# Super-Twisting Control of 2-DOF Robotic Manipulator using Higher-Order Sliding Mode Observer

Thiyagarajan Anushalalitha, Rahul Kumar Sharma, and Bhimavarapu Y. Anusha

*Abstract*—**This paper considers trajectory tracking control problem for a class of non-linear systems using only position measurement information. Super-Twisting Control law is designed using linear sliding surface which contains both position and velocity errors. The required velocity information is obtained in finite time by using Higher-Order Sliding Mode Observer. The observer achieves a faster convergence of the estimation errors as compared to the convergence of the tracking errors of the system with the control law. The control law achieves finite-time convergence of the sliding surface and its derivative to zero while the tracking errors asymptotically converge to the origin. The technique requires prior information of the upper bounds of disturbances and their derivatives used in the control law. Simulation studies are illustrated using the example of 2-Degrees-of-Freedom (DOF) Robotic Manipulator which show the accuracy and robustness of the technique.**

*Index Terms*—**Super-Twisting Control, Higher-Order Sliding Mode Observer, 2-DOF Robotic Manipulator.**

## I. Introduction

Trajectory tracking is considered as one of the most significant problems in the design of non-linear systems [1]. Generally, such systems are subjected to parametric uncertainties, external disturbances and unmodeled dynamics which make it challenging to achieve the desired trakectory tracking objectives [2] [3]. For the tracking problem, state feedback control law may be designed but it requires the information of all the states which may not be accessible for measurement through sensors [4]. Also, the system may require separate sensors for the measurement of all the states which increases the ovarall cost. So, it is very important to consider this problem and explore some possible control design techniques to overcome the significant challenges. This work considers the design of robust control law for tracking problem of a class of non-linear systems in the presence of parametric uncertainties and external disturbances [4]. It requires only position information to be used in the designed control law which uses the estimated velocity information provided by a non-linear observer in finite time [5] [6]. It is ensured that the estimation error of the observer converges faster than the tracking error.

Thiyagarajan Anushalalitha, Rahul Kumar Sharma and Bhimavarapu Y. Anusha are with the Department of Instrumentation and Control Engineering, National Institute of Technology, Tiruchirappalli, India (e-mail: 410323051@nitt.edu, rahul@nitt.edu, 410123053@nitt.edu).

Thiyagarajan Anushalalitha is also with the Department of Electronics and Telecommunication Engineering, B. M. S. College of Engineering, Bengaluru, India.

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There are different control laws designed for various classes of non-linear systems. Sliding Mode Control (SMC) is one of the non-linear control design approaches providing robustness to uncertainties and disturbances [2] [3]. It is simple and easy to implement for most of the systems. However, conventional first-order SMC suffers from the undesired chattering problem and only ensures asymptotic convergence of the states [5]. There are various approaches to minimize the chattering effect like using sigmoid function or saturation function approximation for the discontinuous signum function. In this context, Higher-Order Sliding Mode (HOSM) Control is a design technique which provides continuous control [6]. Super-Twisting Control (STC) is a second-order SMC approach which contains the integration of the signum function resulting in continuous control [7] [8]. It requires the relative degree of the system to be one with respect to the sliding surface [7]. This work utilizes STC for a class of non-linear systems with parametric uncertainties and external disturbances.

Sliding surface may be selected in many possible ways. It may be a linear function or a non-linear function of the states [5] [9]. Both have their own characteristic properties and their choice depends on the class of systems considered and the tracking performance requirements [10]. As the design of STC requires a relative degree of one, a natural choice of the sliding surface is a linear combination of the states [12]. With this choice, the control input is present in the derivative of the sliding surface which makes the relative degree equal to one [13] [14]. However, such a sliding surface requires feedback of all the states of the system which is difficult to obtain by measurement [11]. This is due to the inaccessibility of some states and cost considerations resulting from the deployment of individual sensors for all the states. Generally, only output information is available by measurement for most of the actual systems which results in an output feedback control problem [12]. In such cases, the remaining states information may be obtained by using observers which provide the estimated states to be used in the control law.

In this work, only position information is assumed to be available by measurement. The remaining states are obtained by using a non-linear observer. There are various observer design techniques employed in output feedback control laws. Luenberger observer is among the simple observers having linear estimation error correction terms. However, it results in asymptotic convergence of the estimation errors due to its linear structure [15] [16]. It is required to obtain the states finite time using some non-linear functions in the observer. Sliding Mode Control is a robust control design technique for non-linear systems [17] - [20]. SMC based non-linear observers may achieve finite-time convergence of the estimation erros to zero [8] [9] [12]. Among the non-linear observers, Sliding Mode Observers and Differentiators are highly effective due to their high accuracy and robustness [8] [7] [21]. Super-Twisting Control used with Super-Twisting Observer results in discontinuous control which is not suitable for implementation on actual systems due to the resulting undesired chattering effect involved with such design as discussed in [12]. In the same work, it is shown that Super-Twisting Control used with the estimated states obtained from Higher-Order Sliding Mode Observer produces continuous control which can be directly provided as input to the actual system. In this way, this technique becomes highly relevant for real-time implementation for actual systems as compared to the conventional SMC based techniques which suffer from the chattering issue. This paper utilizes the technique of HOSM Observer for finite-time estimation of the velocity information to be used in the sliding surface for the design of STC for a class of non-linear systems based on [12].

A non-singular fast terminal SMC is designed for fault-tolerant control of robotic manipulators in [22]. Its design uses the estimated information of actuator faults and unknown disturbances using the technique of time delay estimation. An adaptive SMC technique using neural networks is designed for tracking problem of robotic system in [23]. It uses neural network based adaptive observer for estimating the unknown velocity. A model reference control for robotic system in the presence to handle the effects of parametric uncertainties and actuator saturation is formulated in [24]. Super-Twisting Control for tracking problem of 2-DOF robotic manipulator using self-tuning adaptive law is considered in [25]. An adaptive generalized STC is designed to analyze the trade-off between the dynamic behaviour and chattering in [26]. It uses a modified Super-Twisting Observer to obtain the estimated states used in the control law. STC based robust altitude tracking is achieved for quadcopter system using HOSM observer for estimation and compensation of unknown disturbances in [27]. An adaptive recursive terminal SMC is designe d for the finite-time convergence of th etracking error to zero for a linear motor positioner [28]. A guidance law using adaptive STC is designed using extended state observer for estimating the unknown disturbances in [29]. A terminal SMC is designed using adaptive disturbance observer for active suspension systems [30]. A continuous fast non-singular terminal SMC technique using finite-time exact observer for uncertainty estimation is designed to achieve high accuracy and robust performance in [31].

The rest part of the paper has the following sections: Section II provides the dynamic equation of motion of the system with parametric uncertaintes and unknown disturbances. Section III explains the design of Super-Twisting Control law using conventional linear Sliding Surface. Section IV discusses the Super-Twisting Control law with Fast Terminal Non-Singular Sliding Surface using estimated velocity information obtained from Higher-Order Sliding Mode Observer. Simulation results are given in Section V and Section VI concludes.

## II. Modeling of 2-DOF Robotic Manipulator

The dynamic equation of motion of 2-DOF robotic manipulator is [1] [4],

$$M_0(q)\ddot{q} + C_0(q,\dot{q})\dot{q} + G_0(q) = \tau_i + \tau_d \tag{1}$$

$$q = \begin{bmatrix} q_1 \\ q_2 \end{bmatrix}, \quad \tau_i = \begin{bmatrix} \tau_{i1} \\ \tau_{i2} \end{bmatrix} \tag{2}$$

Here, $q \in \mathbb{R}^2$ is the joint vector angular positions of the manipulator. The two joint variables are $q_1$ and $q_2$, respectively. $\dot{q} \in \mathbb{R}^2$ is the velocity vector containing the two joints velocities. Similarly, $\ddot{q} \in \mathbb{R}^2$ is the acceleration vector for the two joints. $\tau_i = [\tau_{i1}, \tau_{i2}]^\top \in \mathbb{R}^2$ is the joint input torque vector. $\tau_d \in \mathbb{R}^2$ is the vector containing the external disturbances and uncertainties as the robot interacts with the environment. $M_0(q) \in \mathbb{R}^{2\times 2}$ is the nominal positive definite inertia matrix and symmetric. The nominal Coriolis and centrifugal forces are contained in $C_0(q,\dot{q})\dot{q} \in \mathbb{R}^2$ and the nominal gravitational vector is $G_0(q) \in \mathbb{R}^2$.

$$M_0(q) = \begin{bmatrix} M_{11} & M_{12} \\ M_{12} & M_{22} \end{bmatrix} \tag{3}$$

$$\begin{aligned} &M_{11} = J_1 + J_2 + m_1 r^2 + m_2(l_1^2 + r_2^2) + 2\cos(q_2) m_2 l_1 r_2 \\ &M_{12} = M_{21} = J_2 + m_2 r_2^2 + m_2 l_1 r_2 \cos(q_2) \\ &M_{22} = J_2 + m_2 r_2^2 \end{aligned} \tag{4}$$

$$\begin{aligned} C_0(q,\dot{q}) &= \begin{bmatrix} -m_2 l_1 r_2 \sin(q_2)\dot{q}_2 & -m_2 l_1 r_2 \sin(q_2)(\dot{q}_1 + \dot{q}_2) \\ m_2 l_1 r_2 \sin(q_2)\dot{q}_1 & 0 \end{bmatrix} \\ C_0(q,\dot{q})\dot{q} &= \begin{bmatrix} -m_2 l_1 r_2 \sin q_2 \dot{q}_2 (2\dot{q}_1 + \dot{q}_2) \\ -m_2 l_1 r_2 \sin q_2 \dot{q}_1^2 \end{bmatrix} \\ G_0(q) &= \begin{bmatrix} (m_1 r_1 + m_2 l_1) g \cos(q_1) + m_2 r_2 g \cos(q_1 + q_2) \\ m_2 r_2 g \cos(q_1 + q_2) \end{bmatrix} \end{aligned} \tag{5}$$

Considering parametric uncertainties,

$$\begin{aligned} (M_0(q) + \Delta M(q))\ddot{q} + &(C_0(q,\dot{q}) + \Delta C(q,\dot{q}))\dot{q} \\ &+ G_0(q) + \Delta G(q) = \tau_i + \tau_d \end{aligned} \tag{6}$$

where, $\Delta M(q), \Delta C(q,\dot{q}), \Delta G(q)$ are the parameter perturbations.

Rearranging,

$$M_0(q)\ddot{q} + C_0(q,\dot{q})\dot{q} + G_0(q) = \tau_i + \tau_{dl} \tag{7}$$

where, $\tau_{dl} = \tau_d - \Delta M(q)\ddot{q} - \Delta C(q,\dot{q})\dot{q} - \Delta G(q)$ is the lumped disturbance.

The model may be represented as,

$$\ddot{q} = M_0^{-1}(q)(\tau_i - C_0(q,\dot{q})\dot{q} - G_0(q) + \tau_{dl}) \tag{8}$$

## III. Super-Twisting Control Design

Consider the class of non-linear systems,

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= f(x) + g(x)\nu + d(t,x) \end{aligned} \tag{9}$$

where, $f(x) : \mathbb{R}^2 \to \mathbb{R}^2$ is the non-linear system function, $g(x) : \mathbb{R}^2 \to \mathbb{R}^2$ is the input non-linear function. $\nu \in \mathbb{R}$ is the nominal control input. $d(t,x)$ is the external bounded disturbance. $x = [x_1, x_2]^\top \in \mathbb{R}^2$ is the state vector. Consider that the full state vector is known. Using the method of Feedback Linearization, [1],

$$\nu = g^{-1}(x)(u - f(x)) \tag{10}$$

provided $g^{-1}(x)$ exists. Here, $u$ is the actual control input. Substituting the nominal control input, $\nu$ given by Eq. (10) in the system described by Eq. (9), the system dynamics reduces to,

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= u + d \end{aligned} \tag{11}$$

Selecting the sliding surface as,

$$s = c_1 x_1 + x_2 \tag{12}$$

where, $c_1$ is a positive constant. From Eq. (12),

$$x_2 = s - c_1 x_1 \tag{13}$$

Using Eq. (13) in Eq. (11), the dynamics of $x_1$ is expressed as,

$$\dot{x}_1 = s - c_1 x_1 \tag{14}$$

Differentiating Eq. (12), the sliding surface dynamics becomes,

$$\begin{aligned} \dot{s} &= c_1 \dot{x}_1 + \dot{x}_2 \\ &= c_1 x_2 + u + d \end{aligned} \tag{15}$$

Using Eq. (14) and Eq. (15), the reduced-order system equations are given by,

$$\begin{aligned} \dot{x}_1 &= s - c_1 x_1 \\ \dot{s} &= c_1 x_2 + u + d \end{aligned} \tag{16}$$

Using Super-Twisting Control law,

$$\begin{aligned} u &= -c_1 x_2 - k_1 |s|^{\frac{1}{2}} \operatorname{sign}(s) + v \\ \dot{v} &= -k_2 \operatorname{sign}(s) d\tau \end{aligned} \tag{17}$$

Substituting the control law (17) in the reduced-order dynamics (16),

$$\begin{aligned} \dot{x}_1 &= s - c_1 x_1 \\ \dot{s} &= -k_1 |s|^{\frac{1}{2}} \operatorname{sign}(s) + v \\ \dot{v} &= -k_2 \operatorname{sign}(s) d\tau + \dot{d} \end{aligned} \tag{18}$$

After finite time, the sliding surface converges to $s = 0$ resulting in,

$$\begin{aligned} \dot{x}_1 &= -c_1 x_1 \\ x_2 &= -c_1 x_1 \end{aligned} \tag{19}$$

So, both $x_1$ and $x_2$ converge to zero asymptotically. The equations of motion of 2-DOF robotic manipulator dynamics is,

$$\begin{aligned} \dot{q}_1 &= q_2 \\ \dot{q}_2 &= M_0^{-1}(q)(\tau_i - C_0(q,\dot{q})\dot{q} - G_0(q) + \tau_{dl}) \end{aligned} \tag{20}$$

Defining the trajectory tracking errors as,

$$e_{q_1} = q_1 - q_d \tag{21a}$$
$$e_{q_2} = q_2 - \dot{q}_d \tag{21b}$$

where, $q_d$ is the desired position and $\dot{q}_d$ is the desired velocity. The error dynamics becomes,

$$\begin{aligned} \dot{e}_{q_1} &= e_{q_2} \\ \dot{e}_{q_2} &= M_0^{-1}(q)(\tau_i - C_0(q,\dot{q})\dot{q} - G_0(q) + \tau_{dl}) - \ddot{q}_d \end{aligned} \tag{22}$$

Designing linear sliding surface [12],

$$\hat{s} = c_1 e_{q_1} + \hat{e}_{q_2} \tag{23}$$

Using Eq. (21b) in Eq. (23),

$$\hat{s} = c_1 e_{q_1} + \hat{q}_2 - \dot{q}_d \tag{24}$$

where, $\hat{q}_2$ is the estimated state obtained from the observer. Using Eq. (21b) in Eq. (22), the error dynamics is,

$$\dot{e}_{q_1} = q_2 - \dot{q}_d \tag{25}$$

The velocity estimation error of the observer is given by,

$$e_2 = q_2 - \hat{q}_2 \tag{26}$$

Substituting the expression of $q_2$ from Eq. (26) in Eq. (25), the error dynamics becomes,

$$\dot{e}_{q_1} = \hat{q}_2 + e_2 - \dot{q}_d \tag{27}$$

Using Eq. (24) in Eq. (27),

$$\dot{e}_{q_1} = \hat{s} - c_1 e_{q_1} + e_2 \tag{28}$$

Differentiating Eq. (24),

$$\begin{aligned} \dot{\hat{s}} &= c_1 \dot{e}_{q_1} + \dot{\hat{q}}_2 - \ddot{q}_d \\ &= c_1 e_{q_2} + \dot{\hat{q}}_2 - \ddot{q}_d \\ &= c_1 q_2 - c_1 \dot{q}_d + \dot{\hat{q}}_2 - \ddot{q}_d \end{aligned} \tag{29}$$

Using Eq. (26) in Eq. (29), the sliding surface dynamics becomes,

$$\dot{\hat{s}} = c_1 \hat{q}_2 + c_1 e_2 + \dot{\hat{q}}_2 - c_1 \dot{q}_d - \ddot{q}_d \tag{30}$$

The reduced-order dynamics of the system may be expressed as,

$$\begin{aligned} \dot{e}_{q_1} &= \hat{s} - c_1 e_{q_1} + e_2 \\ \dot{\hat{s}} &= c_1 \hat{q}_2 + c_1 e_2 + \dot{\hat{q}}_2 - c_1 \dot{q}_d - \ddot{q}_d \end{aligned} \tag{31}$$

The reduced-order system dynamics given by Eq. (31) is utilized in the next section for the design of Super-Twisting Control using the estimated velocity information provided by HOSM Observer.

## IV. Super-Twisting Control using Higher-Order Sliding Mode Observer

A Higher-Order Sliding Mode (HOSM) observer is designed to estimate the unknown velocity $q_2 = \dot{q}$. The estimated velocity information, $\hat{q}_2$ is used by the designed control law for trajectory tracking. With Super-Twisting Observer, the resulting control law becomes discontinuous as discussed in [12]. So, HOSM Observer is designed to obtain continuous control input based on [12]. Using HOSM observer, the information of the position, $\hat{x}_2$ is obtained in finite time and is provided to the STC based control law. Using Eq. (20), the HOSM based observer for the nominal model is designed as [6],

$$\begin{aligned}\dot{\hat{q}}_1 &= \hat{q}_2 + \alpha_1|q_1-\hat{q}_1|^{\frac{2}{3}}\operatorname{sign}(q_1-\hat{q}_1)\\ \dot{\hat{q}}_2 &= \hat{q}_3 + \alpha_2|q_1-\hat{q}_1|^{\frac{1}{3}}\operatorname{sign}(q_1-\hat{q}_1)\\ &\qquad + M_0^{-1}(q)(\tau_i - C_0(q,\dot{q})\dot{q} - G_0(q))\\ \dot{\hat{q}}_3 &= \alpha_3\operatorname{sign}(q_1-\hat{q}_1)\end{aligned} \tag{32}$$

Defining the error variables as,

$$\begin{aligned}e_1 &:= q_1 - \hat{q}_1\\ e_2 &:= q_2 - \hat{q}_2\end{aligned} \tag{33}$$

The error dynamics takes the form,

$$\begin{aligned}\dot{e}_1 &= -\alpha_1|e_1|^{\frac{2}{3}}\operatorname{sign}(e_1) + e_2\\ \dot{e}_2 &= -\alpha_2|e_1|^{\frac{1}{3}}\operatorname{sign}(e_1) - \hat{q}_3 + d\\ \dot{\hat{q}}_3 &= \alpha_3\operatorname{sign}(e_1)\end{aligned} \tag{34}$$

Defining new variable,

$$e_3 := -\hat{q}_3 + d$$

The error dynamics is,

$$\begin{aligned}\dot{e}_1 &= -\alpha_1|e_1|^{\frac{2}{3}}\operatorname{sign}(e_1) + e_2\\ \dot{e}_2 &= -\alpha_2|e_1|^{\frac{1}{3}}\operatorname{sign}(e_1) + e_3\\ \dot{e}_3 &= -\alpha_3\operatorname{sign}(e_1) + \dot{d}\end{aligned} \tag{35}$$

The error variables, $e_1$, $e_2$, $e_3$ converge to zero in finite time [6]. Rewriting the reduced-order dynamics of 2-DOF robotic manipulator,

$$\begin{aligned}\dot{e}_{q_1} &= \hat{s} - c_1 e_{q_1} + e_2\\ \dot{\hat{s}} &= c_1\hat{q}_2 + c_1 e_2 + \dot{\hat{q}}_2 - c_1\dot{q}_d - \ddot{q}_d\end{aligned} \tag{36}$$

Using the observer dynamics, $\dot{\hat{q}}_2$ in the reduced-order system dynamics (36),

$$\begin{aligned}\dot{e}_{q_1} &= \hat{s} - c_1 e_{q_1} + e_2\\ \dot{\hat{s}} &= c_1\hat{q}_2 + c_1 e_2 + \alpha_2|e_1|^{\frac{1}{3}}\operatorname{sign}(e_1) + \hat{q}_3\\ &\quad + M_0^{-1}(q)(\tau_i - C_0(q,\dot{q})\dot{q} - G_0(q)) - c_1\dot{q}_d - \ddot{q}_d\end{aligned} \tag{37}$$

From (34),

$$\hat{q}_3 = \int_0^t \alpha_3\operatorname{sign}(e_1)d\tau \tag{38}$$

Substituting the expression of $\hat{q}_3$ from Eq. (38) in (37),

$$\begin{aligned}\dot{e}_{q_1} &= \hat{s} - c_1 e_{q_1} + e_2\\ \dot{\hat{s}} &= c_1\hat{q}_2 + c_1 e_2 + \alpha_2|e_1|^{\frac{1}{3}}\operatorname{sign}(e_1) + \int_0^t \alpha_3\operatorname{sign}(e_1)d\tau\\ &\quad + M_0^{-1}(q)(\tau_i - C_0(q,\dot{q})\dot{q} - G_0(q)) - c_1\dot{q}_d - \ddot{q}_d\end{aligned} \tag{39}$$

Designing the control input as [12],

$$\begin{aligned}\tau_i = C_0(q,\dot{q})\dot{q} + G_0(q) + M_0(q)\big(&-c_1\hat{q}_2 - \alpha_2|e_1|^{\frac{1}{3}}\operatorname{sign}(e_1)\\ &- \int_0^t \alpha_3\operatorname{sign}(e_1)d\tau - k_1|\hat{s}|^{\frac{1}{2}}\operatorname{sign}(\hat{s})\\ &- \int_0^t k_2\operatorname{sign}(\hat{s})d\tau + c_1\dot{q}_d + \ddot{q}_d\big)\end{aligned} \tag{40}$$

Substituting the control input (40) in the reduced-order dynamics (39),

$$\begin{aligned}\dot{e}_{q_1} &= \hat{s} - c_1 e_{q_1} + e_2\\ \dot{\hat{s}} &= c_1 e_2 - k_1|\hat{s}|^{\frac{1}{2}}\operatorname{sign}(\hat{s}) - \int_0^t k_2\operatorname{sign}(\hat{s})d\tau\end{aligned} \tag{41}$$

It may be expressed as,

$$\begin{aligned}\dot{e}_{q_1} &= \hat{s} - c_1 e_{q_1} + e_2\\ \dot{\hat{s}} &= c_1 e_2 - k_1|\hat{s}|^{\frac{1}{2}}\operatorname{sign}(\hat{s}) + v\\ \dot{v} &= -k_2\operatorname{sign}(\hat{s})d\tau\end{aligned} \tag{42}$$

which has the structure of the STC and guarantees the convergence of the sliding surface and its derivative, $\hat{s}, \dot{\hat{s}}$ to zero in finite time before which the observer estimation errors, $e_1, e_2$ reduce to zero in finite time. As the observer dynamics is designed faster, $e_1 = e_2 = 0$ occurs before $\hat{s} = \dot{\hat{s}} = 0$ results. After the finite time of convergence, the tracking error dynamics reduces to,

$$\begin{aligned}\dot{e}_{q_1} &= -c_1 e_{q_1}\\ e_{q_2} &= -c_1 e_{q_1}\end{aligned} \tag{43}$$

So, both the tracking errors, $e_{q_1}, e_{q_2}$ asymptotically converge to the origin which results in the asymptotic tracking of the desired joint positions by the actual joint positions.

## V. Simulation Results

The designed STC based control law with the HOSM Observer is simulated by taking the example of 2-DOF robotic manipulator. The system parameters are $m_1 = m_2 = 1$ kg, $r_1 = r_2 = 0.5$ m, $J_1 = J_2 = 5$ kgm$^2$, $g = 9.8$ m/s$^2$. The gain parameters of the STC based control law are $k_1 = [25, 20]^\top$, $k_2 = [25, 20]^\top$ and $c_1 = 0.1$. For the HOSM observer, $\alpha_1 = 10\times 12^{1/3}$, $\alpha_2 = 5\times 12^{1/2}$ and $\alpha_3 = 1.5\times 12$. The actual joint positions and velocities accurately track the desired joint positions and velocities as clear from Fig. 1. to Fig. 4. Fig. 5 shows the sliding surface converging to zero in finite time. The joint position and velocity tracking errors converge to zero as shown in Figs. 6. and 7. The control input is shown in Fig. 8. The joint position and velocity estimation errors converge to zero with high accuracy as shown in Figs. 9. and 10.

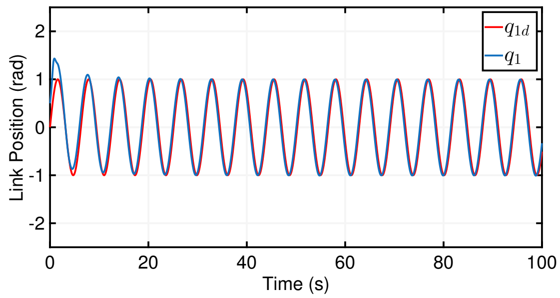


Fig. 1. Link Position

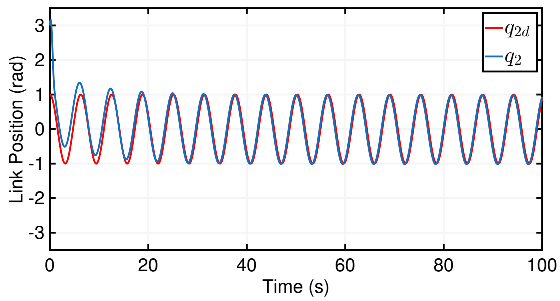


Fig. 2. Link Position

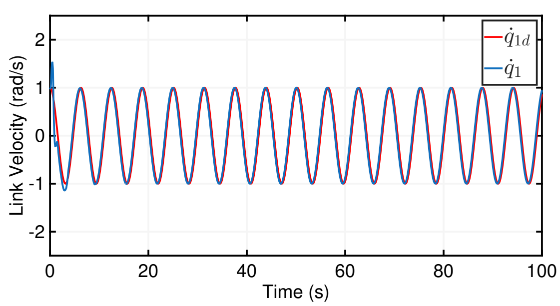


Fig. 3. Link Velocity

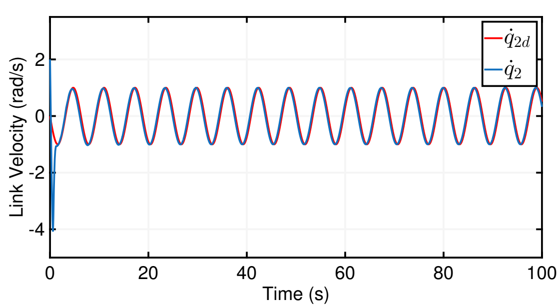


Fig. 4. Link Velocity

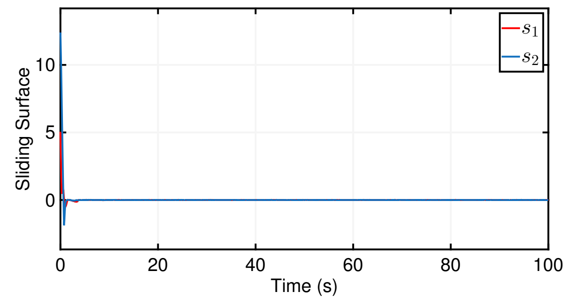


Fig. 5. Sliding Surface

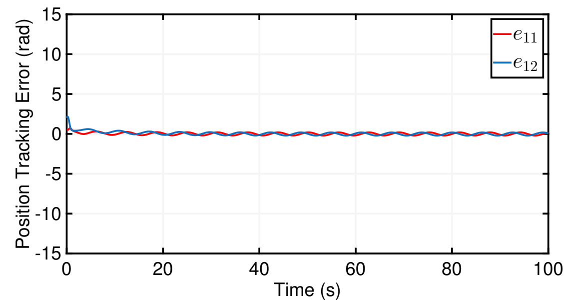


Fig. 6. Link Position Tracking Errors

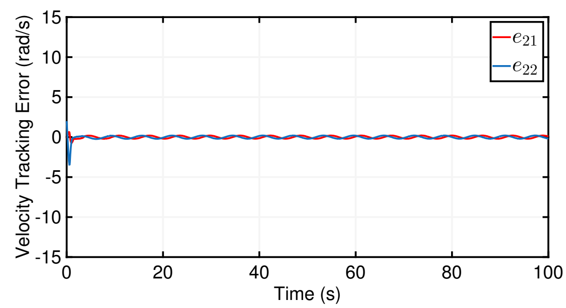


Fig. 7. Link Velocity Tracking Errors

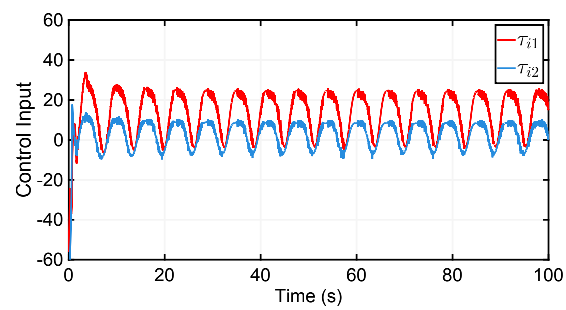


Fig. 8. Control Input

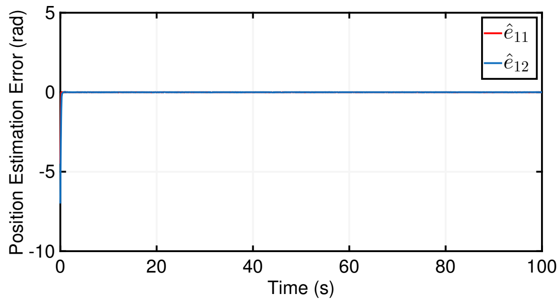


Fig. 9. Link Position Estimation Errors

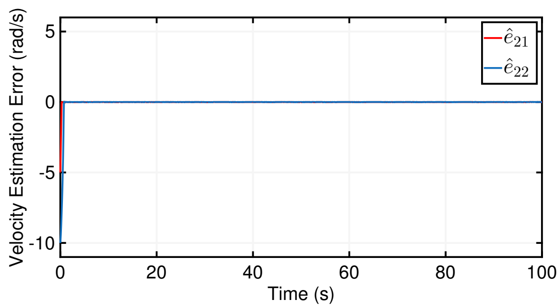


Fig. 10. Link Velocity Estimation Errors

## VI. Conclusion

In this work, Super-Twisting Control law is designed for 2-DOF robotic manipulator. It assumes the availability of link positions information only for the design of linear sliding surface. The link velocities information required for the sliding surface is obtained from Highr-Order Sliding Mode Observer in finite time by using the measured link positions information. The asymptotic tracking is highly accurate as it is clear from the simulation results.

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