# A novel fuzzy logic based sliding mode control scheme for non-linear systems

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**ABSTRACT**

Sliding mode control (SMC) has been widely used in the control of non-linear systems due to many inherent properties like superposition, multiple isolated equilibrium points, finite escape time, limit cycle, bifurcation. This research proposes super-twisting controller architecture with a varying sliding surface; the sliding surface being adjusted by a simple single input-single output (SISO) fuzzy logic inference system. The proposed super-twisting controller utilizes a varying sliding surface with an online slope update using a SISO fuzzy logic inference system. This rotates sliding surface in the direction of enhancing the dynamic performance of the system without compromising steady state performance and stability. The performance of the proposed controller is compared to that of the basic super-twisting sliding mode (STSM) controller with a fixed sliding surface through simulations for a benchmark non-linear system control system model with parametric uncertainties and disturbances. The simulation results have confirmed that the proposed approach has the improved dynamic performance in terms of faster response than the typical STSM controller with a fixed sliding surface. This improved dynamic performance is achieved without affecting robustness, system stability and level of accuracy in tracking. The proposed control approach is straightforward to implement since the sliding surface slope is regulated by a SISO fuzzy logic inference system. The MATLAB/Simulink is used to display the efficiency of proposed system over conventional system.



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## 1. INTRODUCTION

Nonlinearity plays a crucial role in nonlinear control systems when it occurs in the regulated process (plant) or the controller itself. Many engineering and organic systems, including as mechanical and biological systems, aerospace and automobile control, and industrial process control, naturally produce nonlinear plants. The study and design of nonlinear control systems are topics covered by nonlinear control theory. The theory of nonlinear systems (system-nonlinear) in general, which supplies its fundamental analysis tools, is strongly tied to this concept. The urgent requirement is to develop an automatic control system that is straightforward, effective, dependable, and robust, with a wide operating range and the ability to resist a large working range in the presence of uncertainties and disruptions. In order to satisfy more severe control design criteria, dealing with the inherent modelling and parametric uncertainties and disturbances has been the basic focus of recent nonlinear system research.

Adaptive control, back-stepping control, model predictive control, and sliding mode control (SMC) are a few famous techniques that have recently seen significant advancements in robust control systems. Even in the presence of parametric uncertainties, exogenous disturbances, and modelling errors, these strategies can guarantee control goals. Among current robust control systems, the SMC technique stands out for its ease of use. Also, it enables the decoupling of the system's overall motion into many component parts of smaller dimensions, reducing the complexity of the feedback design. The created system is also stable, has a predetermined time interval for convergence, and is resilient. In recent decades, first-order SMC concepts have successfully been applied to a variety of real industrial systems, including mobile robotics, electric motors, underwater ships, spaceships, and a great deal more. The fundamental idea behind SMC is to push the system along a subspace of its typical behavior. Using a discontinuous control signal makes it possible for the system to always slide over the limited subspace as the first order. Gain on an infinite scale is used by SMC as the control signal, and this high frequency switching causes oscillations known as chattering.

This activates an uncontrolled dynamic in the system, which occasionally can even result in complete plant destruction. As a result, SMC should only be used with caution in systems with small control action. Second order SMC is one of the newest and most efficient methods for minimizing the chattering effects of the first order SMC. The basic second order SMC, in contrast to the basic SMC, necessitates the value of the sliding variable's time derivative. The fundamental second order SMC system is complicated by the need for this extra information, which hinders their widespread application. The super-twisting sliding mode (STSM) controller is the most recent type of second order SMC. The STSM control approach generates a superior control signal than a first order SMC because it keeps the distinctively strong properties of second order sliding mode approaches. For this reason, STSM control chatters less than first order SMC. Furthermore, as compared to the basic second order SMC, the STSM control technique does not require the derivative of the sliding variable and hence affords a simple methodology for straightforward implementation. The effectiveness of STSM control is very much influenced by the choice of the sliding surface. The design of appropriate sliding surface can ensure that STSM control minimizes chattering without compromising transient responsiveness, steady-state response, or durability, whereas the inappropriate design of sliding surface may have unfavorable impacts on the response. Finding the best sliding surface alternatively is a difficult and time-consuming operation. Using a varying sliding surface as opposed to a constant one is an effective sliding surface design strategy for improving the controller performance. In this research, a transient voltage surge suppressor (TVSS) STSM control technique is introduced to enhance the dynamic performance of the traditional STSM control strategy for non-linear systems. The sliding surface is adjusted using a simple mechanism that does not compromise the simplicity and stability of the typical STSM control technique. For non-linear systems, the suggested approach is resilient, stable, and demonstrates excellent transient and steady-state responses.

## 2. LITERATURE REVIEW

In control engineering, SMC is a control technique that falls under nonlinear system controllers and can change the outcome of such a system by the deployment of abrupt control techniques owing to the control function sides along a cross-section of the system's typical behaviour. However, this could result in some errors or issues these can be eliminated by an observer-based technique, but this method may create additional load on the system, to boost performance logarithmic quantizer synthesis can be used [1], the transmitted signal creates a fluctuation, for reflecting such reflection multiplicative fading model can be used [2]. The SMC can be used to control a chaotic system, this can be achieved by considering a unique sliding-manifold which establishes new law which helps to achieve asymptotical stability [3]. Abdollahzadeh *et al.* [4] showed that to overcome chattering in the nonlinear system we can use fuzzy-based SMC and based on this principle they created magnetic levitation system. The SMC are efficient to handle system with large uncertainties in such a situation we can use decentralized-fuzzy-SMC and the parameter of these techniques can be boosted by jaya algorithm [5], by integrating mamdani type proportional integral derivative (PID) fuzzy algorithm with SMC the system can handle non-affine non-linear system [6]. In singularly perturbed descriptor systems for the analysis of stability few methods are available, hence for simplifying practical application calculation an integral SMC strategy is proposed in [7], a new type of control scheme based on scalar sign function technique and on parallel-distributed-compensator is given in [8], in [9] an efficient stabilizer for the power system is designed on the base of fuzzy logic, here they integrated differential evolution algorithm with SMC, this helps to handle power system in different conditions and also combining genetic algorithm gives additional boost for the system [10]. In [11]–[17] based on SMC design of quad-rotor is carried out here two loop architecture is used and it proves fussy based SMC is superior to PID, the Takagi-Sugeno (T-S) fuzzy descriptor is also one of the popular methods, since the system design is mainly depending upon mathematics the paper proposed by Sun and Zhang [13] gives mathematical background and an extended version is given in [16]. Since compared to traditional systems the fuzzy based SMC are efficient a variable delay control for chemical processing is designed in [18]–[27], this reduces settling time. Since spherical robot kinematics and non-holo-monics are coupled with their system dynamics the design becomes complex, to overcome complexity and to utilize the complete potential of spherical robot fuzzy-based SMC is employed in [15].

## 3. STSM CONTROL USING FUZZY LOGIC CONTROL

The STSM control scheme is an efficient control method that removes the chattering effect of traditional SMC schemes without compromising tracking performance. The performance of STSM control, on the other hand, is significantly dependent on the sliding surface. If the sliding surface is appropriately built, STSM control may minimize chattering without compromising transient responsiveness, steady-state response, or durability. If the sliding surface is not appropriately constructed, it may have unfavorable impacts on the response. Deciding the best sliding surface alternatively is a time-consuming operation. Instead of a steady sliding surface, use of a TVSS is an effective sliding surface design strategy for increasing controller performance. This can be done by using a controller which can update the sliding surface slope online based on error variables. Consider the system dynamics with disturbance given by (1).

$$\dot{X}(t) = f(X,t) + b(t)u(t) + d(t) \tag{1}$$

Consider the time-varying sliding surface given by (2):

$$s(t) = \dot{e}(t) + \lambda(t)e(t) \tag{2}$$

Assuming $\lambda(t) > 0$, the control objective is to drive the system trajectory to reach the time-varying sliding manifold $\dot{s}(X,t) = s(X,t) = 0$ in finite time. Taking the first and second derivatives of $\sigma(X)$, we obtain (3) and (4):

$$\dot{s}(X,t) = \frac{\partial s}{\partial t} + \frac{\partial s}{\partial X}(f(X,t) + b(t)u(t) + d(t)\,) \tag{3}$$

$$\ddot{s}(X) = \frac{\partial \dot{s}}{\partial t} + \frac{\partial \dot{s}}{\partial X}(f(X,t) + b(t)u(t) + d(t)\,) + \frac{\partial \dot{s}}{\partial u}\dot{u}(t) \tag{4}$$

Suppose that for some positive constants $\phi, \Gamma_{min}, \Gamma_{max}$, the following condition holds as in (5):

$$\begin{cases} \left|\frac{\partial \dot{s}}{\partial t} + \frac{\partial \dot{s}}{\partial X}\left(f(X,t) + b(t)u(t) + d(t)\right)\right| < \phi \\ 0 \le \Gamma_{min} \le \left|\frac{\partial \dot{s}}{\partial u}\right| \le \Gamma_{max} \end{cases} \tag{5}$$

Then, the control law is designed as shown in (6):

$$\begin{cases} u = -c_1|s|^{\frac{1}{2}}\, sign(\sigma) + v \\ \dot{v} = -c_2\, sign(s) \end{cases} \tag{6}$$

Where:

$$\begin{cases} c_2 > \frac{\phi}{\Gamma_{min}} \\ {c_1}^2 \ge \frac{4\phi}{{\Gamma_{min}}^2}\frac{\Gamma_{max}(c_2+\phi)}{\Gamma_{min}(c_2-\phi)} \end{cases} \tag{7}$$

If the conditions given in (7) are satisfied, the control given by (6) drives the sliding variable $s(t)$ and its derivative $s(\dot{t})$ to zero in finite time. However, there is no exact mathematical model describing the relationship between the sliding surface slope and error variables, but some approximate rules can be derived to establish it. Because fuzzy logic control is a useful tool for regulating the system using certain approximation rules, it may be used to update the sliding surface slope depending on error variables.

The safety factor (SF) movement may be performed by updating the value of a SF slope online depending on the error values variables $e(t)$ and its rate of variation of error $e(t)$, and system should satisfy a condition that the SF slope should be positive to ensure stability. There is no precise mathematical explanation of the relationship between the error variables and the gradient of the sliding surface. Therefore, a fuzzy logic inference system can update the sliding surface slope.

The input to the single input-single output (SISO) fuzzy logic controller is the difference between the magnitudes of $E(t)$ and $\dot{E}(t)$ as given in (8). The output of the fuzzy logic controller $\lambda_N(t)$, adjusted via an output scaling factor yields the sliding surface slope $\lambda(t)$.

$$E_d(t) = |E(t)| - |\dot{E}(t)| \quad (8)$$

The rule basis is one-dimensional, and the rules have the form "If $E_d(t)$ is $E_{df}$, then $\lambda_N(t)$ is lambda" where $E_{df}$ and lambda are fuzzy logic sets of $E_d(t)$ and $\lambda_N(t)$. The variable $E_d(t)$may have both negative and positive values. However, in order to ensure stability, the fuzzy logic controller $\lambda_N(t)$ output must always be positive. Hence input is selected between (-1, +1) and output is selected between (0, +1). As shown in Figure 1, the membership functions of the input $E_d(t)$ are negative big (NB), negative medium (NM), negative small (NS), zero (ZE), positive small (PS), positive medium (PM), and positive big (PB), while the membership functions of the output are very-very small (VVS), very small (VS), small (S), medium (M), big (B), very big (VB), and very very big (VVB) as shown in Figure 2. The rule base of the fuzzy controller is given in Table 1. The defuzzification is performed by the centroid approach.

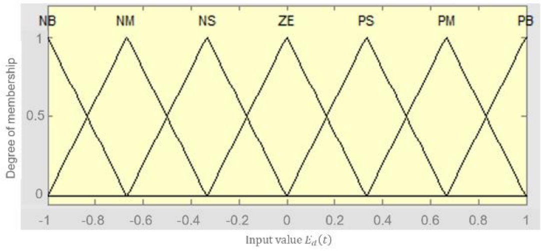


Figure 1. Input functions for membership

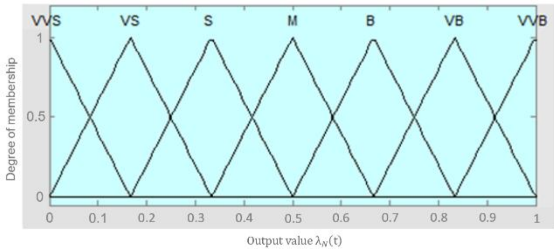


Figure 2. Output functions for membership

Table 1. Fuzzy rule base

| Rules | Variables | | | | | | |
|---|---|---|---|---|---|---|---|
| $E_d(t)$ | NB | NM | NS | ZE | PS | PM | PB |
| $\lambda_N(t)$ | VVB | VB | B | M | S | VS | VVS |

## 4. RESULTS AND DISCUSSION

The proposed controller's performance is compared to the standard STSM regulator for a non-linear uncertain system provided by (9) and (10).

$$\frac{d^2y}{dt^2} = -f(y) - 100\frac{dy}{dt} - 70sign\left(\frac{dy}{dt}\right) + 120u(t) \quad (9)$$

Where:

$$f(y) = 80(y - y_0) + 150sign(y - y_0) \quad (10)$$

Here $y$ indicates outputand $u(t)$ indicates control input. The range of value of $y_0$ is uncertain with known bounds $0 \leq y_0 \leq 0.095$. The suggested controller's performance is investigated for the control aim of keeping y constant at 1.57. Horn and Reichhartinger [28] presented a standard STSM with a constant sliding surface, with the sliding surface, $\sigma = \dot{e}(t) + \lambda\, e(t)$. Here $e(t)$ holds the value of error angle, which is caused by throttle valve and $\dot{e}(t)$ indicates time derivative of error angle $e(t)$. The sliding surface slope is $\lambda = 10$. The gains of controller are $c_1 = 1$, $c_2 = 90$. The control input is bounded such that $-10 \leq u(t) \leq 10$ . This study's controller is a STSM controller with a sliding surface fuzzy-based control. As a result, the sliding surface is $\sigma = \dot{e}(t) + \lambda(t)e(t)$, with the sliding surface slope $\lambda(t)$ is determined by the fuzzy logic controller. The values of $e(t)$ and $\dot{e}(t)$ have scaling factors of 0.64 and 30 respectively. The fuzzy logic controller's output scaling factor is 20, which is set so that the sliding surface is constantly recorded, enhancing the system's dynamic performance, with the requirement that the slope of sliding surface is always positive, assuring stability. The gains of the controller are $c_1 = 1$ and $c_2 = 90$, which are the same as those of a traditional STSM controller with a fixed sliding surface.

### 4.1. Case 1: $y_0 = 0.095$

For $y_0 = 0.095$, the responses of the proposed controller and the standard STSM controller with a constant sliding surface are simulated. The simulation results are depicted in Figures 3 to 8. Figure 3 depicts the system output response for the proposed controller as well as the standard STSM controller. The suggested controller clearly outperforms the standard STSM controller in terms of reaction time. The suggested controller and the traditional STSM controller have rising times of 0.18 and 0.29 sec, respectively, and settling times of 0.26 and 0.48 sec. The time required for the response to achieve the steady-state value in the system with the suggested controller is 0.46 sec, while it is 1.01 sec for the traditional STSM controller. In both circumstances, the steady-state error and overshoot are zero.

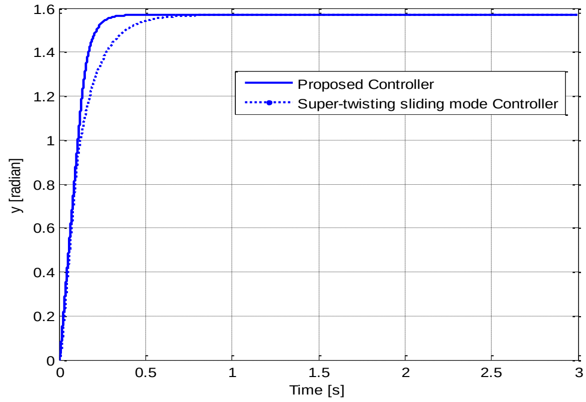


Figure 3. Output y for $y_0 = 0.095$

The integral absolute error (IAE) and integral time absolute error (ITAE) curves in Figures 4 and 5 respectively demonstrate that the proposed controller is quicker throughout the response. The IAE indices for the proposed controller and the traditional STSM controller are 0.15 and 0.21, respectively. The ITAE indices are 0.01 and 0.03, confirming the quicker reaction of the system with the suggested controller.

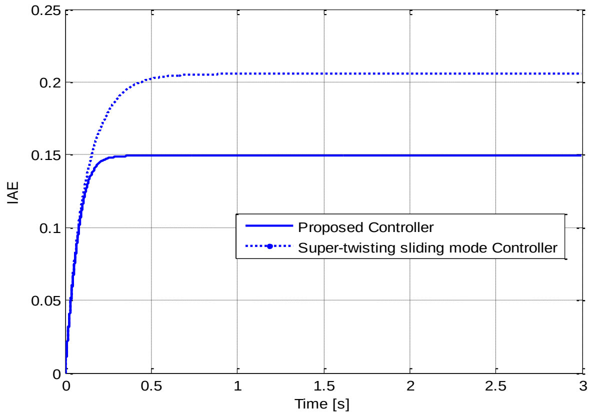


Figure 4. IAE of the output y for $y_0 = 0.095$

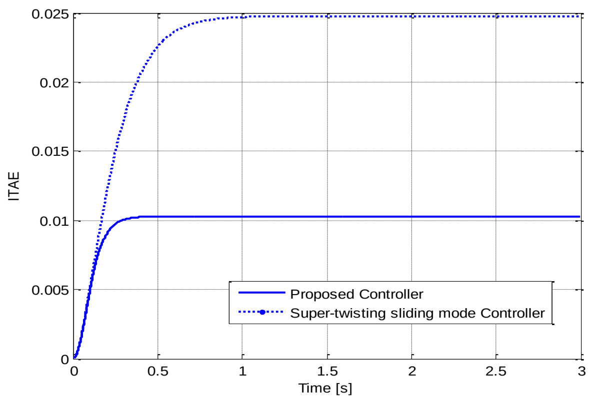


Figure 5. ITAE of the output y for $y_0 = 0.095$

The enhanced performance of the suggested control strategy is because of the varying sliding surface slope, as illustrated in Figure 6. The sliding surface slope increases during starting phase of the response to improve the speed of response and then reduces near the steady state to ensure tracking accuracy. Figure 7 depicts the sliding variables. The reaching times of the presented controller and the traditional STSM controller are 0.10 and 0.072 sec, respectively, confirming that the robustness of the suggested controller is not significantly compromised while boosting dynamic performance. Table 2 summarizes the performance metrics. Figure 8 shows the suggested scheme's stability and quicker error convergence. The simulation results demonstrate that the suggested approach increases the system's dynamic performance while maintaining its stability and robustness.

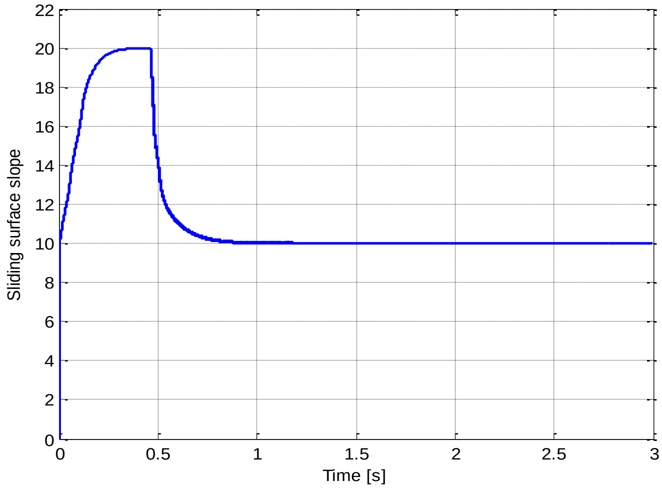


Figure 6. Slope of sliding surface for proposed scheme for $y_0 = 0.095$

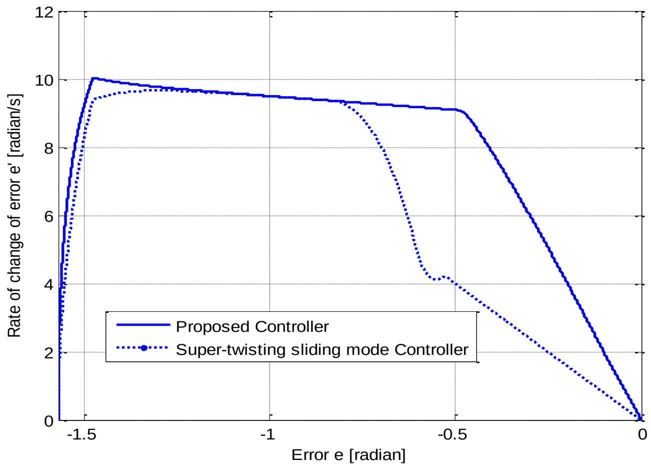


Figure 7. Sliding variable for $y_0 = 0.095$

Table 2. Comparison between proposed and conventional controller for $y_0 = 0.095$

| Performance parameters | Proposed controller | Conventional STSM controller |
|---|---|---|
| $t_r$ (sec) | 00.18 | 00.29 |
| ts (sec) | 00.26 | 00.48 |
| tst (sec) | 00.46 | 01.01 |
| ess (rad) | 00.00 | 00.00 |
| IAE | 00.15 | 00.21 |
| ITAE | 00.01 | 00.03 |
| tre (s) | 00.10 | 00.072 |

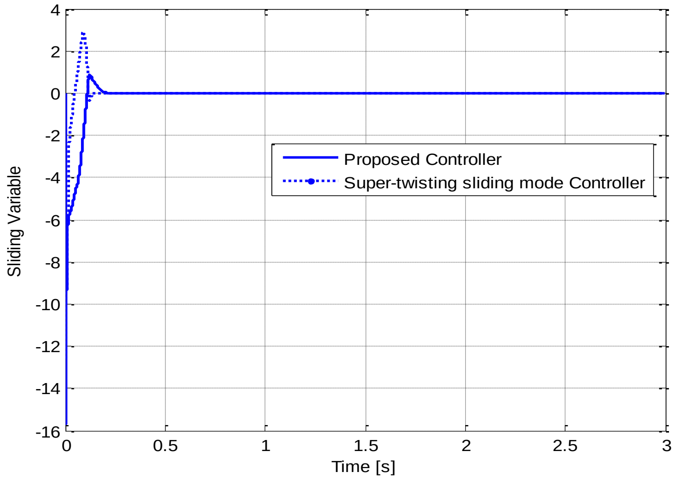


Figure 8. Error convergence for $y_0 = 0.095$

### 4.2. Case 2: $y_0 = 0$

For $y_0 = 0$, the responses of the presented controller and the standard STSM controller with a constant sliding surface are simulated. The simulation results are shown in Figures 9 to 14. Figure 9 depicts the system output response for the presented controller and the standard STSM controller for $y_0 = 0$. The suggested controller clearly outperforms the standard STSM controller in terms of reaction time. The suggested controller and the standard STSM controller have rising times of 0.18 and 0.29 sec, respectively, and settling times of 0.26 and 0.49 sec. The time required for the response to achieve the steady-state value in the system with the suggested controller is 0.49 sec, while it is 1.03 sec for the traditional STSM controller. In both circumstances, the steady-state error and overshoot are zero.

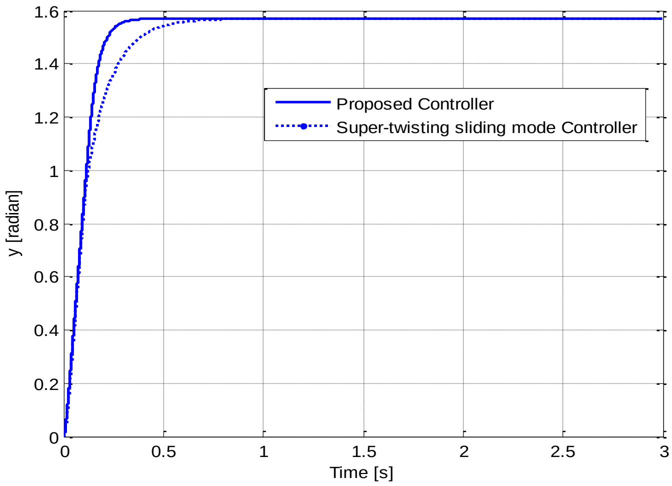


Figure 9. Output y for $y_0 = 0$

The IAE and ITAE curves in Figures 10 and 11 demonstrate that the designed controller is quicker throughout the response. The IAE indices for the proposed controller and the traditional STSM controller are 0.16 and 0.22, respectively, but the ITAE indices are 0.011 and 0.025, confirming the quicker reaction of the system with the suggested controller. Here the varying sliding surface slope is the reason for the performance boost in suggested controller, as shown in Figure 12. For improving the speed of the response at the beginning sliding surface slope increases and at steady state point sliding surface slope decreases, this ensures tracking accuracy.

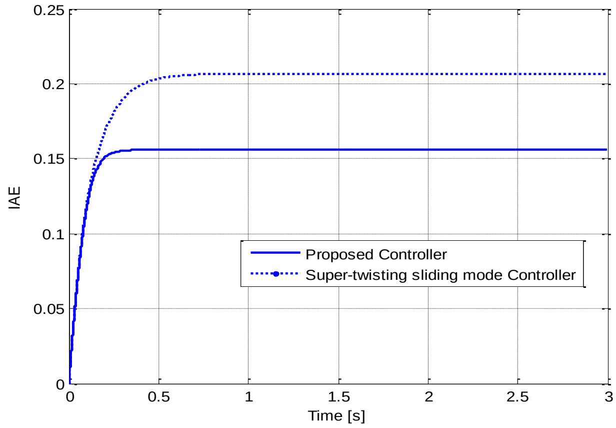


Figure 10. IAE of the output y for $y_0 = 0$

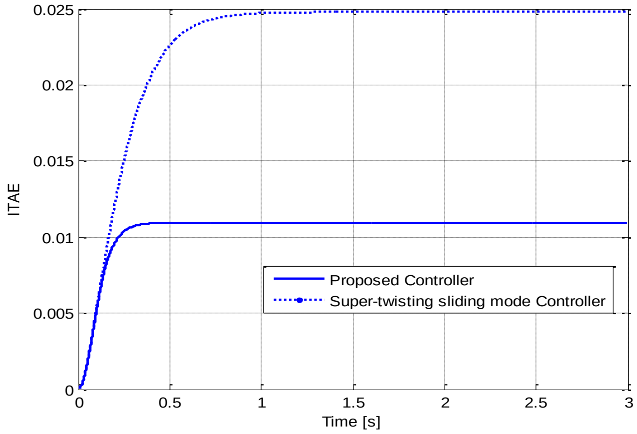


Figure 11. ITAE of the output y for $y_0 = 0$

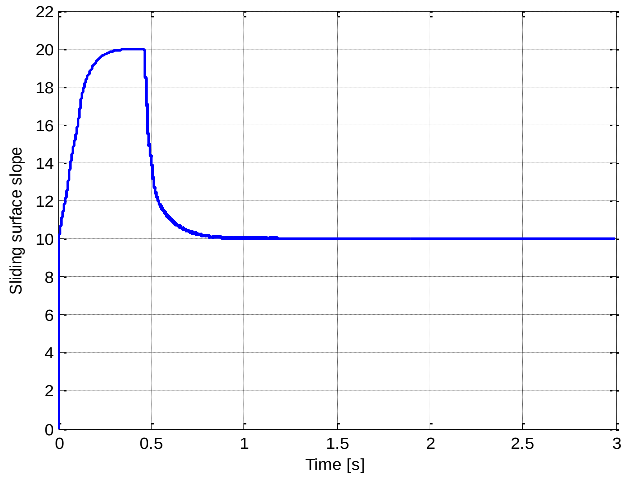


Figure 12. Slope of the sliding surface for the proposed control scheme for $y_0 = 0$

Figure 13 depicts the sliding variables. The reaching times for the proposed controller and the traditional STSM controller are 0.1 and 0.07 sec, respectively, confirming that the robustness of the suggested controller is not significantly compromised while boosting dynamic performance. Figure 14 shows the suggested scheme's stability and quicker error convergence. The simulation results demonstrate that the suggested approach increases the system's dynamic performance while maintaining its stability and resilience. Table 3 summarizes the performance metrics.

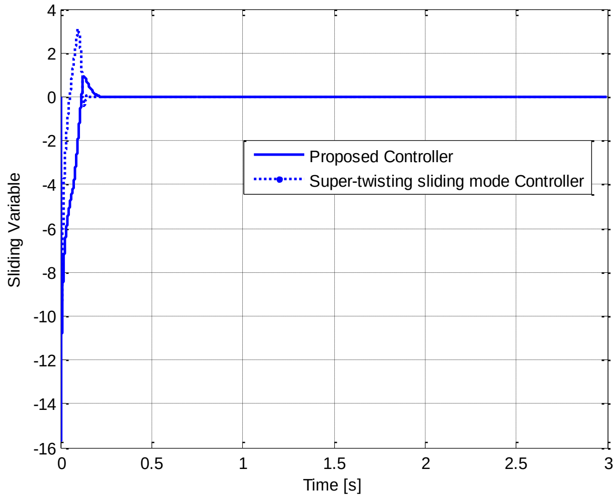


Figure 13. Sliding variable for $y_0 = 0$

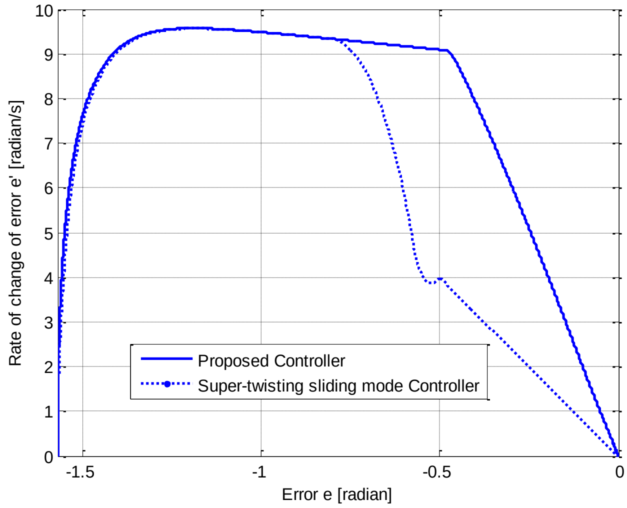


Figure 14. Error Convergence for $y_0 = 0$

Table 3. Comparison between proposed and conventional controller for $y_0$=0.

| Performance Measure | Proposed Controller | Conventional STSM Controller |
|---|---|---|
| tr (sec) | 00.18 | 00.29 |
| ts (sec) | 00.26 | 00.49 |
| tst (sec) | 00.49 | 10.03 |
| ess (rad) | 00.00 | 00.00 |
| IAE | 00.16 | 00.22 |
| ITAE | 00.011 | 00.025 |
| tre (sec) | 00.1 | 00.07 |

#### 4.1.1. Disturbance in the control channel

In this section we will compare rejection of step disturbance on control channel side with traditional STSM system, the Figures 15 to 20 helps to visually compare the response of both traditional and proposed design for the same parameters for a disturbance at t=2 sec. The proposed system takes 0.08 sec to bring back the response to stable level, while the typical STSM controller takes 0.8 sec. For the proposed controller and the standard STSM controller, the position overshoot are 0.1 and 9.62%, respectively. The IAE and ITAE curves in Figures 16 and 17, respectively, show that the proposed controller rejects the disturbance faster than the conventional STSM controller. The proposed controller's faster reaction is because of the varying slope, as illustrated in Figure 18. The error convergence in Figure 20 demonstrates the proposed controller's stability and quicker disturbance rejection.

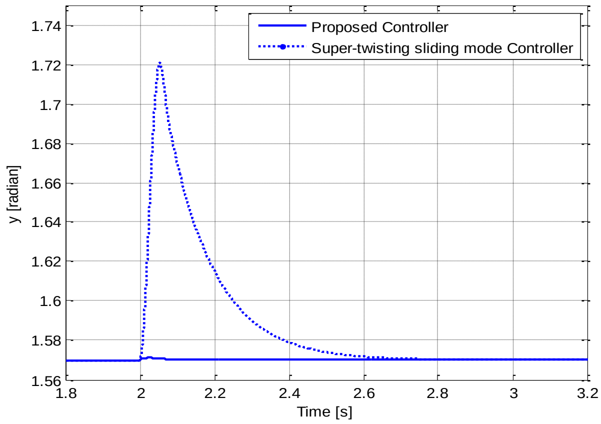


Figure 15. Output y in presence of a disturbance

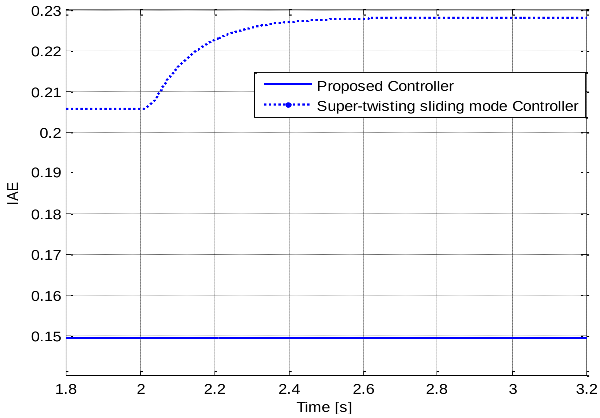


Figure 16. IAE of y in presence of a disturbance

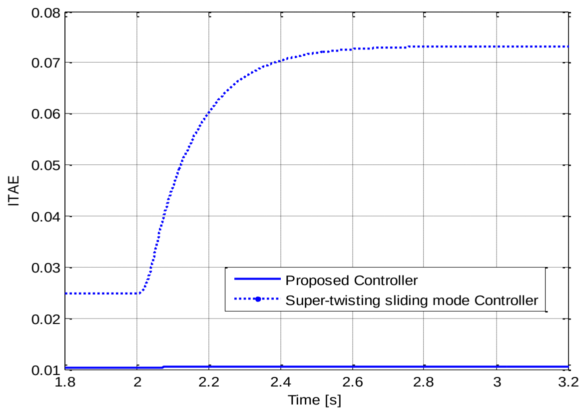


Figure 17. ITAE in presence of a disturbance

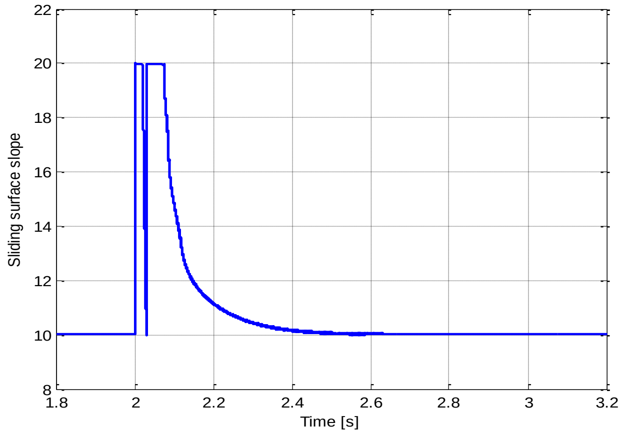


Figure 18. Sliding surface slope in presence of a disturbance

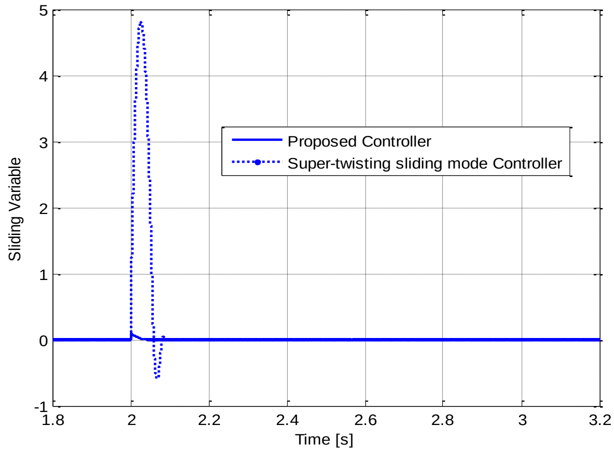


Figure 19. Sliding variable in presence of a disturbance

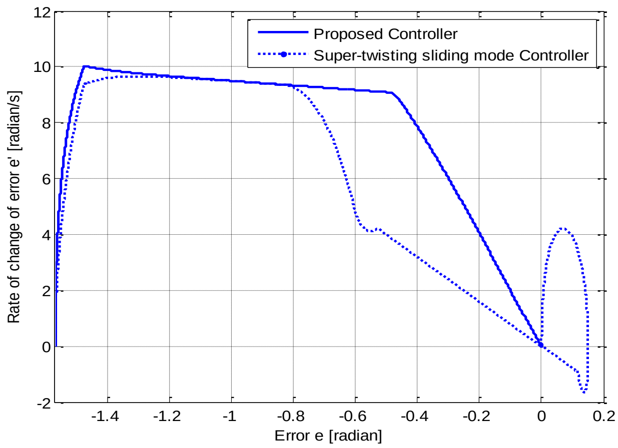


Figure 20. Error convergence in presence of a disturbance

## 5. CONCLUSION

This research work proposed a varying sliding surface for a STSM controller using a SISO fuzzy logic controller. The concept behind this control scheme is to use a varying sliding surface function, with the gradient of the surface being updated online using a simple SISO fuzzy logic controller to rotating the sliding surface in the direction of improved dynamics. The improvement in the dynamic performance of the proposed controller is verified with a benchmark non-linear system with parametric uncertainties and disturbances. From the simulation results, it is clear that the response time of the proposed controller is much lessrer compared to the conventional STSM controller with a fixed sliding surface. The dynamic perfromance is improved without affecting stability, robustness, or tracking accuracy. The propoed control technique is relatively simple and straightforward to implement as the sliding surface slope is adjusted by a SISO fuzzy control scheme.


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## AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

| Name of Author | C | M | So | Va | Fo | I | R | D | O | E | Vi | Su | P | Fu |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Abdul Kareem | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | | ✓ | ✓ | |
| Varuna Kumara | | ✓ | | | | ✓ | | ✓ | ✓ | ✓ | ✓ | | | |

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

## CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

## DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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