Single Input Single Output Fuzzy Logic Control Based Sliding Surface Adjustment of Second-Order Sliding Mode Controllers

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Abstract

The authors of this study provide a brand-new second-order sliding mode control that is based on fuzzy logic and a time-varying sliding surface. A potent approach for enhancing controller performance is sliding surfaces that vary over time. After factoring in mathematical model mistakes and environmental perturbations, we first build a sliding variable with a relative degree of 2. "Then, using a simple single-input single-output fuzzy logic inference system, a time-varying sliding surface is constructed to enhance the controlled system's tracking performance. The proposed controller ensures that the system will be accessible, stable, and resilient. In terms of development and implementation, the proposed controller is relatively simple. Theoretically, it has been shown that the resultant closed-loop system is globally finite-time stable. We investigate a nonlinear system using MATLAB/SIMULINK and contrast the suggested controller with a conventional, fixed-sliding-surface, second-order sliding mode controller. In terms of dynamic performance, the suggested controller performs better than a conventional second-order sliding mode controller with a fixed sliding surface.

Keywords: Second-order sliding mode control, Sliding surface rotation, Fuzzy logic control, Error convergence, Tracking accuracy

1. Introduction

Dynamic uncertain systems have seen significant application of the sliding mode control strategy with considerable success. Sliding mode controls are so well-liked because they have several useful features, such as robustness against disturbances, parameter violations, and uncertainty. Sliding mode control employs a plain and easy-to-understand approach. The two steps of a sliding mode control layout are designing the appropriate sliding surface and then enforcing the sliding mode. Sliding mode controllers have traditionally made use of relay controllers or unit controllers. Chattering, a high-frequency oscillation resulting from switching and temporal delays in the system's dynamics, prevents the system trajectory from reaching the optimal sliding mode and is the fundamental problem with these control systems. Additionally, the normal sliding mode controller with a fixed sliding surface has the drawback that the tracking inaccuracy cannot be easily modified while the system states are in the reaching mode.

In order to maintain resilience and tracking performance in the presence of uncertainties and disturbances, second-order sliding mode (SOSM) control employs higher-order sliding modes. The aim of sliding-mode (SOSM) control is to confine the dynamical development of the system to a sliding surface, a reduced-dimensional manifold. Performance of a second-order sliding mode controller is strongly influenced by the properties of the surface. Regarding the creation of a sliding surface, there are no unbending restrictions. This makes creating the ideal sliding surface a difficult challenge. Additionally, while in reaching mode, a second-order sliding mode controller with a fixed sliding surface is more susceptible to changes in the controller's settings. Reduce this sensitivity by cutting down on the time spent in reaching mode. This paper thus proposes a sliding surface whose characteristics change over time.

The idea behind time-varying sliding surfaces is to rotate the sliding region in the direction of better dynamic performance. You may monitor time-varying references or reject time-varying disturbances using the SOSM control approach with a time-varying sliding surface. It is common practise to use a Lyapunov function when developing the SOSM controller with a time-varying sliding surface to evaluate the departure from the sliding surface. Then, we create a control rule to move the system closer to the sliding surface using the gradient of the Lyapunov function. The SOSMC approach, which employs a sliding surface that changes over time, could prove to be an efficient way to control uncertain systems robustly and precisely. However, the controller's design may be difficult, requiring expertise in both the system's dynamics and the relevant control theory. Also, there is no strict and hard rules for rotation of the sliding surface in the direction of improved dynamic performance, only some approximate rules are available.

Sliding mode control is an appropriate strategy for robust control because its decreased order dynamics offer desirable benefits like matching uncertainties and disturbances and sensitivity to parameter fluctuations.[1] Sliding mode controllers have been shown to be effective for stabilizing uncertain nonlinear systems that contain nonlinearities and uncertainties [2]. We provide a framework in [3] for realising high-performance control applications using a particular type of underactuated mechanical systems using reliable and smooth second-order sliding mode control. Particularly, external disturbances, parameter uncertainties, etc. affect practically all real systems inexorably, degrading the performance of many control schemes. Since un-actuated states are far more susceptible to shocks than actuated ones, stabilising such a system is a formidable challenge in general, and it is made much more so for underactuated systems.[4]

Although it has the capacity to produce a closed-loop system that is highly robust to plant uncertainty and outside disturbances, sliding mode control has chattering issues. Second-order sliding mode control may effectively suppress obtrusive noises. The SOSM is an excellent technique for addressing the chattering problems of the first-order SMC [5–9]. A continuous compensation term may be used to reduce the effects of uncertainty with the noise associated with the magnitude of the switching gain, which is chosen to be larger than the finite value of the uncertainty and disturbance.[10]

The sliding surface can be reached in finite time under SMC due to the linear sliding variable design [11], but this is insufficient for the system to converge to the origin in finite time. The SOSM strategy may also be applicable in situations with asymmetric output limitations [12]. Using an SMC-based controller, [13] implements the buck converter circuit. In [14], a new sliding mode control strategy is suggested and used to nonlinear uncertain SISO systems of relative degree 2. The globally fixed-time control issue is investigated for a large class of uncertain nonlinear systems in [15].

Because of its flexibility in dealing with uncertainties and approximations, fuzzy logic has found widespread usage in a broad range of industrial applications, making it a popular control approach. [16-17] Particularly helpful for mathematically challenging control issues. The difficulty of creating a fuzzy adaptive SOSM controller is described in [18], which focuses on a subset of nonlinear systems. A sliding mode control (SMC) method and fuzzy logic are used to create a fuzzy sliding mode controller (FSMC) in [19]. Uncertain dynamic systems are handled in [20] via a new fuzzy-based adaptive super-twisting sliding mode controller.

Although traditional second-order sliding mode control schemes with fixed sliding surfaces reduce the chattering phenomenon of the classical first-order sliding mode controller and ensure higher accuracy in the presence of system flaws and uncertainties, this approach has the disadvantage that the performance of the system is highly dependent on the sliding surface. Calculating the ideal slope for a sliding surface is a time-consuming and difficult operation. In [21], the author proposes using a super-twisting sliding mode to regulate a dynamically uncertain system whose sliding surface changes over time. An implementation of the Lyapunov-based SOSM algorithm from [22], which uses the saturation approach. When used to a time-varying sliding surface, the SOSMC approach may be an effective means of establishing robust and precise management of uncertain systems [23]. Using time-varying sliding surfaces rather than continuous ones is an effective sliding surface design technique for enhancing controller performance. The authors of [24] suggest using a two-input, single-output fuzzy logic controller to implement a time-varying sliding surface correction for a ship steering model.

In this study, we create a novel SISO (single-input, single-output) second-order sliding mode control system based on fuzzy logic control. Using the suggested control technique, the sliding surface may be dynamically modified online depending on the sliding variable values to provide the required performance. Additionally, the spinning surface may spin either clockwise or anticlockwise. It is possible to rapidly and simply determine the sliding surface change using a simple input and output fuzzy logic control system. Computational simulations demonstrate that the suggested control system outperforms the traditional second-order sliding mode controller with a fixed sliding surface.

2. Design of Proposed SOSM Controller

The SOSM control method offered here is a variant of the SOSM control algorithm described in [18]. The control design process has two steps. In the first stage, a customised SOSM controller is developed using iterative iterations of the SOSM technique [25], and a thorough mathematical analysis is performed too though. The second phase presents a comprehensive simulation strategy for the suggested SOSM algorithm.

2.1 Brief Description of SOSM

For instance, consider the nonlinear dynamical system.

$$\dot{x} = f(t,x) + g(t,x)U, s = s(t,x) \tag{1}$$

where the system's real state is $x \in \mathbb{R}^n$ and the input being utilised to influence it is $U \in \mathbb{R}$. The two Smooth functions, f(t, x) and g(t, x), together produce the sliding variable, $s \in \mathbb{R}$. It is presumable that the other two sliding variables, s and s, are known. In regard to the controller U, one obtains if one assigns the sliding variable s a relative degree of r=2.

$$\ddot{s} = a(t,x) + b(t,x)U \tag{2}$$

where $a(t,x) = \ddot{s}|_{U=0}$and $b(t,x) = \frac{\partial \ddot{s}}{\partial U}$ Two modes exist for the SOSM controller.: U = 1 or U = -1. It is clear from the following relation that the switch μ can be identified [26]:

$$\mu = \frac{1}{2}\left(1 + sign(U)\right) \tag{3}$$

However, it is evident from (3) that the sign function will result in an infinite switching frequency when the sliding variables approach. $\lceil \dot{s} \rfloor^2 + \beta_1 s = 0$. The results indicate that the nonlinear system's high switching frequency precludes the direct implementation of controller (3). Although it is impossible to know how large the range is, the operation frequency can still be limited within it. A hysteresis modulation is one method of doing this. As part of this study, we restate (3) as

$$sat(\lceil \dot{s} \rfloor^2 + \beta_1 s) = \begin{cases} -1, & for\ \lceil \dot{s} \rfloor^2 + \beta_1 s < -1 \\ \lceil \dot{s} \rfloor^2 + \beta_1 s, & for\ -1 < \lceil \dot{s} \rfloor^2 + \beta_1 s < 1 \\ 1, & for\ \lceil \dot{s} \rfloor^2 + \beta_1 s > 1 \end{cases} \tag{4}$$

providing the region indicated by $\Omega = -1 < \lceil \dot{s} \rfloor^2 + \beta_1 s < 1$

This area will no longer be switched after the upgrade is implemented. Because of this adjustment, the SOSM control's infinite switching frequency may be reduced. Eventually, the output voltage error will stabilise where $|\lceil \dot{s} \rfloor^2 + \beta_1 s| < 1$.

It should be noted that the sliding variables will converge to the region $|\lceil \dot{s} \rfloor^2 + \beta_1 s| < 1$. It is simple to acquire that $\dot{s}|\dot{s}| < 1 - \beta_1 s$. If $V(s) = \frac{1}{2} s^2$. A quick computation provides us with $\dot{V}(s) \leq \frac{-\beta_1 s^2 + |s|}{|\dot{s}|}$, this suggests that the sliding variables will eventually converge to the region $s: |s| \leq \frac{1}{\beta_1}$

2.2 SOSM with Time-Varying Sliding Surface

A second-order sliding mode controller in reaching mode that has a fixed sliding surface increases the system's sensitivity to parameter changes. Reduce this sensitivity by cutting down on the time spent in reaching mode. The right value of the sliding surface slope must also be chosen, which is challenging and time-consuming. Sliding surfaces that change over time are preferable than static ones when developing a controller. The method for modifying the sliding surface in real time is thus essential in second-order sliding mode control systems.

Designing an SOSM controller U is now necessary for the output x_1 to follow the desired value $x_{1d.}$ To make the expression easier to understand, we first define $\lceil x \rfloor^{\alpha} = |x|^{\alpha}$ sign (x). The SOSM controller for system (2) is designed as

$$U = -sign(\lceil \dot{s} \rfloor^2 + \beta_1(s, \dot{s}) s) \quad (5)$$

with an appropriately tuned value for $\beta_1(s, \dot{s})$.

In this research, we want to provide a method for controlling a system subject to lumped disturbances $w_1(t)$ and $w_2(t)$ in such a way that the output x_1 closely tracks the target value x_{1d}.

You will have a list of three lemmas to utilise as a launching pad for the controller design that follows at the conclusion of this part.

Lemma 1 (see [21]): The following inequality exists if $p_1 > 0$ and $0 < p_1 \leq 1$:

$$|\lceil x \rfloor^{p_1 p_2} - \lceil y \rfloor^{p_1 p_2}| \leq 2^{1-p_2} |\lceil x \rfloor^{p_1} - \lceil y \rfloor^{p_1}|^{p_2} \forall x, y \in R \quad (6)$$

Lemma 2 (see [18]): Both c and d are thought to be positive numbers. With respect to every positive function, the following inequality appears to apply $\gamma > 0$:

$$|y|^d \leq \frac{c}{c+d} \gamma |x|^{c+d} + \frac{d}{c+d} \gamma^{-\frac{c}{d}} |y|^{c+d} \forall x, y \in R \quad (7)$$

Lemma 3 (see [22]): Assume that p is a real number, where $0 < p < 1$: then one has

$$(|x_1| + \cdots |x_n|)^p \leq |x_1|^p + \cdots |x_n|^p, \forall x_i \in R, i = 1, \ldots, n. \quad (8)$$

To generate SOSM $s = \dot{s} = 0$ in finite time, given the SOSM dynamics (2), the controller (5) must ensure that the output x_1 follows the desired value x_1d.

Assume $y_1 = s$ and $y_2 = \dot{s}$. It is possible to rewrite controller (5) and system (3) as

$$\dot{y}_1 = y_2,\ \dot{y}_2 = a(t, x) + b(t, x) U \quad (9)$$

$$U = -sign(\lceil y_2 \rfloor^2 + \beta_1(y_1, y_2) y_1) \quad (10)$$

respectively. We will demonstrate the finite-time stability of the closed-loop systems (9) and (10) using the approach of adding a power integrator described in [27] and [28]. There will be two steps in the proof. In order to stabilise y_1 to zero, a virtual controller called y_1^* will first be built. To ensure that the state y_2 will track y_1^* in finite time, the real controller U will be created

Step 1: Lyapunov function the one we select is $V_1(y_1) = \frac{2|y_1|^{\frac{5}{2}}}{5}$ The result of taking the derivative of $V_1(y_1)$ is

$$\dot{V}_1(y_1) = \lceil y_1 \rfloor^{\frac{3}{2}} y_2 = \lceil y_1 \rfloor^{\frac{3}{2}} y_2^* + \lceil y_1 \rfloor^{\frac{3}{2}} (y_2 - y_2^*) \quad (11)$$

in which y_2^* is a virtual control law. Designing y_2^* so that $y_2^* = -\beta_1(y_1, y_2)^{\frac{1}{2}} \lceil y_1 \rfloor^{\frac{1}{2}}, \beta_1(y_1, y_2) > 0$ produces

$$\begin{aligned} \dot{V}_1(y_1) &= \lceil y_1 \rfloor^{\frac{3}{2}} y_2^* + \lceil y_1 \rfloor^{\frac{3}{2}} (y_2 - y_2^*) \\ &= -\beta_1(y_1, y_2)^{\frac{1}{2}} \lceil y_1 \rfloor^{\frac{3}{2}} \lceil y_1 \rfloor^{\frac{1}{2}} + \lceil y_1 \rfloor^{\frac{3}{2}} (y_2 - y_2^*) \\ &= -\beta_1(y_1, y_2)^{\frac{1}{2}} y_1^2 + \lceil y_1 \rfloor^{\frac{3}{2}} (y_2 - y_2^*) \end{aligned} \quad (12)$$

Step 2: Select a function as

$$V_2(y_1, y_2) = V_1(y_1) + W(y_1, y_2) \quad (13)$$

with $W(y_1, y_2) = \int_{y_2^*}^{y_2} \lceil \lceil k \rfloor^2 - \lceil y_2^* \rfloor^2 \rfloor^2 dk$.

The function $V_2(y_1, y_2)$ is C^1, positive definite, and proper, which may be simply proven. The estimation from (13) is as follows:

$$\dot{V}_2(y_1, y_2) \le -\beta_1(y_1, y_2)^{\frac{1}{2}} y_1^2 + \lceil y_1 \rfloor^{\frac{3}{2}} (y_2 - y_2^*) + \frac{\partial W(y_1, y_2)}{\partial y_1} \dot{y}_1 + \lceil \xi \rfloor^2 \dot{y}_2 \quad (14)$$

with $\xi = \lceil y_2 \rfloor^2 - \lceil y_2^* \rfloor^2$. Then, we give an assessment for each word in the right hand (14).

By using Lemma 1, we are able to

$$\lceil y_1 \rfloor^{\frac{3}{2}} (y_2 - y_2^*) \le |y_1|^{\frac{3}{2}} \left| \lceil y_2 \rfloor^{2 \times \frac{1}{2}} - \lceil y_2^* \rfloor^{2 \times \frac{1}{2}} \right| \le 2^{\frac{1}{2}} |y_1|^{\frac{3}{2}} |\xi|^{\frac{1}{2}} \quad (15)$$

However, with Lemma 2, we have

$$2^{\frac{1}{2}} |y_1|^{\frac{3}{2}} |\xi|^{\frac{1}{2}} \le 2^{\frac{1}{2}} \times \frac{3}{4} \gamma y_1^2 + 2^{\frac{1}{2}} \times \frac{1}{4} \gamma^{-3} \xi^2 \quad (16)$$

Using $2^{\frac{1}{2}} \times \frac{3}{2} \gamma = \frac{\beta_1(y_1, y_2)^{\frac{1}{2}}}{4}$, one get $\gamma = \frac{\beta_1(y_1, y_2)^{\frac{1}{2}}}{3 \times 2^{\frac{1}{2}}}$. The estimation stated below is valid by (15) and (16):

$$\lceil y_1 \rfloor^{\frac{3}{2}} (y_2 - y_2^*) \le \frac{\beta_1(y_1, y_2)^{\frac{1}{2}}}{4} y_1^2 + \left(\frac{3}{\beta_1(y_1, y_2)^{\frac{1}{2}}}\right)^3 \xi^2 \quad (17)$$

Given that $\frac{\partial \lceil y_2^* \rfloor^2}{\partial y_1} = -\beta_1(y_1, y_2)$, it follows from Lemma 1 that,

$$\frac{\partial W(y_1, y_2)}{\partial y_1} \dot{y}_1 \le \left| \lceil y_2 \rfloor^{2 \times \frac{1}{2}} - \lceil y_2^* \rfloor^{2 \times \frac{1}{2}} \right| |\xi| \left| \frac{\partial \lceil y_2^* \rfloor^2}{\partial y_1} y_2 \right| \le 2^{\frac{1}{2}} \beta_1(y_1, y_2) |\xi|^{\frac{3}{2}} |y_2| \quad (18)$$

Since, $|y_2| = |\lceil y_2 \rfloor^2|^{\frac{1}{2}} = |\xi + \lceil y_2^* \rfloor^2|^{\frac{1}{2}} \le (|\xi| + |y_2^*|^2)^{\frac{1}{2}}$, according to the lemma 3 $|y_2| \le |\xi|^{\frac{1}{2}} + |y_2^*|$. As a result, (18) can be rephrased as

$$\frac{\partial W(y_1, y_2)}{\partial y_1} \dot{y}_1 \le 2^{\frac{1}{2}} \beta_1(y_1, y_2) |\xi|^{\frac{3}{2}} \left(|\xi|^{\frac{1}{2}} + |y_2^*| \right) \le 2^{\frac{1}{2}} \beta_1(y_1, y_2) \xi^2 + 2^{\frac{1}{2}} \beta_1(y_1, y_2)^{\frac{3}{2}} |\xi|^{\frac{3}{2}} |y_1|^{\frac{1}{2}} \quad (19)$$

Once more applying Lemma 2, one has

$$2^{\frac{1}{2}} \beta_1(y_1, y_2)^{\frac{3}{2}} |\xi|^{\frac{3}{2}} |y_1|^{\frac{1}{2}} \le 2^{\frac{1}{2}} \beta_1(y_1, y_2)^{\frac{3}{2}} \times \frac{1}{4} \gamma y_1^2 + 2^{\frac{1}{2}} \beta_1(y_1, y_2)^{\frac{3}{2}} \times \frac{3}{4} \times \gamma^{-\frac{1}{3}} \xi^2 \quad (20)$$

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If $2^{\frac{1}{2}}\beta_1(y_1,y_2)^{\frac{3}{2}} \times \frac{1}{4}\gamma = \frac{1}{2}\beta_1(y_1,y_2)^{\frac{1}{2}}$, then $\gamma = \frac{2^{1/2}}{\beta_1(y_1,y_2)}$ follows. By using (20) and a straightforward calculation, it is evident that,

$$2^{\frac{1}{2}}\beta_1(y_1,y_2)^{\frac{3}{2}}|\xi|^{\frac{3}{2}}|y_1|^{\frac{1}{2}} \le \frac{1}{2}\beta_1(y_1,y_2)^{\frac{1}{2}}y_1^2 + \beta_1(y_1,y_2)^{\frac{11}{6}}\xi^2 \quad (21)$$

Putting (21) into (19) results in

$$\frac{\partial W(y_1,y_2)}{\partial y_1}\dot{y}_1 \le \frac{1}{2}\beta_1(y_1,y_2)^{\frac{1}{2}}y_1^2 + (2^{\frac{1}{2}}\beta_1(y_1,y_2) + \beta_1^{\frac{11}{6}})\xi^2 \quad (22)$$

From (14) it may be inferred that by combining (17) and (22)

$$\dot{V}_2\,(y_1,y_2) \le (\frac{27}{\beta_1(y_1,y_2)^{\frac{3}{2}}} + 2^{\frac{1}{2}}\beta_1(y_1,y_2) + \beta_1(y_1,y_2)^{\frac{11}{6}})\xi^2 - \frac{\beta_1(y_1,y_2)^{\frac{1}{2}}}{4}y_1^2\lceil\xi\rfloor^2(a(t,x)+b(t,x)U) \quad (23)$$

In light of the knowledge that $\lceil y_2\rfloor^2 - \lceil y_2^*\rfloor^2 = \lceil y_2\rfloor^2 + \beta_1(y_1,y_2)y_1 = \xi$ and $b(t,x) = \frac{V_{ino}}{L_0C_0}$, putting (12) into (23) results in.

$$\begin{aligned}\dot{V}_2\,(y_1,y_2) \le& -\frac{\beta_1(y_1,y_2)^{1/2}}{4}y_1^2 + (\frac{27}{\beta_1(y_1,y_2)^{3/2}} + 2^{1/2}\beta_1(y_1,y_2) + \beta_1(y_1,y_2)^{11/6})\xi^2 + \xi^2|a(t,x)| \\ &- b(t,x)\lceil\xi\rfloor^2.sign(\xi) \\ \le& -\frac{\beta_1(y_1,y_2)^{1/2}}{4}y_1^2 + (\frac{27}{\beta_1(y_1,y_2)^{3/2}} + 2^{1/2}\beta_1(y_1,y_2) + \beta_1(y_1,y_2)^{11/6})\xi^2 + \xi^2|a(t,x)| \\ &- \xi^2 b(t,x)\end{aligned}$$

Based on condition (9), we are aware that

$$b(t,x) > |a(t,x)| + \frac{27}{\beta_1(y_1,y_2)^{3/2}} + 2^{1/2}\beta_1(y_1,y_2) + \beta_1(y_1,y_2)^{11/6} + \frac{1}{4}\beta_1(y_1,y_2)^{1/2}$$

It suggests that $\dot{V}_2\,(y_1,y_2) \le -\frac{\beta_1(y_1,y_2)^{1/2}}{4}(y_1^2+\xi^2)$. Due to the fact

$$\int_{y_2^*}^{y_2} \lceil\lceil k\rfloor^2 - \lceil y_2^*\rfloor^2\rfloor^2 dk \le |y_2 - y_2^*||\xi|^2 \le 2^{\frac{1}{2}}|\xi|^{\frac{5}{2}}$$

we get

$$V_2(y_1,y_2) \le 2\left(|y_1|^{\frac{5}{2}} + |\xi|^{\frac{5}{2}}\right) \quad (24)$$

By assuming that $c = 2^{-\frac{14}{5}}\beta_1(y_1,y_2)^{\frac{1}{2}}$, $\alpha = \frac{4}{5}$ and applying Lemma 3 and (24), we get $\dot{V}_2\,(y_1,y_2) + cV_2^{\alpha}\,(y_1,y_2) \le 0$. Observe that $0 < \alpha < 1$. According to the finite-time Lyapunov theory described in [29], system (9) can be stabilised globally with controller (10) in a finite amount of time.

2.3 Fuzzy Logic Based Sliding Surface Adjustment of Second Order Sliding Mode Controllers.

A sliding mode controller with a new sliding surface is the method mentioned above. $\lceil\dot{s}\rfloor^2 + \beta_1 s$. However, providing a clear formula to compute the parameter β_1 is challenging. The approximate rule for designing β_1 is derived from the study of the dependence of the system response on the slope β_1. Error convergence is shown to be quicker with the controller with the highest slope β_1 , although tracking accuracy may suffer as a result. The system's performance may degrade significantly or perhaps become unusable if β_1 is set too high. Error convergence time is an important consideration, but monitoring time is also important. This problem may be solved by altering the sliding surface of the second-order sliding mode controller, as shown in Figure 1. Hence, the best solution is to utilize a time-varying slope, which depends on s and $\dot{s}$, ie., $\beta_1(s,\dot{s})$.

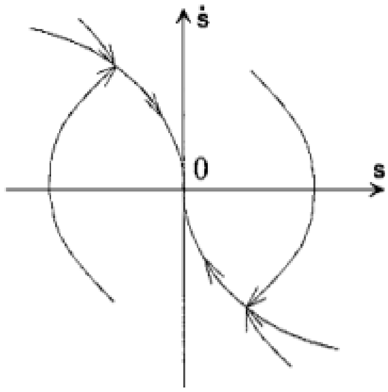

Figure. 1 Movement of Sliding Surface

The stability of a sliding surface depends on its having a positive slope. By regularly updating the slope value with the most recent values of the sliding variable s and its derivative $\dot{s}$, it is feasible to calculate the velocity of a sliding surface". There is a lot of uncertainty in the mathematical models that try to explain the connection between the error factors and the slope of the sliding surface. In order to change the slope of the sliding surface, a single-input single-output fuzzy logic controller may be built using the approximation rules provided by the expert knowledge.

The input to the SISO FLC is the magnitude difference between s and $\dot{s}$, as given by Equation (25). Sliding surface gradient is the result of multiplying FLC output by some output scaling factor.

$$s_d = |s| - |\dot{s}| \quad (25)$$

s_d can have both positive and negative values. To guarantee stability, the FLC's output must, however, always be positive.

As depicted in Figure 2, the input variable s_d is characterized by membership functions representing negative big (NB), negative medium (NM), negative small (NS), zero (ZE), positive small (PS), positive medium (PM), and positive big (PB). Similarly, Figure 3 illustrates the membership functions associated with the output variable, namely very very small (VVS), very small (VS), small (S), medium (M), big (B), very big (VB), and very very big (VVB). This is possible using the rule base presented in Table 1.

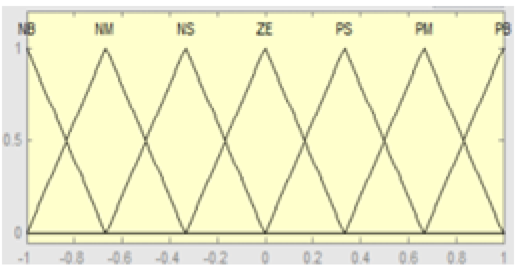

Figure. 2 Input membership functions

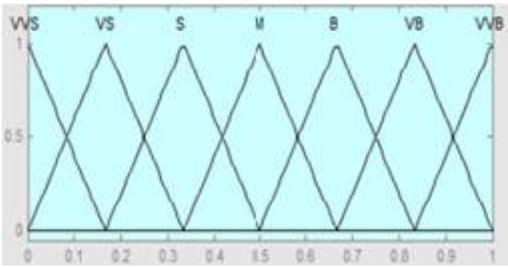

Figure. 3 Output membership functions

Table 1 One-dimensional Fuzzy Rule Base

S_d	NB	NM	NS	ZE	PS	PM	PB
Output	VVB	VB	B	M	S	VS	VVS

Defuzzification can be accomplished using the centroid approach. Figure 4 shows the relationship between a single-input, single-output fuzzy logic controller's input and output.

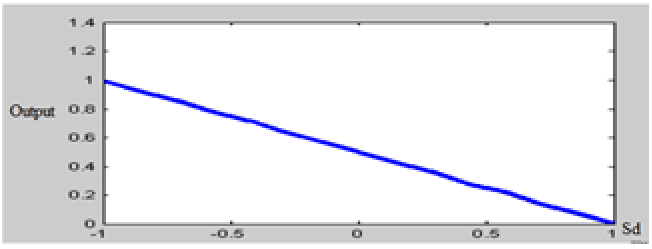

Figure 4. Input-Output Characteristics of Single Input-Single Output FLC

The control strategy can now be illustrated as seen in Figure 5.

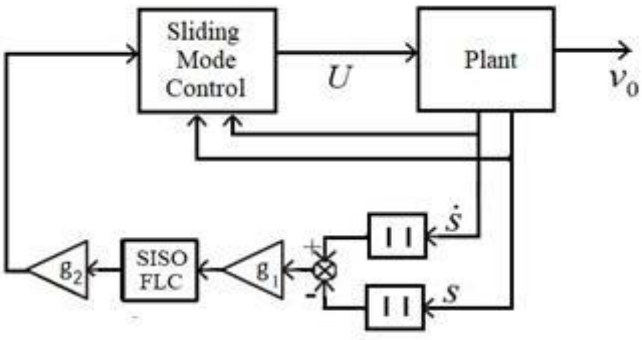

Figure 5. Proposed Control Scheme

3. Results and Discussion

The suggested controller is assessed and contrasted with an ordinary sliding-surface controller using a nonlinear system [18]. The simulation results for the proposed controller and the traditional second-order sliding mode controller with a fixed sliding surface are shown in Figures 6–13. The system's reaction to the proposed controller is contrasted with that of a traditional second-order sliding mode controller, as shown in Figure 6, for different values for β_1. The proposed controller reacts more quickly than the conventional sliding-surface controller.

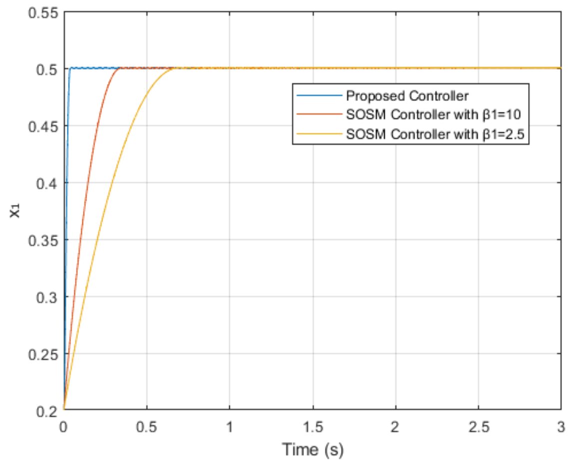

Figure 6. Responses of the Proposed Controller and SOSM Controller with $\beta_1 = 10$ and $\beta_1 = 2.5$

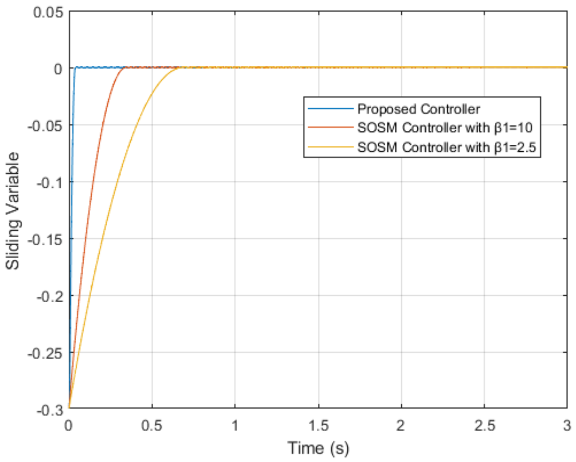

Figure 7. Sliding Variable of the Proposed Controller and SOSM Controller with $\beta_1 = 10$ and $\beta_1 = 2.5$

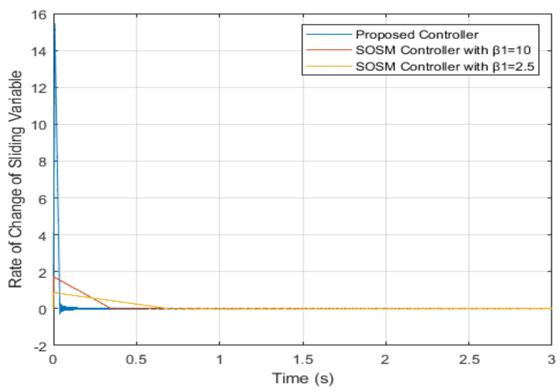

Figure 8. Rate of Change of Sliding Variable of the Proposed Controller and SOSM Controller with $\beta_1 = 10$ and $\beta_1 = 2.5$

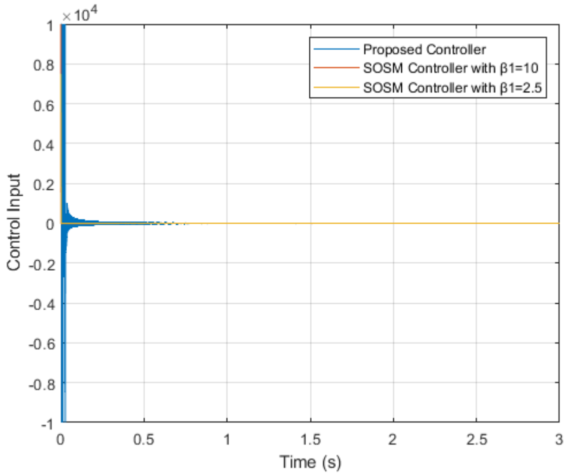

Figure 9. Control Input of the Proposed Controller and SOSM Controller with $\beta_1 = 10$ and $\beta_1 = 2.5$

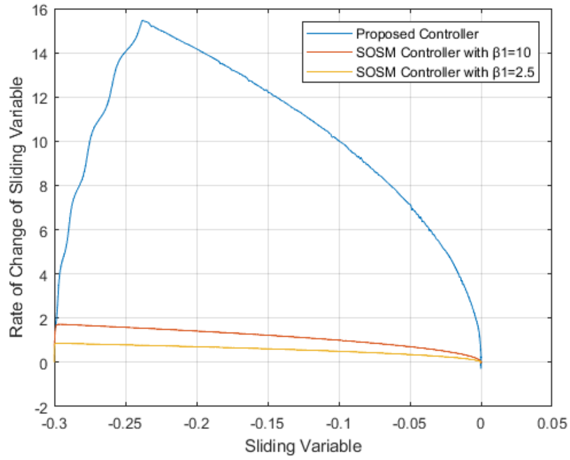

Figure 10. Error Convergence of the Proposed Controller and SOSM Controller with $\beta_1 = 10$ and $\beta_1 = 2.5$

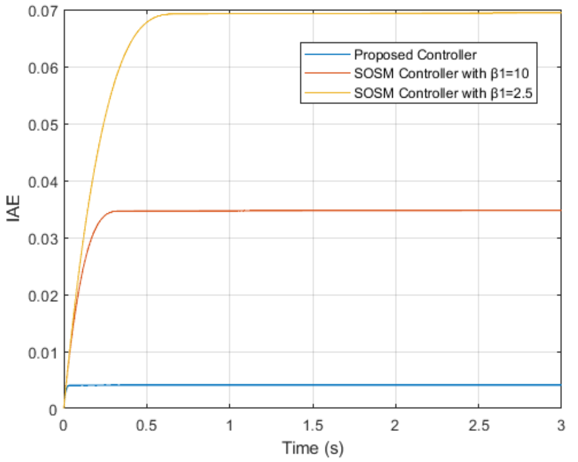

Figure 11. IAE of Sliding Variable of the Proposed Controller and SOSM Controller with $\beta_1 = 10$ and $\beta_1 = 2.5$

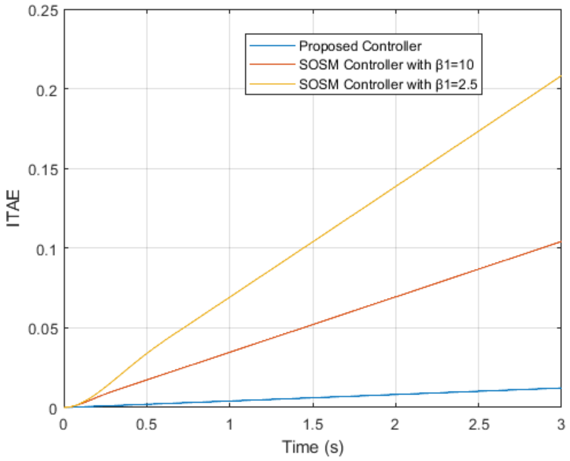

Figure 12. ITAE of Sliding Variable of the Proposed Controller and SOSM Controller with $\beta_1 = 10$ and $\beta_1 = 2.5$

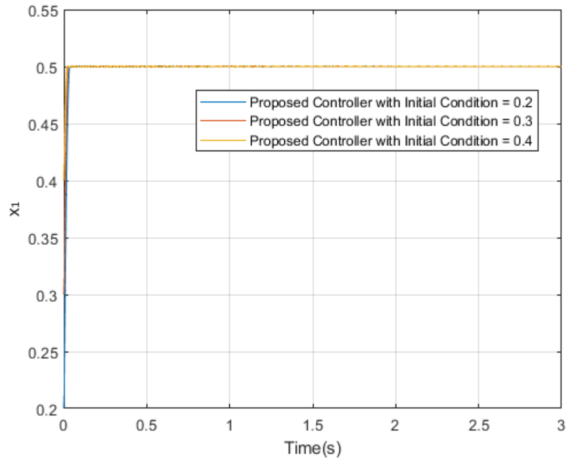

Figure 13. Responses of the Proposed Controller with Various Initial Conditions

Table 2. Performance comparison

Parameter	Proposed Controller	SOSM with β1=10	SOSM with β1=2.5
Rise Time	0.028s	0.238s	0.475s
Settling Time	0.033s	0.285s	0.565s
Peak Time	0.039s	0.347s	0.693s
Peak Overshoot	0	0	0
IAE	0.004	0.035	0.069

ITAE	0.012	0.104	0.208

The suggested controller and the conventional second-order sliding mode controller with β_1=10 and β_1=2.5 had rising times of 0.028s, 0.238s, and 0.475s, and settling times of 0.033s, 0.285s, and 0.565s, respectively. The suggested controller-operated system has a response time to peak value of 0.039s, which is significantly faster than the 0.347s and 0.693s achieved by a typical second-order sliding mode controller with gains of β_1=10 and β_1=2.5, respectively. Overshoot and steady-state error both cancel out to zero in every scenario. Figure 7 depicts the sliding variables. Figure 9 shows how the suggested controller, compared to the conventional second-order sliding mode controller, may deliver a faster response due to the higher control effort in the initial phase. Figure 10 demonstrates that using the suggested technique improves the error convergence rate. Figures 11 and 12 show integral absolute error (IAE) and integral time-weighted absolute error (ITAE) curves, respectively, which show that the suggested controller has a quicker response time. The conventional second-order sliding mode controller with β_1 =2.5, the conventional second-order sliding mode controller with β_1 =10, the IAE indices (0.069, 0.035, and 0.004), and the ITAE indices (0.218, 0.104, and 0.012) for the proposed controller, respectively, confirm the quicker response of the system with the proposed controller. Figure 13 displays the suggested system's reactions for a range of starting points. The suggested technique is superior to the usual method in both speed and robustness, since its effectiveness is unaffected by changes to the beginning circumstances. The performance metrics for the responses are summarised in Table 2.

Simulation findings show that the suggested controller is more responsive than a standard second order sliding mode controller. Dynamic performance is enhanced without compromising on stability, durability, or tracking precision.

4. Conclusion

In this research, an unique fuzzy logic controller for sliding mode control at the second order is developed. It is demonstrated that a fuzzy logic control, by rotating the sliding line in the phase plane, can enhance the controller's dynamic responsiveness. The proposed strategy is demonstrated using simulation results for a dynamically uncertain system. The suggested controller is compared to a conventional sliding mode controller of the second order with a fixed sliding surface using a nonlinear system. Based on simulation results, it can be concluded that the suggested controller improves upon the dynamics and reduces the time required to achieve the mode by a significant margin compared to a second order sliding mode controller with a fixed sliding surface. In addition, the suggested control mechanism is simple, requires less computing time and easy to implement.

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