Design of Super Twisting Integral Sliding Mode Control for Industrial Robot Manipulator

Original Scientific Paper

Shankar J Gambhire
Koneru Lakshmaiah Education Foundation,
Vaddeswaram, Guntur, AP 522302, India.
Faculty with ECE, MIT School of Engineering & Sciences, MIT ADT University,
Pune(MH), India.
sjgambhire@gmail.com

D Ravi Kishore
Godavari institute of engineering and technology,
EEE, Rajahmundry, AP 533296. India.
dravikishore@gmail.com

Malligunta Kiran Kumar
Koneru Lakshmaiah Education Foundation, EEE,
Vaddeswaram, Guntur, AP 522302, India.
mkkumar@kluniversity.in

Sushant N Pawar
Ramrao Adik Institute of Technoloy, Navi Mumbai,
Maharashtra, India.
sushantnpawar@gmail.com

Abstract – *In the present work, integral sliding mode based continuous control algorithm is extended to multi input multi output system. The typical integral sliding mode control (ISMC) contains nominal control with discontinuous feedback control due to which overall control becomes discontinuous in nature. The proposed controller is a fusion of two continuous terms and one of which is able to handle, estimate and reject the disturbance successfully. A proposed robust ISMC technique is applied for industrial robot manipulators which utilizes interactive manipulation activity. Here, robust position tracking control obtained via ISMC principle for two link IRM scheme influenced by parametric uncertainties and external disturbances. The proposed ISMC design replaces the discontinuous part by continuous control, which super twisting control is able to handle the disturbance rejection completely. The effectiveness of the proposed control technique is tested under uncertain conditions and comparison study with other controllers has been done. The simulation result shows that the tracking error is effectively minimized by the proposed technique in presence of uncertain conditions.*

Keywords: *Sliding mode control (SMC), Non-singularity, Super twisting control (STM), Industrial robotic manipulator (IRM)*

1. INTRODUCTION

In recent years, industrial robotic manipulator (IRM) applications used to carry out advanced tasks in industrial automation like robotic surgery, welding, painting, polishing, laser cutting work etc. have added great importance. Accurate besides precise robot manipulators motion control is required to perform such classy tasks. Hence, design of motion control schemes for IRM systems has emerged as an active research area. Because of its complex dynamics comprising time changing dynamical-structure in addition strong dynamic coupling, inherent non-linearities, parameter uncertainties a dedicated motion control structure designing for IRM scheme is tough task [1]. Several advanced control schemes studied comprehensively by a number of researchers over a period of time. These are mostly comprises continuous sliding mode control, feedback linearization [2], decentralized control, model predictive control, adaptive control, fuzzy and neural network control. Intelligent control method like fuzzy plus neural network is good option for addressing nonlinear plus uncertain IRM dynamics. However, it embroil many of design parameters and complex rules that would lead to complex design procedure and sometimes impossible for implementation point of view.

Among all said methods, sliding mode control (SMC) is popular, robust control and widely executed for many input many output (MIMO) linear plus nonlinear systems. Robustness property in presence of external disturbances and parameter uncertainties is the primary feature of SMC. A variety of second order sliding mode control algorithms are discussed in [3-5, 15-19], one of the most potential algorithms of all of them is super twisting. This approach is developed to avoid chattering in systems having relative degree of one. The twisting around the origin characterizes trajectory on the two sliding planes. Super twisting control is a continuous control that ensures all key features of first order SMC for system with smooth matched bounded uncertainties or disturbances. Super twisting algorithm with initial stability findings are majorant curve based concept. Thereafter, the Lyapunov scheme was introduced for proofs by [6]. From the several SMC approaches, integral SMC [7-14,17], may be readily integrated other new latest control strategies like proportional integral derivative (PID) control, linear feedback control, model predictive control, optimum control and so on, while retaining their features. As a result, ISMC may be described as bridge in between other control methods plus sliding mode which has greater robustness than other existing control systems. Though ISMC only has one issue, it has a discontinuous portion of control. This issue will be resolved if control is held continuously.

In this work, ISMC has 2 parts viz. first nominal control $u_{nominal}$ next continuous control $u_{continuous}$ or discontinuous control (given by Utkin). To obtain desired trajectory for a system nominal-control is designed (without disturbance). $u_{nominal}$ and $u_{continuous}$ design are totally sovereign. It may be noted that once trajectories on the sliding surface, continuous control acts like a disturbance observer with its value equal to negative of the disturbance. Thus $u = u_{nominal} + u_{continuous}$ is applied to structure with disturbance, $u_{continuous}$ discards disturbance plus desired trajectory is obtained through application of $u_{nominal}$.

This work considers a continuous SMC algorithm based on ISMC. Continuous control is replaced with ISMC discontinuous part. The property of disturbance rejection of super twisting control is utilized here by replacing discontinuous control with super twisting control. Discontinuous term will result in chattering, in addition it is undesirable from practical execution point of view. Presented algorithm has been implemented for two link IRM (Fig.1.).

Here robust position tracking control pattern is planned in addition realistic for 2 link IRM method using condition which is uncertain. Significant contribution is given as below

- Convergence speed is accelerated as well as chattering is reduced by replacing with a continuous control with discontinuous part of ISMC.
- The property of disturbance rejection of super twisting control is utilized here by replacing discontinuous control with super twisting control.
- There are two phases in sliding mode. I. reaching phase, where system states are driven to the switching manifolds from any initial state in finite time and II. Sliding phase, where system is induced into sliding-motion on switching manifold, i.e. it becomes attractor.
- Singularity free control is possible with the proposed sliding manifold.
- An effective disturbance estimator as a super twisting control is presented to counteract unexpected unmodeled dynamics impacts, unidentified parameters owing to uncertainties in the parameters plus measurement noises of the IRM system.
- In this study, it is not necessary to have former knowledge of upper bounds of lumped disturbance.
- This control provides greater robustness against lumped uncertainty while maintaining excellent tracking precision.

This technique is tested to verify using a generic 2 link IRM model meant for monitoring predefined complex trajectory in indefinite work environment.

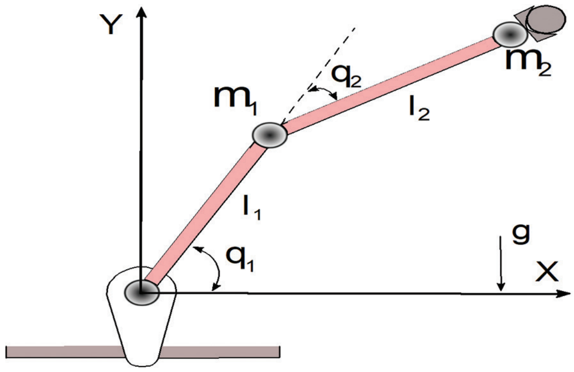

Fig.1. Two link industrial robotic manipulator

2. PROBLEM DEFINITION

For n-link IRM system equation for dynamic motion may be given as

$$G(q) + C(q,\dot{q})\dot{q} + M(q)\ddot{q} = \tau_{ex} + \tau \quad (1)$$

Given: $\dot{q}, q, \ddot{q} \in \Re^{n\times 1}$ vectors of velocity, position plus acceleration of joints of IRM separately. Applied joint torques vector: $\tau \in \Re^{n\times 1}$, $\tau_{ex} \in \Re^{n\times 1}$ unknown external disturbances vector, $M(q) \in \Re^{n\times 1}$ IRM inertia matrix, $C(q,\dot{q})\dot{q} \in \Re^{n\times n}$ centripetal and Coriolis forces matrix, gravitational forces vector: $G(q) \in \Re^{n\times 1}$.

Uncertainties of IRM model matrices, i.e.

$$\Delta M(q) = M(q) - M_0(q)$$
$$\Delta C(q,\dot{q}) = C(q,\dot{q}) - C_0(q,\dot{q})$$
$$\Delta G(q) = G(q) - G_0(q) \quad (2)$$

Given: $M_0(q)$, $C_0(q,\dot{q})$ and $G_0(q)$ are the nominal terms; $\Delta M(q)$, $\Delta C(q,\dot{q})$ and $\Delta G(q)$ model matrices perturbations.

So IRM dynamic model takes form as

$$M_0(q)\ddot{q} + C_0(q,\dot{q})\dot{q} + G_0(q) = \tau + \tau_d \quad (3)$$

A term (Lumped-uncertainty vector) given $\tau_d = \tau_{ex} + H(q,\dot{q},\ddot{q})$ besides $H(q,\dot{q},\ddot{q}) = -\Delta M(q) - \Delta C(q,\dot{q}) - \Delta G(q)$ which is circumscribed thru subsequent function

$$\|H(q,\dot{q},\ddot{q})\| \le p_0 + p_1 \|q\| + p_2 \|\dot{q}\|^2 \quad (4)$$

where positive constants p_2, p_1, p_0.

Eq. 1 known as dynamic equation possesses properties useful in controller design plus to analyses stability

(P: 1) $M(q)$ is positive beside symmetric plus bounded by $m_1 \leq \|M(q)\| \leq m_2$ where constants $m_1, m_2 \geq 0$

(P: 2) Skew symmetric matrix is $\dot{M}(q)-2C(q, \dot{q})$

(P: 3) Bounded matrix $C(q, \dot{q})$ gives $\|C(q, \dot{q})\| \leq \lambda_0 \|\dot{q}\|$ for $\lambda_0>0$

3. CONTROLLER DESIGN

3.1. SUPER TWISTING MULTIVARIABLE (STM) ALGORITHM

Super twisting algorithm is designed to regulate the schemes in presence of lumped uncertainty and as well it reduces the chattering phenomenon. It gives continuous control signal that assures all of fundamental features of first-order SMC, given first derivative of the matched disturbance is finite. Improvement on well-known super twisting technique is STM method. It may be utilized for MIMO system control without system states decoupling.

Let us take MIMO scheme as,

$$\dot{x} = B(d+u) \tag{5}$$

where B, x is invertible as well as known, u as a control and d is the bounded but unknown uncertainty.

The term d involves, $d=d_1\|x\|+d_2$ where $d_1 \leq \Delta_1$ besides $d_2 \leq \Delta_2$

Super twisting multivariable control u is given below

$$u = B^{-1}\left[-k_1 \frac{x}{\|x\|^{\frac{1}{2}}} + v - k_2\, x\right]$$

$$\dot{v} = -k_3 \frac{x}{\|x\|} - k_4\, x \tag{6}$$

where $k_i>0, i=1,2,3,4$ are the constant parameters chosen in way that the aforementioned controller would be able to stabilize the MIMO structure in finite-time. Putting u as of (6) to (5), we can write

$$\dot{x} = -k_1 \frac{x}{\|x\|^{\frac{1}{2}}} + v - k_2\, x + d_1\|x\| + d_2]$$

$$\dot{v} = -k_3 \frac{x}{\|x\|} - k_4\, x \tag{7}$$

By specifying $\eta = v + d_2$, we get (7)

$$\dot{x} = -k_1 \frac{x}{\|x\|^{\frac{1}{2}}} - k_2\, x + d_1\|x\| + \eta]$$

$$\dot{\eta} = -k_3 \frac{x}{\|x\|} - k_4\, x + \dot{d}_2 \tag{8}$$

State variables finite-time convergence x, $\dot{x}$ as well η are to be achieved and keep zero for subsequent time by k_1, k_2, k_3, k_4. As of eq (8) when states touches origin we get, $\eta=v+d_2=0$

$$d_2=\eta \tag{9}$$

Because of the aforementioned characteristic, the multivariable super twisting algorithm is used as both a controller and a disturbance estimator. In the next part, we will present continuous ISMC for MIMO systems based on the previously described disturbance observation characteristic.

3.2. ROBUST INTEGRAL SMC (ISMC) FOR ROBOT MANIPULATOR SCHEME

The ISMC consists of two parts: u nominal control ($u_{nominal}$), besides (II) continuous or discontinuous control ($u_{continuous}$). The nominal control is aimed at keeping the system on the planned trajectory in the absence of disturbance. The concepts of $u_{nomoinal}$ plus $u_{continuous}$ are entirely separate. It should be highlighted that once sliding-surface with trajectories (= 0 as per property of multi variable super twisting disturbance observation) are established, continuous control works as disturbance estimator, with its value equal to negative of disturbance. As a result, when $u= u_{nomoinal} + u_{continuous}$ is applied to a system with a disturbance, $u_{continuous}$ castoffs disturbance besides $u_{nomoinal}$ produces required trajectory.

This technique is mathematically described as follows,

Ponder the structure

$$\dot{x}=Ax+B(d+u) \tag{10}$$

Given A, B, u, x, d are system-matrix, input matrix, control,state plus disturbance separately. Depending on the system's nature, the input matrix in addition system matrix might be nonlinear or linear .The control input for the system (10) is to be considered as

$u = u_{nomoinal} + u_{continuous}$, where $u_{nomoinal}$ is acting as a servo control and $u_{continuous}$ is acting as a regulatory control under the effect of lumped disturbances. Here, $u_{nomoinal}$ can be chosen as PID, any multivariable linear control, state-feedback, linear quadratic regulator (LQR) optimal control, adaptive-control, time variant control, and so on. The systems (10) required sliding surface defined as

$$s = [x(t) - x(t_0) - \int_0^t (Ax + B\, u_{nominlal})d\tau]G \tag{11}$$

Where, projection-matrix plus initial-condition of scheme G, $x(t_0)$ the sliding surface is designed so that system trajectories begin from it, plus if a disturbance comes into play, $u_{continuous}$ becomes functional and disturbances are corrected. It would be explicated mathematically as

$$\dot{s} = G[Ax + Bu + d - Ax - Bu_{nominal}]$$

$$= G[Ax + B(u_{nominal} + u_{continuous} + d) - Bu_{nominal}]$$

$$= GB[u_{continuous} + d] \tag{12}$$

Assume devoid of loss of generality $GB=\Phi^{m\times m}$, given n dimensional unit square matrix I (or else $u_{continuous}$ is $((GB)^{(-1)})$ scaled control, thus

$$\dot{s}=[u_{continuous}+d] \tag{13}$$

Assuming $u_{continuous}$ is formed using STM control

$$u_{continuous} = -k_1 \frac{s}{\|s\|^{\frac{1}{2}}} + v - k_2 s$$

$$\dot{v} = -k_3 \frac{s}{\|s\|} - k_4 s \quad (14)$$

where $k_i>0$, $i=1, 2, 3, 4$ are chosen appropriately by considering the stabilization of system. After substituting u_continuous from (14) to (13), we can get

$$\dot{s} = -k_1 \frac{s}{\|s\|^{\frac{1}{2}}} + v - k_2 s + d$$

$$\dot{v} = -k_3 \frac{s}{\|s\|} - k_4 s \quad (15)$$

By specifying $\eta=v+d$ we can write (15)

$$\dot{s} = -k_1 \frac{s}{\|s\|^{\frac{1}{2}}} - k_2 s + \eta$$

$$\dot{v} = -k_3 \frac{s}{\|s\|} - k_4 s + d \quad (16)$$

Remark 1. s and v initial conditions essential for the solution of system eq. (15). We have previously designed s due to its zero initial conditions, since v is a fictional variable, it is always possible to pick $v = 0$ as an initial condition. Therefore, in order to initiate the 2nd order SMC from the beginning moment, starting values of s and $\ddot{s}$ need to be zero. The starting value of converted variable η contains initial value of disturbance d shown in (16). All the time it is difficult to estimate starting condition of the disturbance d, with the exception of some special circumstances where there is no disturbance at all, such as fault diagnosis difficulties when no fault there at all, which indicate $d = 0$. Hence, $\eta = 0$ for $t\geq 0$ from now both s plus $\dot{s}$ are zero from the beginning moment. Therefore, when there is nonzero starting disturbance then sliding mode will begin subsequently some finite time $t\geq\tau$ as $z\neq 0$ this may be made very trivial if possible with selecting apposite values of k_i= 1, 2, 3, 4. Hence, when s and fictitious variable η are achieved to zero, so $\dot{s}$ turn into zero and it relics zero all the time even in presence of disturbance.

As per eq. (16), we can make conclusive remark as $s = \eta = 0$ which implies $\dot{s}$ =0 in finite time for appropriate values of gains k_i = 1, 2, 3, 4. In the final step, from eq (16) $v = -d$. And from eq (14) $u_{continuous}=v=-d$. This indicates that while the scheme is in sliding mode, the value of the 'disturbance' $d=-v$ and is cancelled out. Therefore, when it is on a sliding surface, the system guided by nominal control then designed to be stable.

4. PERFORMAQNCE ANALYSIS PLUS NUMERICALL SIMULATIONS

With general two link IRM model performane of existing procedure has been appraised here [14] it gives

$$M(q) = \begin{bmatrix} a_{11}(q_2) & a_{12}(q_2) \\ a_{12}(q_2) & a_{22} \end{bmatrix},$$

$$C(q,\dot{q}) = \begin{bmatrix} -b_{12}(q_2)\dot{q}_1^2 - 2b_{12}(q_2)\dot{q}_1\dot{q}_2 \\ b_{12}(q_2)\dot{q}_2^2 \end{bmatrix},$$

$$G(q) = \begin{bmatrix} c_1(q_1,q_2)g \\ c_2(q_1,q_2)g \end{bmatrix}, \tau = \begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix}, \tau_{ex} = \begin{bmatrix} \tau_{ex_1} \\ \tau_{ex_2} \end{bmatrix} \quad (17)$$

Where:

$a_{11}(q_2) = (m_1 + m_2)l_1^2 + m_2 l_2^2 + 2\, m_2 l_1 l_2 \cos(q_2) + J_1$,

$a_{12}(q_2) = m_2 l_2^2 + m_2 l_1 l_2 \cos(q_2)$,

$a_{22} = m_2 l_2^2 + J_2$,

$b_{12}(q_2) = m_2 r_1 r_2 \sin(q_2)$,

$c_1(q_1,q_2) = (m_1 + m_2)l_1 \cos(q_2) + m_2 l_2 \cos(q_1 + q_2)$,

$c_1(q_1,q_2) = m_2 l_2 \cos(q_1 + q_2)$

The IRM model parameters are shown in Table 1.

The high frequency effect of external disturbances plus measurement noises are considered in simulation for presenting the effectiveness of control in uncertain environment. The same external disturbances as in eq (18) used in simulation.

$$\tau_{ex_1} = 2\sin(t) + \frac{1}{2}(\sin(200\pi t))$$

$$\tau_{ex_2} = \cos(2t) + \frac{1}{2}(\sin(200\pi t)) \quad (18)$$

Table 1. Model parameters of IRM

Symbol	Definition	Value
l_1	Length of link 1	1 m
l_2	Length of link 2	0.85 m
J_1	Moment of Inertia of Motor 1	5 kg m
J_2	Moment of Inertia of Motor 2	5 kg m
m_1	Mass of Link 1	0.5 kg
m_2	Mass of Link 2	1.5 kg
$\hat{m}_1$	Estimated Mass of Link 1	0.4 kg
$\hat{m}_2$	Estimated Mass of Link 2	1.2 kg
G	Gravitational Constant	9.8 m/s^2

Also the control behavior is tested in presence of parametric uncertainty by introducing 20 % parameter uncertainties in model matrices of the IRM.

IRM initial values elect as q_1 (0)=1.0, q_2 (0)=1.5, $\dot{q}_1$ (0)=0 and $\dot{q}_2$ (0)=0

IRM system chosen trajectory to be trailed is picked as

$$q_d = [q_{d_1}, q_{d_2}] \text{ with}$$

$$q_{d_1} = 1.25 - \left(\frac{7}{5}\right)e^{-t} + \left(\frac{7}{20}\right)e^{-4t}$$

$$q_{d_2} = 1.25 + e^{-t} - \left(\frac{1}{4}\right)e^{-4t} \quad (19)$$

Comparison of proposed method with benchmark controllers like conventional SMC, computed-torque controller (CTC) in addition to this a non singular terminal SMC are considered. The corresponding control laws are mentioned as below,

$$\tau = M_0(q)\,(K_P\, e(t) + K_V \dot{e}(t) + \ddot{q}_d) + C_0(q,\dot{q}) + G_0(q)$$
:CTC

$$\tau = M_0(q)\,(K_1\, sat(s(t),\phi) + K_2\, s(t) + \alpha\dot{e}(t) + \ddot{q}_d) + C_0(q,\dot{q}) + G_0(q)$$
:SMC

$$\tau = [M_0(q)\,(\ddot{q}_d - \beta^{-1}\gamma^{-1}\, sig\dot{e}^{2-\gamma} - K_1\, sat - K_2 sig(s)^{\rho}) + C_0(q,\dot{q}) + G_0(q)]$$
:NTSMC

$$\tau = -\eta_1\left(\frac{e}{\|e\|^{\frac{2}{3}}}\right) - \eta_2\left(\frac{e_d}{\|e\|^{\frac{1}{2}}}\right) - k_1\left(\frac{s}{\|s\|^{\frac{1}{2}}}\right) v - k_2\, s$$
: Proposed

CTC: nominal controller settings: - $K_p = 25I_2$, $K_v = 10I_2$, SMC: $\alpha=6I_2$, $k_1= 4.3I_2$, $k2 = 2.6I_2$, $\varphi=0.009I_2$, thru $(t)+\dot{e}(t)=s(t)$, NTSMC: $k_1=k_2=2.5$, $\beta=1I2$ and $\gamma=1.5$ using $\beta sig(e(t))^{\gamma}+e(t)=s(t)$. Intended $\eta_1=35$, $\eta_2=15$, $k_1=2.1$, $k_2=40$, $k_3=2.5$ and $k_4=60$

With suggested robust ISMC numerical simulation results obtained for this effort as per in Eq. (14) with Figs 2-9. Fig 2 and 3 explains joint 1 and joint 2 position tracking control each. Offered control tactic not only show the tight control performance but also quickly follow the desired trajectory all through simulation run. NTSMC over SMC and CTC for position tracking control provides small-steady state error nevertheless NTSMC [14] gives better tracking results as related to SMC and CTC as shown in Figs 4-5. Even though projected proposed robust ISMC control provides all through the run zero steady state error in presence of parameter uncertainties plus time varying external disturbance. The corresponding control torque generated during position tracking by following controllers are shown in Figs 6-7. It should be noted that projected control requires minimum control torque among all controllers, to attain perfect position tracking control. Figs 8-9 clearly shows disturbance estimation in both the joints.

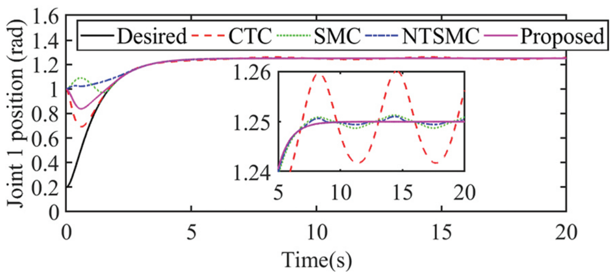

Fig. 2. Joint 1 Position Tracking

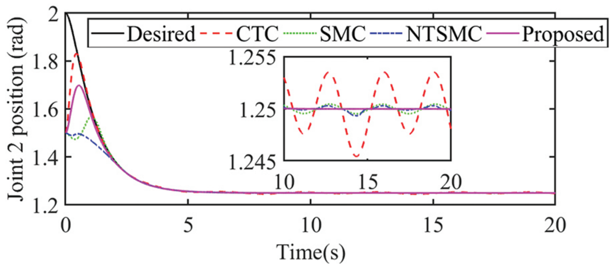

Fig.3. Joint 2 Position Tracking

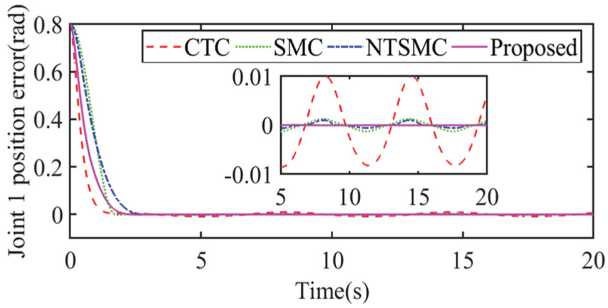

Fig. 4. Joint 1 Position Tracking Error

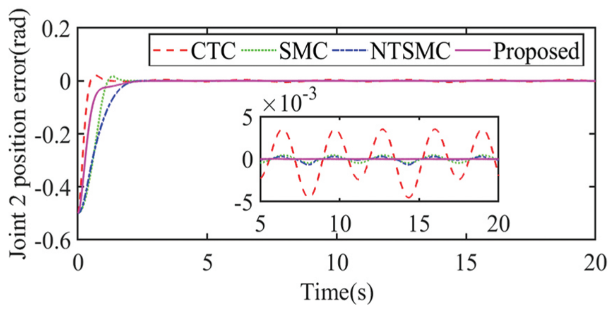

Fig. 5. Joint 2 Position Tracking Error

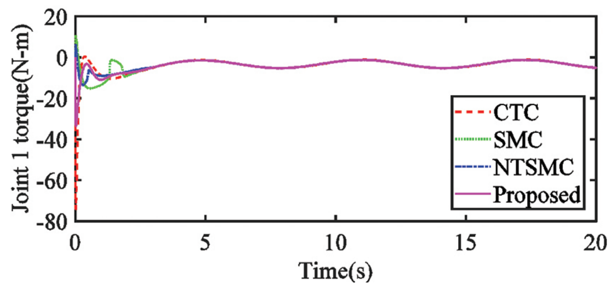

Fig. 6. Joint 1 Position Tracking Control Input

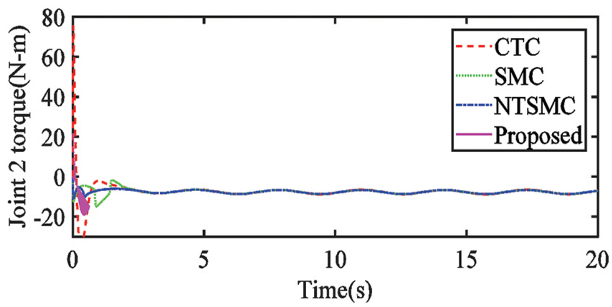

Fig. 7. Joint 2 Position Tracking Control Input

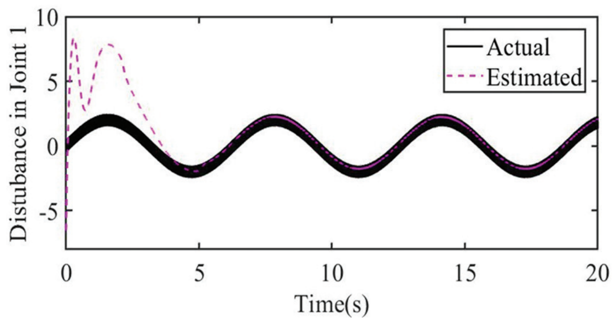

Fig. 8. Disturbance Estimation in Joint 1

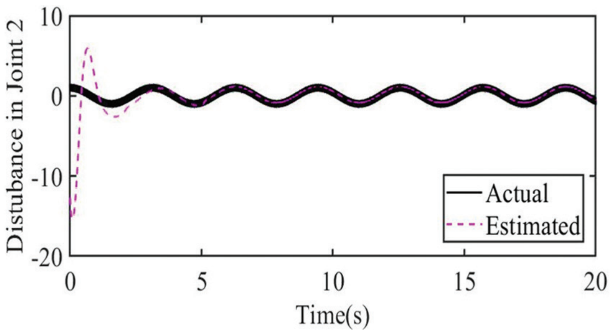

Fig. 9. Disturbance Estimation in Joint 2

Performance measures appraising quantitative performance of controllers castoff shown below;

a) Root mean square (RMS) error

$$RMS = \sqrt{\frac{\sum_{i=1}^{n} e_i{}^2}{n}}$$

b) Norm of the error (Euclidean) L^2

$$L^2\ norm = \sqrt{\sum_{i=1}^{n} e_i{}^2}$$

c) Absolute error value Integral (IAE)

$$IAE = \int |e(t)|\, dt$$

d) Using time interval integration then multiplication thru absolute error value (ITAE)

$$IATE = \int t|e(t)|\, dt$$

Table 2 shows computed performance indexes .

As compared to other control schemes from these indices, it can be confirmed that projected controller has excellent dynamic performance, using agitation estimator in control regulation negates lumped uncertainty effects per sampling instant.

In overall, using disturbance estimator finite and fast convergence property thru enriched robustness is strength of this control structure .As per use of perturbation from dynamics of terminal sliding-manifold estimator estimates uncertainties together with unknown nonlinear dynamics of the manipulator in addition external disturbances. So control input compensate for uncertainty which exists throughout position trajectory tracing of IRM system, at every sampling period. In consequence it eliminates the need for information about the bounds of the existing lumped disturbance vector. Efforts displays merely one restriction that initial control inputs nevertheless that would be resolved through employing computer provided soft limiters, which are used to smoothen the signal known as low pass filters. It may be simply extended to any kind to robotic system together with serial as well parallel robots due to simplicity in design control procedure.

Table 2. IRM system position tracking control quantitative analysis with initial condition $q_1(0)=0.2$, $q_2(0)=2$

Control Laws	e1				e2			
	RMS	L^2 norm	IAE	ITAE	RMS	L^2 norm	IAE	ITAE
CTC	0.0923	41.2572	4.3737×10^3	1.2118×10^8	0.0441	22.2635	2.5851×10^3	4.5228×10^7
SMC	0.1430	63.9588	6.9782×10^3	4.9020×10^8	0.0784	35.0708	3.3289×10^3	1.8469×10^7
NTSMC	0.1376	61.5485	7.2406×10^3	5.0729×10^7	0.0799	35.7276	3.8895×10^3	2.3393×10^7
PROPOSED	0.0390	21.0201	2.2565×10^3	8.1910×10^6	0.0210	15.2050	0.9820×10^3	3.2210×10^6

5. CONCLUSION

This work has proven the effect of robust integral sliding mode control to the IRM system in presence of uncertain conditions. The replacement of discontinuous term with continuous super twisting control gives the multi feature of control as well as disturbance estimation and rejection. The proposed control scheme efficiency has been tested by comparing with well-known controllers. The proposed technique has several advantages, including higher accuracy, faster finite-time convergence, singularity free control plus no need for prior knowledge of the uncertainty bounds. The suggested solution also increases closed-loop system overall stability in presence of lumped disturbances due to super twisting control term. The design method presented here is based on a rational design technique that considers trade-off between response to set-point changes, stability of overall process with controller and robustness to plant parameter variations. The present work can be extended in future directions by noting the features like, SMC generally effectively handles the matched disturbance part of the plant and observer based structure is able to handle the mismatched disturbance part of the system. Also this kind of structure of the control can be extended to other actuated and under actuated systems.

6. REFERENCES

[1] Z. Li, Y. Kun, B. Stjepan, X. Bugong, "On motion optimization of robotic manipulators with strong nonlinear dynamic coupling using support area level set algorithm", International Journal of Control, Automation & Systems, Vol. 11, No. 6, 2013, pp. 1266-1275.

[2] K. Kreutz, "On manipulator control by exact linearization", IEEE Transactions on Automatic Control, Vol. 34, No. 7, 1989, pp. 763-767.

[3] L. Fridman, A. Levant, "Higher order sliding modes", Sliding mode control in engineering, Vol. 11, 2002, pp. 53-102.

[4] A. Levant, "Homogeneity approach to high-order sliding-mode design", Automatica, Vol. 41, No. 5, 2005, pp. 823-830.

[5] A. Levant, "Principles of 2-sliding mode design", Automatica, Vol. 43, No. 4, 2007, pp. 576-586.

[6] J. A Moreno, M. Osorio, "Strict Lyapunov functions for super twisting algorithm", IEEE Transactions on Automatic Control, Vol. 57, No. 4, 2012, pp. 1035-1040.

[7] Z. Li, F. Wang, D. Ke, J. Li, W. Zhang, "Robust continuous model predictive speed & current control for pmsm with adaptive integral sliding mode approach", IEEE Transactions on Power Electronics, Vol. 36, No. 12, 2021, pp. 14398-14408.

[8] X. Zhang, Y. Huang, Y. Rong, G. Li, H. Wang, C. Liu, "Recurrent neural network based optimal integral sliding mode tracking control for four wheel independently driven robots", IET Control Theory & Applications, Vol. 15, No. 10, 2021, pp. 1346-1363.

[9] W. Ji, Q. Jianbin, H. R. Karimi, Y. Fu, "New results on fuzzy integral sliding mode control of nonlinear singularly perturbed systems", IEEE Transactions on Fuzzy Systems, Vol. 29, No. 7, 2020, pp. 2062-2067.

[10] S. Yu, M. Xie, H. Wu, J. Ma, Y. Li, H. Gu, "Composite proportional-integral sliding mode control with feedforward control for cell puncture mechanism with piezoelectric actuation", ISA transactions, Vol. 124, 2020, pp. 427-435.

[11] L. Zhao, L. Dai, Y. Xia, P. Li, "Attitude control for quadrotors subjected to wind disturbances via active disturbance rejection control & integral-sliding mode control", Mechanical Systems & Signal-Processing, Vol. 129, 2019, pp. 531-545.

[12] S. Yu, X. Yu, B. Shirinzadeh, Z. Man, "Continuous finite time control for robotic manipulators with terminal sliding mode", Automatica, Vol. 41, No. 11, 2005, pp. 1957-1964.

[13] D. Zhao, S. Li, F. Gao, "A new terminal sliding mode control for robotic manipulators", International Journal of Control, Vol. 82, No. 10, 2009, pp. 1804-1813.

[14] J. Yuh, "Design and control of autonomous underwater robots", A survey. Autonomous Robots, Vol. 8, No. 1, 2000, pp. 7-24.

[15] S. Kolahi, M. Reza, M. R. Gharib, A. Heydari, "Design of a non-singular fast terminal sliding mode control for second-order nonlinear systems with compound disturbance." Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, Vol. 235, No. 24, 2021, pp. 7343-7352.

[16] S. J. Gambhire, D. R. Kishore, P. S. Londhe and S. N. Pawar, "Review of sliding mode based control techniques for control system applications." International Journal of Dynamics and Control, Vol. 9, 2021, pp. 363-378.

[17] H. Xiao, D. Zhao, S. Gao and S. K. Spurgeon, "Sliding mode predictive control: A survey " Annual Reviews in Control, 2022. (in press)

[18] J. Davila, L. Fridman, A. Poznyak, "Observation & identification of mechanical systems via second order sliding modes", Proceedings of the International Workshop on Variable Structure Systems, Alghero, Italy, 2006, pp. 232-237.

[19] A. Levant, "Quasi continuous high order sliding mode controllers", IEEE Transactions on Automatic Control, Vol. 50, No. 11, 2005, pp. 1812-1816.