\dot{z}_F$ , which corresponds to the designed observer in (7) consists of two components: one is from the estimated friction state  $\hat{z}_F$  and the further from the switched sliding surface. The LuGre friction model parameters were acquired from the literature [21] and are shown in Table. I.

### III. TERMINAL SLIDING MODE CONTROLLER DESIGN

The difference between the actual and reference trajectories is used as a performance indicator in the controller, which produces the control inputs. When the control inputs are applied to the actuator, the speed of the respective motors changes. As a result, the intended motion of the underlying system is realised. The reference tracking errors are specified for this purpose as follows:

$$\begin{aligned} e_h &= h_1 - h_d \\ \dot{e}_h &= h_2 - \dot{h}_d \\ \ddot{e}_h &= \dot{h}_2 - \ddot{h}_d \end{aligned} \quad (10)$$

where  $h_d \in \mathbb{R}^n$  is the reference trajectory. For getting the main control objectives, consider the sliding surface in the following form [22].

$$S_T = \dot{e}_h + \beta|e_h|^\gamma \text{sign}(e_h) \quad (11)$$

where  $S_T \in \mathbb{R}^n$ ,  $\beta > 0$  and  $0 < \gamma < 1$  is positive number.

$$\dot{S}_T = \ddot{e}_h + \beta\gamma|e_h|^{\gamma-1}\dot{e}_h \quad (12)$$

In TSMC, the purpose is achieved by establishing  $\dot{S}_T = 0$ . Substituting this value in Eq. (12)

$$0 = \ddot{e}_h + \beta\gamma|e_h|^{\gamma-1}\dot{e}_h \quad (13)$$

Substituting the value of  $\ddot{e}_h$  and  $\dot{e}_h$  in (12)

$$0 = \ddot{h}_2 - \ddot{h}_d + \beta\gamma|h_1 - h_d|^{\gamma-1}h_2 - \dot{h}_d \quad (14)$$

$$0 = M^{-1}\{\tau_r - (C_F h_2 + G h_1 + \sigma_0 \tilde{z}_F + \sigma_2 h_2 + \sigma_1 \dot{\tilde{z}}_F)\} - \dot{h}_d + \beta\gamma|h_1 - h_d|^{\gamma-1}h_2 - \dot{h}_d \quad (15)$$

Simplifying the expression for  $\tau_r$ , we attain

$$\tau_r = M\{\ddot{h}_d - \beta\gamma|h_1 - h_d|^{\gamma-1}h_2 - \dot{h}_d\} + C_F h_2 + G h_1 + \sigma_0 \tilde{z}_F + \sigma_2 h_2 + \sigma_1 \dot{\tilde{z}}_F \quad (16)$$

Consider the robotic manipulator system's overall control law ( $\tau_{rc}$ ) as

$$\tau_{rc} = \tau_{req} + \tau_{rdis} \quad (17)$$

The whole control input of TSMC law contains two components. The first component is related to equivalent control law  $\tau_{req}$  and it is a continuous term. The second component is about discontinuous control law ( $\tau_{rdis}$ ) with the signum function. The discontinuous control and continuous control manifold is described in (18) and (19), respectively.

$$\tau_{rdis} = -K_t \text{sign}(S_T) - \zeta S_T \quad (18)$$

$$\tau_{req} = M\{\ddot{h}_d - \beta\gamma|h_1 - h_d|^{\gamma-1}h_2 - \dot{h}_d\} + C_F h_2 + G h_1 + \sigma_0 \tilde{z}_F + \sigma_2 h_2 + \sigma_1 \dot{\tilde{z}}_F \quad (19)$$

The total control input  $\tau_{rc}$  of AUTAREP robotic manipulator is given by (20).

$$\tau_{rc} = M\{\ddot{h}_d - \beta\gamma|h_1 - h_d|^{\gamma-1}h_2 - \dot{h}_d\} + C_F h_2 + G h_1 + \sigma_0 \tilde{z}_F + \sigma_2 h_2 + \sigma_1 \dot{\tilde{z}}_F - K_t \text{sign}(S_T) - \zeta S_T \quad (20)$$

#### A. Stability with Lyapunov Function

TSMC's stability study has been performed utilising the Lyapunov function for an AUTAREP robotic manipulator. Therefore, the (21) defines the Lyapunov function candidate.

$$V_T = \frac{1}{2}S_T^2 + \frac{1}{2}\tilde{z}_F^2 \quad (21)$$

Where  $\tilde{z}_F$  is derived from the difference between the friction of SMO given in (7) and the friction model given in (2). By taking derivative with respect to time of (21), We'll get (22)

$$\dot{V}_T = S_T \dot{S}_T + \tilde{z}_F \dot{\tilde{z}}_F \quad (22)$$

Then, from (9), (12) and (14), the (23) will be

$$\dot{V}_T = (\dot{e}_h + \beta|e_h|^\gamma \text{sign}(e_h))(\ddot{e}_h + \beta\gamma|e_h|^{\gamma-1}\dot{e}_h) - \tilde{z}_F(\sigma_0 \frac{|h_2|}{g(h_2)} \tilde{z}_F + \mu_0 \text{sign}(S_T)) \quad (23)$$

where  $\ddot{e}_h = \ddot{h}_2 - \ddot{h}_d$  and  $\dot{e}_h = \dot{h}_1 - \dot{h}_d$ , by replacing the values of  $\ddot{e}_h$  and  $\dot{e}_h$  in (23) we get

$$\dot{V}_T = \dot{e}_h + \beta|e_h|^\gamma \text{sign}(e_h)\{(\ddot{h}_2 - \ddot{h}_d) + \beta\gamma|e_h|^{\gamma-1}(\dot{h}_1 - \dot{h}_d)\} - \tilde{z}_F\{\sigma_0 \frac{|h_2|}{g(h_2)} \tilde{z}_F + \mu_0 \text{sign}(S_T)\} \quad (24)$$

Replacing the value of  $\ddot{h}_2$  in (24), we obtain

$$\dot{V}_T = \dot{e}_h + \beta|e_h|^\gamma \text{sign}(e_h)\{M^{-1}(\tau_{rc} - (C_F h_2 + G h_1 + \sigma_0 \tilde{z}_F + \sigma_2 h_2 + \sigma_1 \dot{\tilde{z}}_F - \ddot{h}_d) + \beta\gamma|e_h|^{\gamma-1}(\dot{h}_1 - \dot{h}_d))\} - \tilde{z}_F\{\sigma_0 \frac{|h_2|}{g(h_2)} \tilde{z}_F + \mu_0 \text{sign}(S_T)\} \quad (25)$$

After solving and simplifying the equation (25), Therefore (25) can be modified in the following method to acquire the requirements for Lyapunov stability.

$$\dot{V}_T \leq -K_t |S_T| - \zeta S_T - (\tilde{z}_F(\sigma_0 \frac{|h_2|}{g(h_2)} \tilde{z}_F + \mu_0 \text{sign}(S_T(t)))) \quad (26)$$

If the parameters are selected in such a way that  $K_t > 0$  and  $\zeta > 0$  then  $\dot{V}_T(t) < 0$  for  $\mu_0 > 0$  and the equation (21) is positive definite, that demonstrates system stability with applied torque input  $\tau_{rc}$ .

## IV. RESULTS AND DISCUSSIONS

The findings of simulations can be used to assist in the design and control of working mechanism. The tracking control of a five DoF robotic manipulator arm has been utilized to evaluate the performance of the TSMC controller. The proposed controller has been simulated in Matlab/Simulink, the plant and controller are built using user defined Matlab functions. In order to follow the trajectory of the robot, we have added a step input signal to the controller as a desired signal. The tracking trajectories of robotic manipulator joints (base, shoulder, elbow, wrist) using the proposed TSMC law is shown in Fig. 3 and Fig. 4 illustrates the sinusoidal response of the robotic manipulator joints.

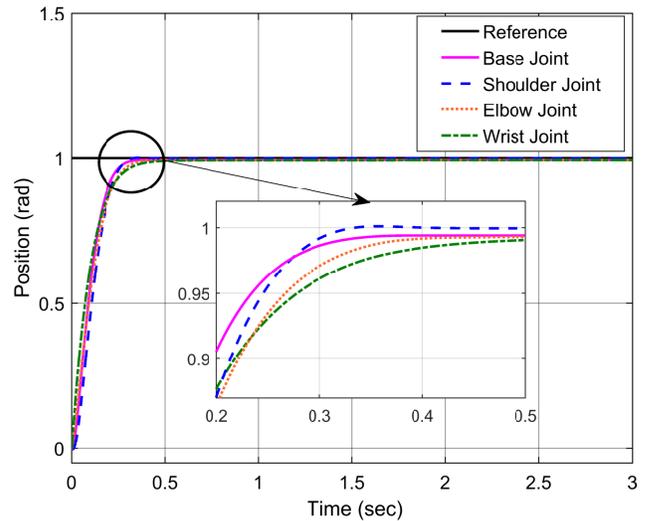


Fig. 3. Step response of AUTAREP manipulator joints

The TSMC ensures the equilibrium convergence of closed-loop in a finite time and it has fast convergence rate. The performance parameters like overshoot and rise time etc., are demonstrated in the Table. II. The suggested control approach's control input is realistic and input torque for robotic manipulator is chattering free as illustrated in Fig. 5.

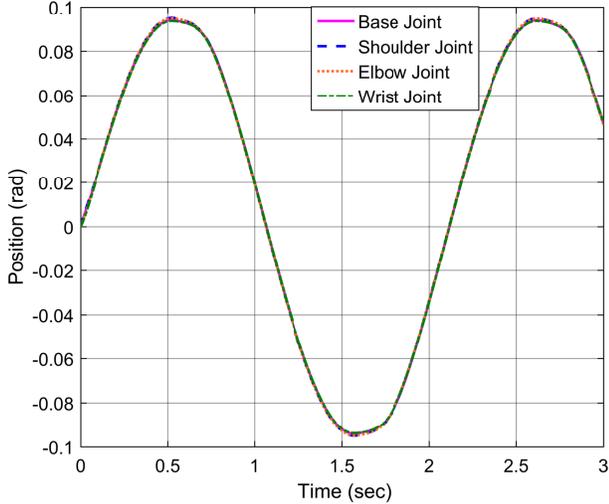


Fig. 4. Sinusoidal response of AUTAREP manipulator joints

TABLE II  
ROBOTIC MANIPULATOR JOINTS PARAMETERS

Parameters	AUTAREP Robotic Manipulator Joints			
	Base	Shoulder	Elbow	Wrist
Overshoot	0.505%	0.505%	0.461%	0.417%
Undershoot	1.969%	1.900%	1.925%	1.99%
Preshoot	0.505%	0.505%	0.505%	0.505%
Rise time	162.917ms	171.702ms	192.822ms	197.382ms

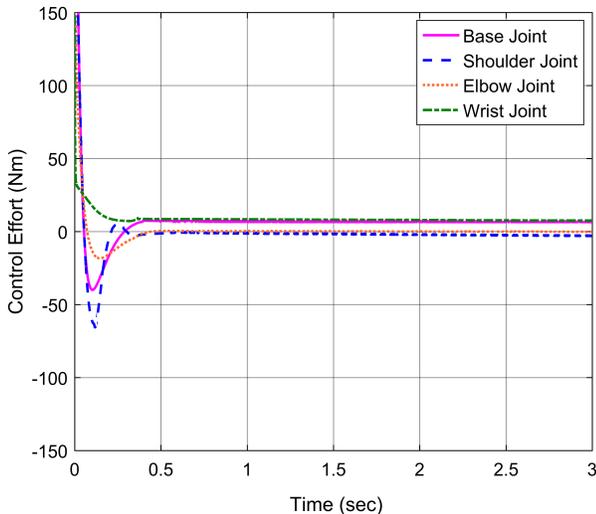


Fig. 5. Control effort of AUTAREP manipulator joints

The tracking error signal for joints of robotic manipulator is demonstrated in Fig. 6. The friction state of the robotic manipulator elbow joint and its estimated state of friction

is depicted in Fig. 7 using observer design. The predicted frictional torque  $\hat{\tau}_F$  of the LuGre dynamic friction model is described in Fig. 8. Fig. 9 describes the position tracking comparison of TSMC with methodology proposed in [23] by applying sinusoidal signal to the base joint of the robotic manipulator.

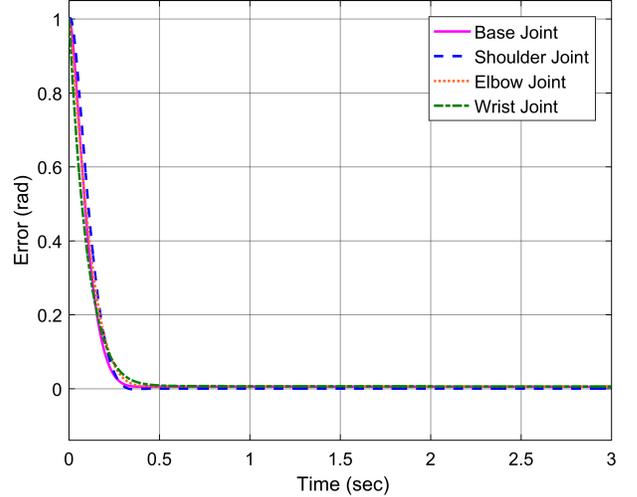


Fig. 6. Error signal of AUTAREP manipulator joints

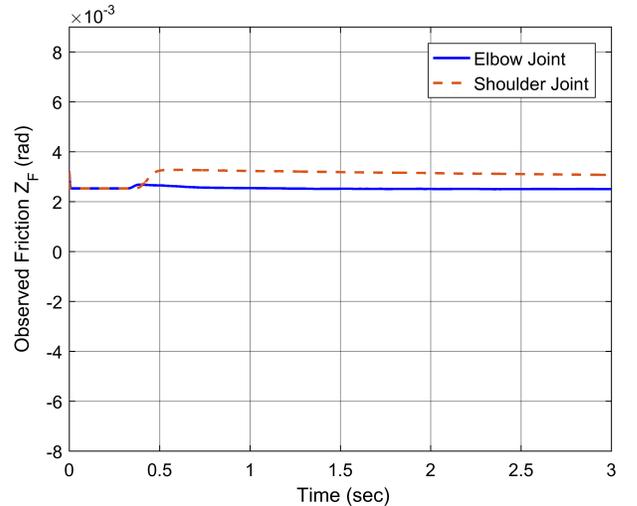


Fig. 7. Estimated friction state ( $\hat{z}_F$ ) of elbow and shoulder joint of robotic manipulator

## V. CONCLUSION

Most of the reported research on modern control of robotic manipulators does not adequately consider the friction which is inherently present in a highly nonlinear system like manipulators. The present paper, in contrast, presents modeling by considering the friction, design, simulation and analysis of a robust control law. Tracking control of a robotic manipulator is challenging due to the significant non-linear features and parametric changes in the real application. To acquire a stabilized robotic manipulator system, dynamic mathematical model of the five DoF robotic manipulator has been formed using lagrangian equation with dynamic LuGre model of friction. Furthermore, the internal state of the friction is unmeasurable,

the sliding mode friction observer is established for the estimation of an internal state of friction. The simulation results verified the performance of the non-linear control law (TSMC) and the Lyapunov stability function is used to demonstrate the stability of the AUTAREP robotic manipulator joints. In the future work, the robotic manipulator can be modelled by considering different dynamic friction models and the friction torque of the robotic manipulator can be trained and estimated through neural networks techniques.

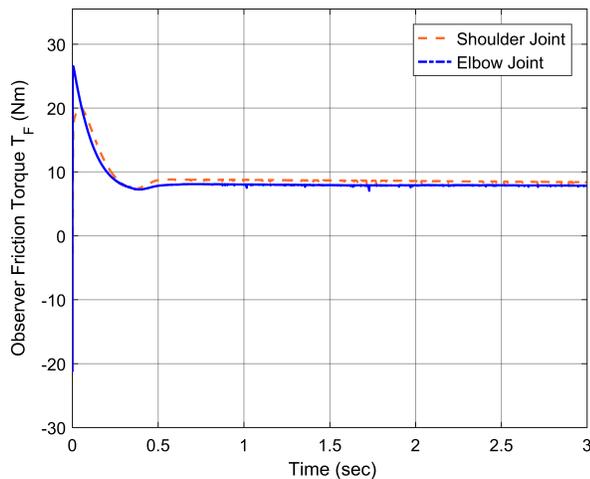


Fig. 8. Estimated friction torques of robotic manipulator joints

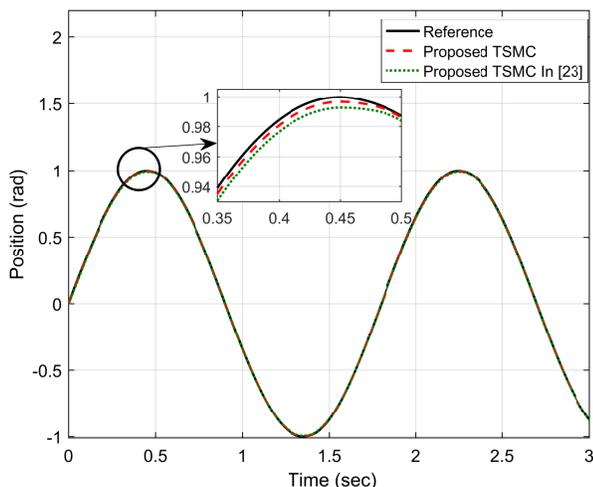


Fig. 9. Position tracking of the robotic manipulator joints [23]

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