A Novel Adaptive Super-Twisting Sliding Mode Controller with a Single Input-Single Output Fuzzy Logic Control based Moving Sliding Surface

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Abstract

In this paper, a new approach to the super-twisting sliding mode control of uncertain systems is proposed. The idea behind this control scheme is to utilize an adaptive sliding surface function, in which the slope of the surface is updated on-line using a simple single input-single output fuzzy logic inference system so that the sliding surface is rotated in such a direction that the tracking performance of the system under control is improved. Computer simulations are performed on a system with parameter uncertainties and external disturbances. The results are compared with a conventional super twisting sliding mode controller with a fixed sliding surface. The results have shown the improved performance of the proposed control approach in terms of a decrease in the reaching and settling times and robustness to parameter uncertainties and disturbances as compared to the conventional super-twisting sliding mode controller with a fixed sliding surface. Moreover, the proposed control scheme is very simple and easy to implement.

Keywords: *sliding mode control; super-twisting sliding mode control; chattering; adaptive control; perturbation; uncertainties; fuzzy logic control; sliding surface slope; Lyapunov function; robustness*

1. Introduction

Sliding mode control is a well known control scheme which has been successfully and widely applied for uncertain systems. The reason for this popularity is the attractive features of sliding mode control; it is robust to external disturbances, parameter variations and uncertainties [1-12]. Also, the sliding mode control approach offers a simple algorithm that can be implemented easily. The sliding mode control design consists of two steps: construction of the desired sliding surface and the sliding mode enforcement. The conventional sliding mode controller uses either relay controllers or unit controllers. One of the main disadvantages of these control strategies is that due to the switching and time delays in system dynamics, it is not possible for the system trajectory to reach the ideal sliding mode and therefore a high frequency oscillation called chattering occurs [13-16]. Also, the conventional sliding mode controller with a fixed sliding surface has the disadvantage that when the system states are in the reaching mode, the tracking error cannot be controlled directly and hence, the system becomes sensitive to parameter variations [4, 11, 17-18].

In recent years, the super-twisting sliding mode control theory has become very popular and therefore, it has been studied widely for the control of uncertain systems. It is a second order sliding mode control and allows for finite time convergence of the sliding variable as well as its derivative to zero [19]. Hence, the super-twisting sliding mode controller maintains the distinctive robust features of the sliding mode techniques, while providing a control signal smoother than that obtained through the conventional first order sliding mode controller. Hence, the super-twisting sliding mode control has the advantage of less chattering compared to the sliding mode control. Moreover, super-twisting sliding mode control method offers a simple algorithm for easy implementation as it does not require the derivatives of sliding surface function compared to the second order sliding mode controllers [19]. However, super-twisting sliding mode controller with a fixed sliding surface has the disadvantage that the system becomes sensitive to parameter variations when the system states are in reaching mode. This sensitivity can be minimized if the reaching mode duration is minimized. Moreover, it is tedious to find the optimum value of the sliding surface slope and it is a complicated task. A successful sliding surface design method for improving the controller performance is to use time varying sliding surfaces instead of constant ones. Thus, the method of adjusting sliding surface online is an important matter in the super-twisting sliding mode controlled systems.

During the past several years, fuzzy logic control has emerged as one of the most powerful approach for the control of uncertain systems. The main feature of fuzzy logic is its capacity to deal with imprecision, uncertainty, partial truth, and approximation to achieve tractability, robustness and low cost solution. The design of fuzzy logic controller does not require the exact mathematical model of the system; they are usually designed based on expert knowledge of the system [7, 11, 15, 17, 18, 20]. Recently, fuzzy logic control has been widely used for sliding surface adjustment of the conventional first order sliding mode controllers to improve the dynamic performance and robustness [11, 17, 18, 20]. In this paper, a new super-twisting sliding mode control scheme using a single input-single output fuzzy logic control based sliding surface adjustment is presented. The main advantage of the proposed control scheme is that the slope of the sliding surface is adjusted online according to the values of the error variables, and the sliding surface moves in clockwise or anti-clockwise direction to achieve the desired performance. As the slope change is computed by a single input-single output fuzzy logic control method using one dimensional rule base, the algorithm is very simple and the computation time is very less. The computer simulation results are presented to illustrate the effectiveness and robustness of the proposed control scheme over the conventional super-twisting sliding mode controller with a fixed sliding surface.

The remainder of this paper is organized as follows. The super-twisting sliding mode control is described in Section 2. The super-twisting sliding mode controller with fuzzy logic based adaptive sliding surface is proposed in Section 3. In Section 4, adaptive super-twisting sliding mode control with a single input-single output fuzzy logic control based sliding surface is proposed. Section 5 presents the simulations to demonstrate the effectiveness of the proposed control scheme. Finally, the concluding remarks are presented in Section 6.

2. Super-twisting Sliding Mode Control

Super-twisting Sliding Mode algorithm (STA) is a second order Sliding Mode Control algorithm which is a unique absolutely continuous Sliding Mode algorithm, ensuring all the main properties of first order sliding mode control for the systems with Lipschitz matched uncertainties with bounded gradients and eliminates the chattering phenomenon [19, 21]. Unlike other second order sliding mode control algorithms, super-twisting algorithm does not require the knowledge of the values of the derivatives and the knowledge of the perturbation.

The work presented by Moreno and Osorio proposed a quadratic like Lyapunov functions for the Super-twisting Sliding Mode controller, making it possible to obtain an explicit relation for the controller design parameters [21].

The super-twisting sliding mode controller for perturbation and chattering elimination is given by

$$v = -\alpha\sqrt{|\sigma|}\, sign(\sigma) - \int_0^t \beta\, sign(\sigma)dt \tag{1}$$

$$\alpha > \sqrt{32\delta},\;\; \beta > 5\delta \tag{2}$$

where σ is the sliding surface and the unknown perturbation function f is such that

$$\left|\frac{d}{dt}f(X,t)\right| \le \delta \tag{3}$$

Consider an uncertain linear time-invariant system

$$\dot{X} = AX + B\big(u + f(X,t)\big) \tag{4}$$

where f is an absolutely continuous uncertainty/disturbance in Equation (4).

Assume that rank of B is m and the system is controllable and the function f and its gradients are bounded by known continuous functions almost everywhere. Then the linear transformation

$\begin{bmatrix}\eta \\ \xi\end{bmatrix} = TX$, T=$\begin{bmatrix}B^+ \\ B^-\end{bmatrix}$, $B^+ = (B^TB)^{-1}B^T, B^-B = 0$ brings Equation (4) to regular form given

by Equation (5).

$$\dot{\eta} = A_{11}\eta + A_{12}\xi\,, \quad \dot{\xi} = A_{21}\eta + A_{22}\xi + u + \tilde{f}(\eta,\xi\,,t) \tag{5}$$

The idea of sliding mode control is to design the sliding variable

$$\sigma = \xi + \lambda\eta \tag{6}$$

such that when the motion is restricted to the manifold s=0, the reduced order model has the required performance. The equivalent controller [19] is

$$u = -\big(A_{21}+A_{22}\lambda - \lambda(A_{11} + A_{12}\lambda)\big)\eta - (A_{22} - \lambda A_{12})\sigma + v \tag{7}$$

The super-twisting sliding mode control can be obtained by using Equations (1) and (2) in Equation (7).

3. Super-twisting Sliding Mode Controller with Fuzzy Logic based Adaptive Sliding Surface

Many researchers combined the attractive features of sliding mode control and fuzzy logic control (FLC) to introduce a sliding mode control based on fuzzy varying sliding surface to improve the dynamic performance and robustness [11, 17, 18, 20]. Motivated by this, it seems that fuzzy logic control can be used for sliding surface slope adjustment of super-twisting sliding mode control to improve its dynamic performance and robustness.

Consider the sliding surfaces of the super-twisting sliding mode controller given in Figure 1. It is clear that the controller with minimum sliding surface slope leads to slower error convergence and longer tracking time, whereas the controller with maximum slope leads to faster error convergence, but at the cost of degrading the tracking accuracy. Therefore, there is a trade-off between tracking time and error convergence time. The rotation of the sliding surface of super-twisting sliding mode controller can be achieved if the value of its slope $\lambda(t)$ is updated according to the values of the error $e(t)$ and its derivative $\dot{e}(t)$ with a condition that the positiveness of the slope must be preserve for ensuring the stability.

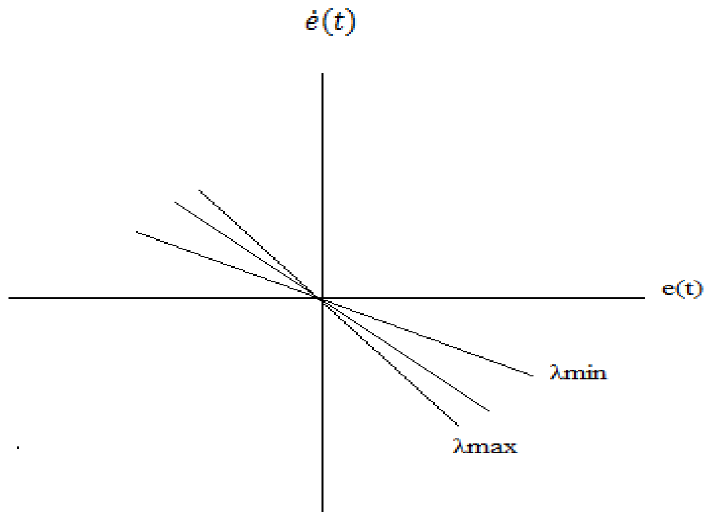

Figure 1. Adaptive Sliding Surfaces

The slope of the sliding surface of super-twisting sliding mode controller can be computed by fuzzy logic inference system with $e(t)$ and its derivative $\dot{e}(t)$ as inputs and $\lambda(t)$ as output using the same method of sliding surface slope adjustment of sliding mode controller proposed by Yagiz and Hacioglu [20]. Assume that error $e(t)$ and its derivative $\dot{e}(t)$ of super-twisting sliding mode controller are scaled down to unit range of [-1,1] before applying them as fuzzy inputs to fuzzy logic controller. The inputs to FLC can take negative and positive values, but the output of the FLC must be positive due to the stability requirement. Hence, the rule base of the fuzzy logic controller plays a very important role and should be constructed so as to improve the performance of the system. The membership functions for the inputs $e(t)$ and $\dot{e}(t)$ are defined by fuzzy linguistic variables negative big (NB), negative medium (NM), negative small (NS), zero (ZE), positive small (PS), positive medium (PM), positive big (PB) as shown in Figure 2, and that for the output, sliding surface slope $\lambda(t)$ are represented by 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 3. The rule base is given in Table 1. The two dimensional fuzzy rule has 49 rules. When the representative point falls into the second and fourth of Figure 1, the rules are in such a manner that the sliding surface of the super-twisting sliding mode controller moves in clockwise direction. When the representative point falls into first and third quadrants, the rules rotate the sliding surface of the controller in counter clockwise direction. Hence with this type of rule base, there is no need to shift the sliding surface up or down to make the representative point fall into second and fourth quadrants so that the time required to reach the sliding surface is reduced. However, the disadvantage of this strategy is that the rule base and computation time are considerably large.

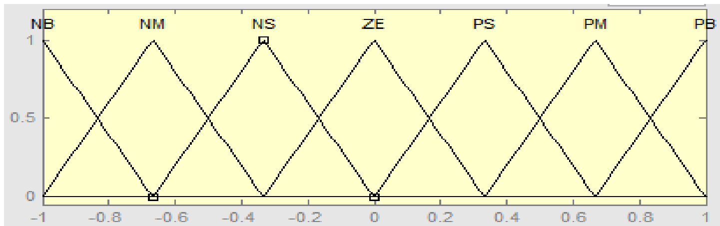

Figure 2. Input Membership Functions

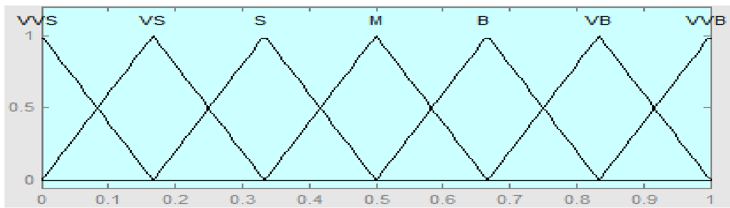

Figure 3. Output Membership Functions

Table 1. Two Dimensional Fuzzy Rule Base

e(t)/ $\dot{e}(t)$	NB	NM	NS	ZE	PS	PM	PB
NB	M	B	VB	VVB	VB	B	M
NM	S	M	B	VB	B	M	S
NS	VS	S	M	B	M	S	VS
ZE	VVS	VS	S	M	S	VS	VVS
PS	VS	S	M	B	M	S	VS
PM	S	M	B	VB	B	M	S
PB	M	B	VB	VVB	VB	B	M

4. Adaptive Super-twisting Sliding Mode Control with a Single Input-Single Output Fuzzy Logic Control based Sliding Surface

Komurcugil [18] proposed a very effective method for converting two dimensional rule base of Table 1 into one dimensional rule base. We propose to extend the same method for sliding surface slope adjustment of super-twisting sliding mode control.

From a careful observation of the rule base for sliding surface slope adjustment of the super-twisting sliding mode controller given in Table 1, it can be observed that the rules in each quadrant are mirror images of the rules in the adjacent quadrants This property can be made use to reduce rule base to one dimensional rule base with absolute magnitude difference between fuzzy inputs of error e(t) and its derivative $\dot{e}(t)$ forming a single input and slope of super-twisting sliding mode controller $\lambda(t)$ as the output [18]. We define a new variable $e_d(t)$ which is the magnitude difference in error variables given by Equation (8)

$$e_d(t) = |e(t)| - |\dot{e}(t)| \quad (8)$$

Assume that $e_d(t)$ is scaled down to unit range of [-1,1] before applying it as fuzzy input to fuzzy logic controller. The membership functions for the input are represented by negative big (NB), negative medium (NM), negative small (NS), zero (ZE), positive small (PS), positive medium (PM), positive big (PB) as shown in Figure 2, and those of output $\lambda(t)$ are very very big (VVB), very big (VB), big (B), medium (M), small (S), very small (VS), very very small (VVS) as shown in Figure 3. The one dimensional rule base to compute slope $\lambda(t)$ is given in Table 2. The centroid method can be used for defuzzification. Obviously, the calculation of the sliding surface slope of the super-twisting sliding mode controller is less complicated compared to the case of having a two dimensional rule base.

Table 2. One Dimensional Fuzzy Rule Base

$e_d(t)$	NB	NM	NS	ZE	PS	PM	PB
$\lambda(t)$	VVB	VB	B	M	S	VS	VVS

The proposed controller is the super-twisting sliding mode controller given by Equation (1) with adaptive sliding surface, varying based on the error variables. Polyakov and Poznyak [9] proposed the condition for the stability of the super-twisting sliding mode controller with a fixed sliding surface as given in Equation (2). Since the sliding surface of the proposed controller is time-varying, the positiveness of the sliding surface slope $\lambda(t)$ must be preserved for ensuring the stability. Hence, the parameters of the proposed controller can be designed so that they satisfy Equation (9).

$$\alpha > \sqrt{32\delta}, \beta > 5\delta, \lambda(t) > 0 \tag{9}$$

5. Simulations

5.1. Model Description

A mass-spring-damper system consists of two masses, three springs, one damper as shown in Figure 4. The dynamics of the system is

$$\dot{x}_1(t) = x_2(t) \tag{10}$$

$$\dot{x}_2(t) = -\frac{(K_1+K_2)}{M_1}x_1(t) + \frac{K_2}{M_1}x_3(t) + \frac{1}{M_1}F(t) \tag{11}$$

$$\dot{x}_3(t) = x_4(t) \tag{12}$$

$$\dot{x}_4(t) = \frac{K_2}{M_2}x_1(t) - \frac{(K_2+K_3)}{M_2}x_3(t) - \frac{B}{M_2}x_4(t) \tag{13}$$

where $x_1(t)$ and $x_3(t)$ are the positions and x_2 (t) and $x_4(t)$ the velocities of masses M_1 and M_2 respectively. F(t) is the input force to mass M_1. Nominal values for the parameters are M_1 = 1.28 kg, M_2 = 1.05 kg, K_1 = 190 N/m, K_2 = 780 N/m, K_3 = 450 N/m, B= 15 Ns/m. The control objective is to maintain the position of mass M_1 fixed at $x_1(t) = x_{1d}$ despite of the behavior of mass M_2, that can be considered as a perturbation. The change of co-ordinates given by Equation (14) brings mass m_1 system to regular form.

$$\eta = \frac{1}{m_1}(x_1 - x_{1d}), \qquad \xi = m_1 x_2 \tag{14}$$

5.2. Control Design

The linear sliding surface given by Equation (15) is selected so that the equilibrium point will be reached exponentially fast, and with a desired performance.

$$\sigma = \xi + \lambda\eta \tag{15}$$

The equivalent control is

$$u = -\frac{\lambda}{M_1^2}(-\lambda\eta + \sigma) + K_1 M_1 \eta + K_1 x_{1d} + v \tag{16}$$

where v is the super-twisting control given by Equation (1).

The upper bound of the derivative of the perturbation is

$$\delta = \mathrm{K}_2(|\mathrm{x}_{4\max}| + |\mathrm{x}_{2\max}|) \tag{17}$$

By detailed analysis and simulation of the system, it is found that $|\mathrm{x}_{4\max}| = |\mathrm{x}_{2\max}| =$ 0.02 m/s. Hence the controller gains are selected as α = 40 and β = 200 so that they satisfy Equation (9). The sliding surface slope of the proposed controller is computed online using single input-single output fuzzy logic controller as explained in Section 4. The input and output scaling factors of fuzzy logic controller are 100 and 3.9 respectively.

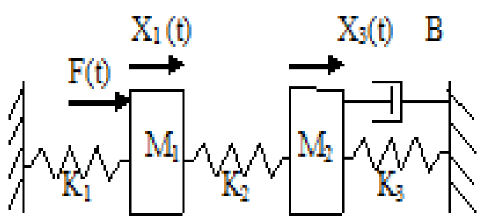

Figure 4. Mass-Spring-Damper System

5.3. Simulation Results

For comparison, two different controllers are simulated using Matlab, the proposed adaptive super-twisting sliding mode controller using fuzzy logic based adaptive sliding surface and the super-twisting sliding mode controller with a fixed sliding surface slope λ=1.95 (the steady-state value of the sliding surface slope for the proposed controller). For the simulations, at time t=0, a reference position x_{1d}=0.01 m is demanded. The simulation results are given in Figure 5 to Figure 10. The performance measures such as steady-state error, time taken for the output to reach 90% and 100% of the steady-state value, percentage overshoot and integral of time multiplied absolute error (ITAE) are used to compare the performances of the controllers. The comparison is given in Table 3. In case of the proposed controller, the time taken to reach 90% of the steady-state value is 1.75 s, and that for the steady-state value is 2.27 s, whereas in case of the conventional super-twisting sliding mode controller with a fixed sliding surface, they are 1.84 s and 4.77 s respectively. The overshoot and steady-state error are zero in both the cases. The integral of time multiplied absolute error (ITAE) for the proposed controller and the conventional super-twisting sliding mode controller with a constant sliding surface are 0.0064 and 0.0083 respectively. From the comparison, it is clear that both the controllers are able to achieve the objective, but the proposed controller exhibits fast dynamic response and it can be considered as an indication of shortening the reaching mode time, thereby improving the robustness compared to super-twisting sliding mode controller with a constant sliding surface.

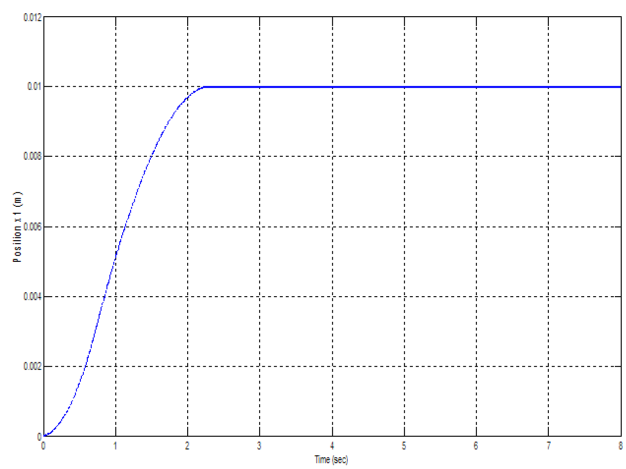

Figure 5. Position of Mass M_1 using the Proposed Controller

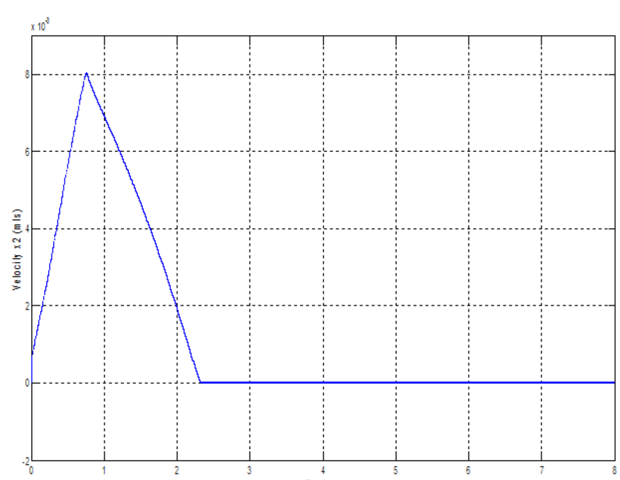

Figure 6. Velocity of Mass M_1 using the Proposed Controller

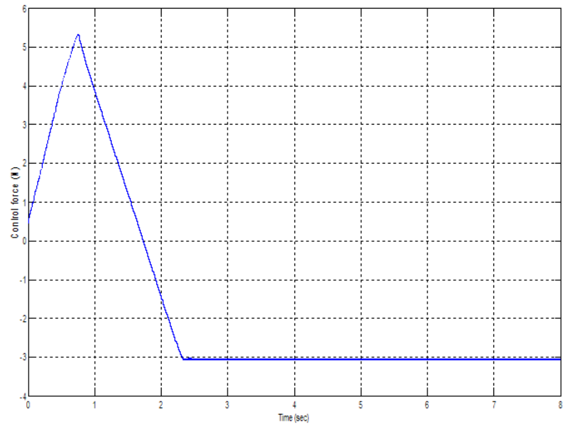

Figure 7. Control Force of Mass M_1 using the Proposed Controller

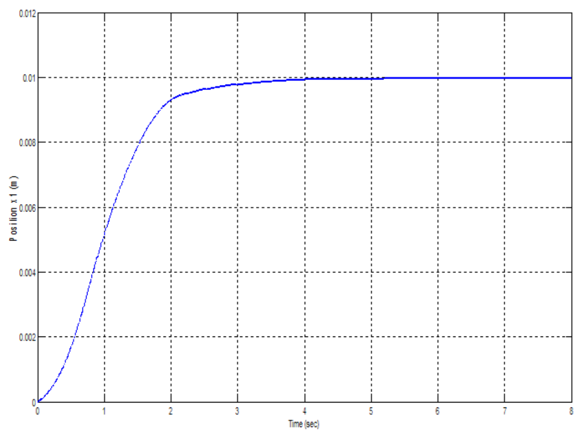

Figure 8. Position of Mass M_1 using the Super-twisting Sliding Mode Controller with a Fixed Sliding Surface

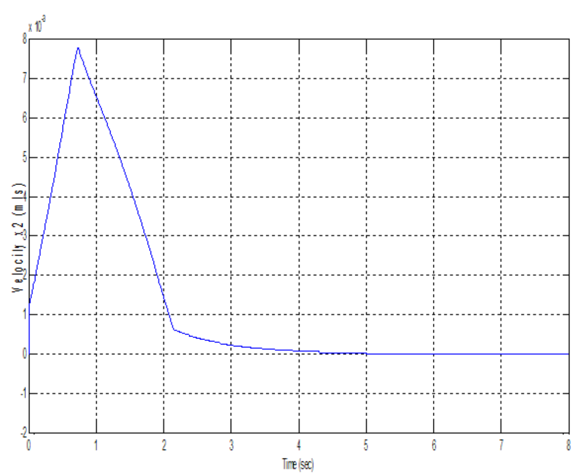

Figure 9. Velocity of Mass M_1 using the Super-Twisting Sliding Mode Controller with a Fixed Sliding Surface

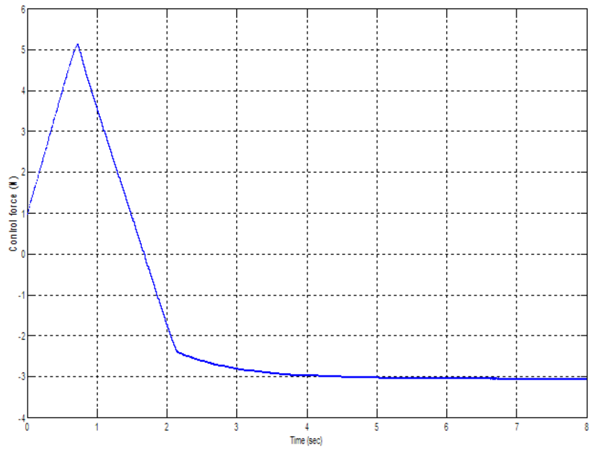

Figure 10. Control Force of Mass M_1 using the Super-Twisting Sliding Mode Controller with a Fixed Sliding Surface

Table 3. Comparison of the Performances of Controllers

Output	Proposed Controller	Super-twisting sliding mode controller with a fixed sliding surface
Time taken to reach 90% of the steady-state value (s)	1.75	1.84
Time taken to reach the steady-state value (s)	2.27	4.77
Percentage overshoot	0	0
Steady-state error	0	0
IATE	0.0064	0.0083

To study the robustness of the proposed controller, the parameter variations in the form of changes in spring constant of K_1 of the system are considered. The responses of the system using the proposed controller and the conventional super-twisting sliding mode controller with a fixed sliding surface for K_1 = 150 N/m are given in Figure 11 and Figure 12 respectively. In case of the proposed controller, the time taken to reach 90% of the steady-state value and is 1.99 s, and that for the steady-state value is 5.35 s, whereas in case of the conventional super-twisting sliding mode controller with a fixed sliding surface, they are 2.18 s and 5.7 s respectively. The overshoot and steady-state error are zero in both the cases. The integral of time multiplied absolute error (ITAE) for the proposed controller and the conventional super-twisting sliding mode controller with a fixed sliding surface slope are 0.01 and 0.012 respectively. Both the controllers are able to reject the effect of parameter variation without any overshoot, but the proposed controller shows faster response. The responses of the system using the proposed controller and the conventional super-twisting sliding mode controller with a fixed sliding surface for K_1 = 230 N/m are given in Figure 13 and Figure 14 respectively. In case of the proposed controller, the time taken to reach 90% of the steady-state value is 1.7 s, and that for the steady-state value is 4.7 s, whereas in case of the conventional super-twisting sliding mode controller with a fixed sliding surface, they are 1.74 s and 5.6 s respectively, the overshoots are 9.45% and 10.1% respectively. The steady-state errors are zero in both the cases. The integral of time multiplied absolute error (ITAE) for the proposed controller and the conventional super-twisting sliding mode controller with a fixed sliding surface are 0.009 and 0.0098 respectively. Again, the proposed controller outperforms the conventional controller with less overshoot and faster dynamics. The comparison of the performances of the controllers for different variations of K_1 is given in Table 4.

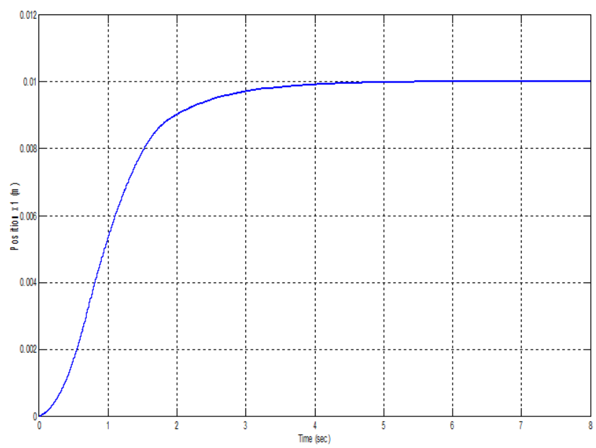

Figure 11. Position of Mass M_1 using the Proposed Controller for Spring Constant K_1 Equal to 150 N/m

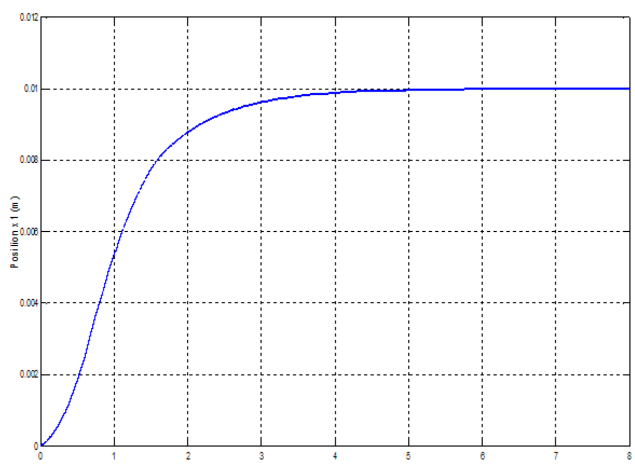

Figure 12. Position of Mass M_1 using the Super-Twisting Sliding Mode Controller with a Fixed Sliding Surface for Spring Constant K_1 Equal to 150 N/m

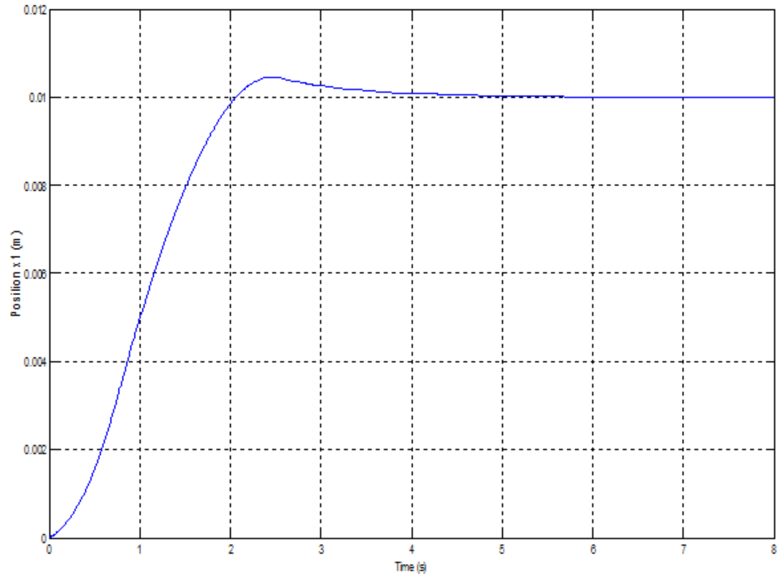

Figure 13. Position of Mass M_1 using the Proposed Controller for Spring Constant K_1 Equal to 230 N/m

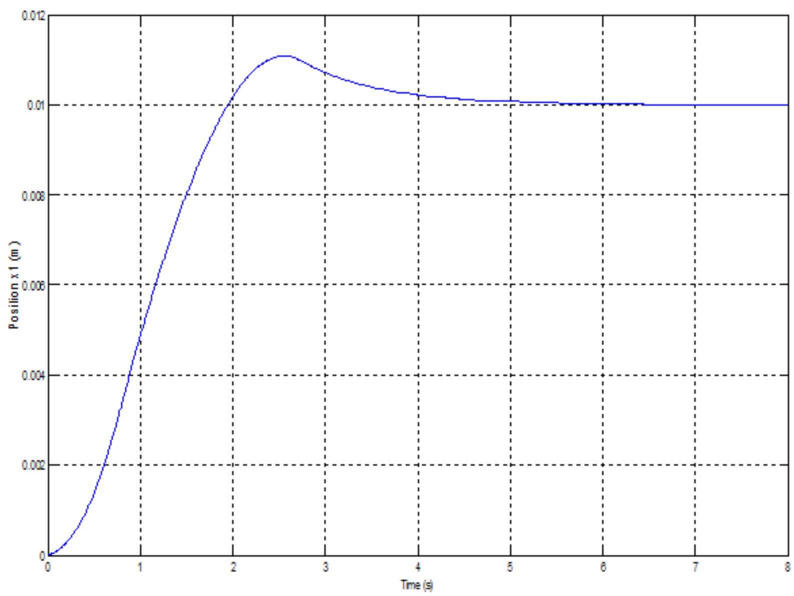

Figure 14. Position of Mass M_1 using the Super-Twisting Sliding Mode Controller with a Fixed Sliding Surface when Spring Constant K_1 Equal to 230 N/m

Table 4. Comparison of the Performances of Controllers for Variations of K_1

Variations of K_1	Output	Proposed Controller	Super-twisting sliding mode controller with a fixed sliding surface
K_1= 150N/m	Time taken to reach 90% of the steady-state value (s)	1.99	2.18
	Time taken to reach the steady-state value (s)	5.35	5.7
	Percentage overshoot	0	0
	Steady-state error	0	0
	IATE	0.01	0.012
K_1 = 230 N/m	Time taken to reach 90% of the steady-state value (s)	1.7	1.74
	Time taken to reach 100% of the steady-state value (s)	4.7	5.6
	Percentage overshoot	9.45	10.1
	Steady-state error	0	0
	IATE	0.009	0.0098

6. Conclusion

In this paper, a new super-twisting sliding mode control using a single input-single output fuzzy logic controller based adaptive sliding surface is proposed. It is shown that the dynamic response and the robustness of the controller can be improved by rotating the sliding line in phase plane by a simple single input-single output fuzzy logic control. The effectiveness of the proposed approach is demonstrated through computer simulations using an uncertain system. The simulation results show that the proposed controller exhibits fast dynamic response and it is an indication of shortening the reaching mode time, thereby improving the robustness compared to super-twisting sliding mode controller with a fixed sliding surface. The robustness of the proposed controller is studied for parameter variations. The results show that the proposed controller outperforms the conventional super-twisting sliding mode control with a fixed sliding surface in terms of improved dynamic response and robustness. Moreover, the proposed control scheme is very simple and easy to implement.

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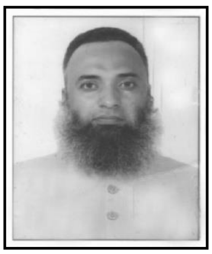

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