Soft Computing Based Sliding Surface Adjustment of Second Order Sliding Mode Controllers: An Application to Ship Steering Model

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Abstract

This work introduces a novel second-order sliding mode (SOSM) controller for the control of dynamic uncertain systems based on fuzzy logic. An efficient sliding surface design approach for improving controller performance is to use time-varying sliding surfaces. The proposed controller incorporates second-order sliding mode control, fuzzy logic control, and adaptive control benefits. The proposed controller ensures the system's reaching conditions, stability, and robustness. The proposed controller is also well-suited for straightforward design and implementation. In order to rotate the sliding surface in a way that improves the tracking performance of the system under control, this control strategy uses a time-varying slope in the sliding surface function and a straightforward two-input single-output fuzzy logic controller. The proposed controller is studied with a ship steering model in comparison with a conventional second-order sliding mode controller with a fixed sliding surface. Simulations of the ship steering system using MATLAB/SIMULINK show that the proposed controller outperforms the typical second-order sliding mode controller.

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

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1.Introduction.

A well-known control strategy that has been effectively and frequently used for dynamic uncertain systems is sliding mode control. The appealing characteristics of sliding mode control, which are resistant to external disturbances, parameter violations, and uncertainties, are the cause of this popularity. The sliding mode control approach also provides a straightforward algorithm that is simple to use. The building of the desired sliding surface and the enforcement of the sliding mode make up the two steps of the sliding mode control design. Either relay controllers or unit controllers are employed by the traditional sliding mode controller. One of the main drawbacks of these control systems is that the system trajectory cannot achieve the ideal sliding mode due to switching and temporal delays in system dynamics, leading to a high-frequency oscillation known as chattering. Additionally, the traditional sliding mode controller with a fixed sliding surface has the drawback that the tracking error cannot be easily regulated when the system states are in the reaching mode, making the system sensitive to parameter changes.

While the system states are in reaching mode, the drawback of a second-order sliding mode controller with a fixed sliding surface is that the system becomes susceptible to parameter fluctuations. If the reaching mode duration is kept to a minimum, this sensitivity can be reduced. Also, determining the sliding surface slope's ideal value is a difficult task that takes a lot of time. Using time-varying sliding surfaces rather than fixed ones is an effective sliding surface design technique for enhancing controller performance. As a result, an important aspect of second-order sliding mode control systems is the technique for modifying the sliding surface online. Fuzzy logic control has become one of the most effective methods for the control of dynamic uncertain systems during the last few years. The ability of fuzzy logic to handle ambiguity, uncertainty, partial truth, and approximation to produce tractable, reliable, and affordable solutions is a key characteristic. Fuzzy logic controllers can be built without having an exact mathematical model of the system because they are often designed using expert knowledge about the system.(Eksin et al., 2002, Pang et al., 2006, Fnaiech et al., 2010, Li et al., 2010) In recent years, fuzzy logic control has been a popular technique for improving the dynamic performance and durability of traditional first-order sliding mode controllers by adjusting the sliding surface. (Eksin et al., 2002, Tokat et al., 2003, Yagiz and Hacioglu 2005, Komurcugil 2012).

Controlling dynamic uncertain systems has also been done using fuzzy logic (FLC) (Smyej et al., 2000, Viswanathan et al., 2002, Qiao et.al., 2003, Tokat et al., 2003, Kuo et.al., 2005, Pang et.al., 2006, Lin et al., 2006, Abiyev, R.H., and Kaynak, O., 2008, Fnaiech et al., 2010, Dianwei et al., 2010, Li et al., 2010, Li, T.H.S. and Huang, Y.C., 2010) Nonlinear time-variant systems are well suited to fuzzy controllers since they don't require a precise mathematical model of the system being governed. They are typically created using knowledge about the system obtained from experts, and they have proven to be a useful method for overcoming the challenges associated with locating mathematical models of systems with complicated dynamics and unforeseen perturbations. The drawback is that the design needs substantial tuning based on a trial-and-error approach. This fine-tuning can take a lot of time. Furthermore, it is difficult to predict the reaction of a system with a fuzzy controller (Dianwei et al., 2010).

This work presents a novel second-order sliding mode control system based on a two-input single-output fuzzy logic control. The primary benefit of the suggested control strategy is that, in order to achieve the required performance, the sliding surface's slope can be changed online in accordance with the values of the error variables. The sliding surface can also move in either a clockwise or anticlockwise direction. The methodology is quite straightforward, and the computation time is very short because the slope change is calculated using a two-input single-output fuzzy logic control method. The effectiveness and reliability of the suggested control technique over the traditional second-order sliding mode controller with a fixed sliding surface are demonstrated through computer simulation results.

2. Proposed SOSM Controller

The second-order sliding mode control scheme is a useful control method that effectively gets rid of the chattering effect of the traditional sliding mode control method without sacrificing tracking performance or durability. Yet, the sliding surface has a significant impact on how well the second-order sliding mode control works. Second-order sliding mode control can reduce the chattering effect without decreasing the transient response, steady-state response, or robustness if the sliding surface is constructed properly. If the sliding surface is not appropriately developed, it could have unfavourable impacts on the reaction. Finding the ideal sliding surface, however, is a difficult challenge. The use of a time-varying sliding surface rather than a constant one is an effective sliding surface design technique for enhancing the performance of the controller. This can be accomplished by utilizing a controller that can online update the slope of the sliding surface based on error variables. Although there is no precise mathematical model that explains the connection between the sliding surface slope and error variables, it is possible to create it with certain approximations. The update of the sliding surface slope depending on error variables can be done by utilizing a fuzzy logic controller because it is a suitable technique for managing the system using some approximations rules.

This study demonstrates the use of fuzzy logic in the construction of a second-order sliding mode controller for dynamic uncertain systems using the example of controlling a ship steering model.

2.1 Brief Description of SOSM

Take the nonlinear dynamical system, for instance.

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

where the system state and the control input, respectively, are represented by $x \in \mathbb{R}^n$ and $U \in \mathbb{R}$. Smooth functions are $f(t, x)$ and $g(t, x)$, and the output is $s \in \mathbb{R}$ (Sliding Variable). It is assumed that the sliding variables s and $\dot{s} = ds/dt$ are known. If the sliding variable s is assumed to have a relative degree of $r=2$ with regard to the controller U, one has

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

where $a(t,x)=\ddot{s}|_{U=0}$ and $b(t,x)=\frac{\partial \ddot{s}}{\partial U}$.

The SOSM controller for system (2) is designed as

$$U = -sign([\dot{s}]^2 + \beta_1 s) \quad (3)$$

2.2. SOSM with a Fuzzy Logic Based Varying Sliding Surface

The proposed controller has a varying sliding surface in which the slope of the surface varies with the s and $\dot{s}$. However, there is no clear formula relating them, but the slope must be varied based on the approximate rule that the slope is rotated in the direction to improve dynamic performance. Fuzzy logic systems allow approximate reasoning for decision-making where knowledge is imprecise or approximate. Hence, we propose a two-input single-output fuzzy logic controller for the sliding surface slope adjustment. Figure 1 shows the block diagram of the proposed controller.

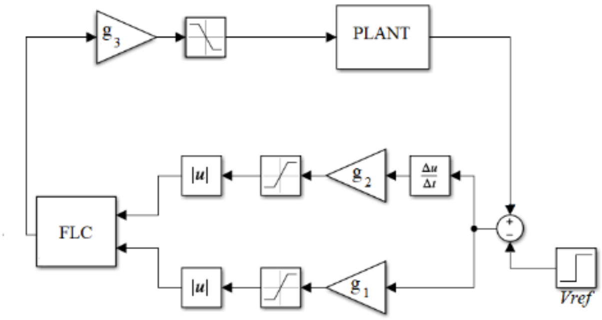

Fig.1. Proposed Control Scheme

The SOSM controller has two modes: $U = 1$ or $U = -1$. However, it is evident from (3) that the sign function will result in an endless switching frequency whenever the sliding variables reach $[\dot{s}]^2 + \beta_1 s = 0$. This suggests that the switching frequency is too high for the controller (3) to be implemented directly for the buck converter. Although it is impossible to know how large the range is, the operation frequency can still be limited within it. This can be achieved via a hysteresis modulation, much like (Tan et al., 2005). The switch μ is clearly determined by the following relationship.

$$\mu = \begin{cases} 1, & \text{when } [\dot{s}]^2 + \beta_1 s < -\lambda \\ -1, & \text{when } [\dot{s}]^2 + \beta_1 s > -\lambda \\ unchanged, & \text{otherwise} \end{cases}$$

where λ is a small number, providing the region indicated by

$$\Omega = \{-\lambda < [\dot{s}]^2 + \beta_1 s < \lambda\}$$

The above algorithm is a sliding mode controller with a new sliding surface $[\dot{s}]^2 + \beta_1 s$ and boundary layer λ. 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. It is found that the controller with maximum slope β_1 leads to faster error convergence, but the tracking accuracy can be degraded. If the value of β_1 is too high, it can cause large overshoot in the system states and may lead to unacceptable performance. Therefore, there is a trade-off between error convergence time and tracking time. This can be rectified by moving the sliding surface of the second order sliding mode controller, as illustrated in figure 2. Hence, the best solution is to utilize a time-varying slope, which depends on s and $\dot{s}$, ie., $\beta_1(s, \dot{s})$.

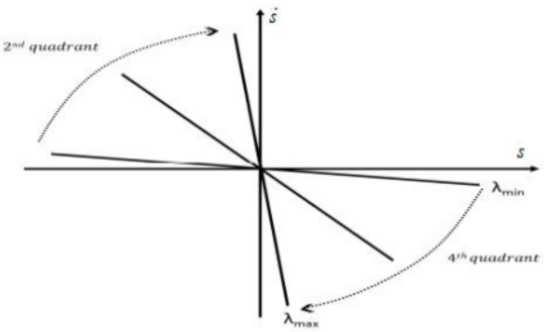

Fig.2. Movement of Sliding Surface

In order to ensure stability, the sliding surface slope must be positive. The movement of the sliding surface can be determined by updating the value of the sliding surface slope online based on the values of the sliding variable s and its derivative $\dot{s}$,. The link between the error variables and the slope of the sliding surface is not exactly modelled mathematically. Therefore, a two-input single-output fuzzy logic controller is created based on the approximation rules produced from the expert knowledge can update the sliding surface slope.

Before applying them to the fuzzy logic controller (FLC), the sliding variable and rate of change of sliding variable are translated to S and $\dot{S}$, which are in the range of [-1,1] using input scaling factors and the saturation function. The scaling factors and saturation ensure that the possible input values are spread within the range [-1, 1]. The sliding surface slope of a second order sliding mode controller is given by the FLC output scaled by an output scaling factor. The fuzzy logic controller's inputs can be both negative and positive. However, the FLC output must always be positive to ensure stability. As a result, inputs are chosen from the range [-1, 1] and outputs are chosen from the range [0, 1]. As shown in Figure 3, the membership functions of the inputs 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 4.

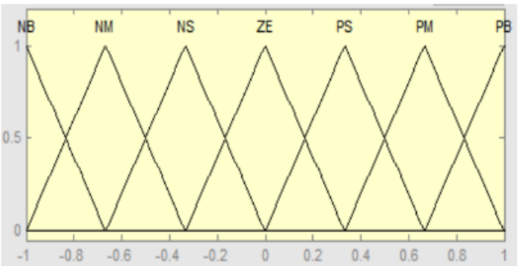

Fig. 3 Input membership functions

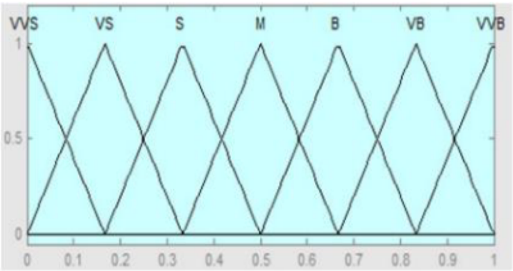

Fig. 4 Output membership functions

The fuzzy logic control (FLC) rule basis should be developed in such a way that the sliding surface is rotated in such a way that the system's performance is improved. Figure 2 shows that when the representative point falls into the second and fourth quadrants, the sliding surface should move in the same direction as the system, i.e., the sliding surface should rotate clockwise. The rule base shown in Table 1 can accomplish this.

Table 1 Two-dimensional Fuzzy Rule base

S $\dot{S}$	NB	NM	NS	ZE	PS	PM	PB
PB	M	B	VB	VVB	VB	B	M
PM	S	M	B	VB	B	M	S
PS	VS	S	M	B	M	S	VS
ZE	VVS	VS	S	M	S	VS	VVS
NS	VS	S	M	B	M	S	VS
NM	S	M	B	VB	B	M	S
NB	M	B	VB	VVB	VB	B	M

Defuzzification can be done using the centroid approach. Figure 5 illustrates the input-output relationship of the fuzzy logic controller with a two-dimensional rule base.

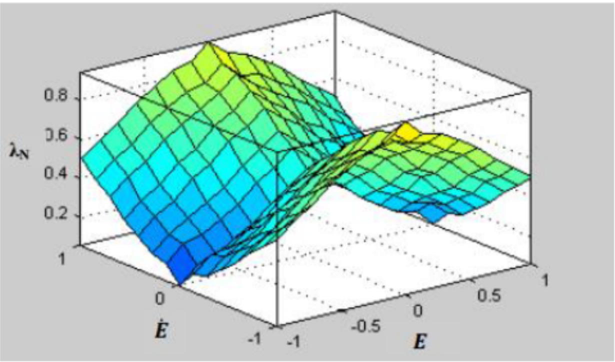

Fig. 5 Input-Output Characteristics of the FLC with Two-dimensional rule base

3. Results and Discussions

The proposed controller is studied in comparison with fixed sliding surface controller for a ship steering model with the following transfer function. (Tzeng et al.,1999)

$$\frac{150s+10}{200s^2+30s+1} \qquad (4)$$

Figures 6 to Figure 10 depict the simulation results of the system responses for the proposed controller and the traditional second-order sliding mode controller with a fixed sliding surface.

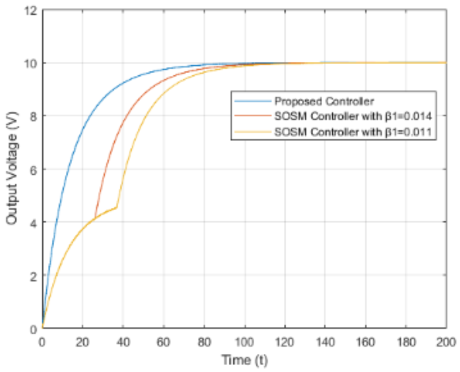

Fig. 6 Responses of the Proposed Controller, SOSM Controller with $\beta_1 = 0.014$ and SOSM Controller with $\beta_1 = 0.011$

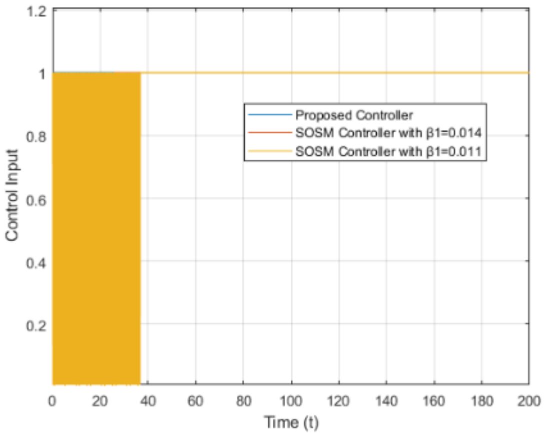

Fig. 7 Control Input of the Proposed Controller, SOSM Controller with $\beta_1 = 0.014$ and SOSM Controller with $\beta_1 = 0.011$

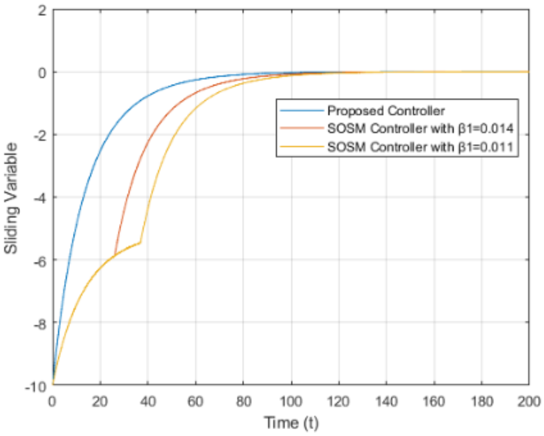

Fig. 8 Sliding Variable of the Proposed Controller, SOSM Controller with $\beta_1 = 0.014$ and SOSM Controller with $\beta_1 = 0.011$

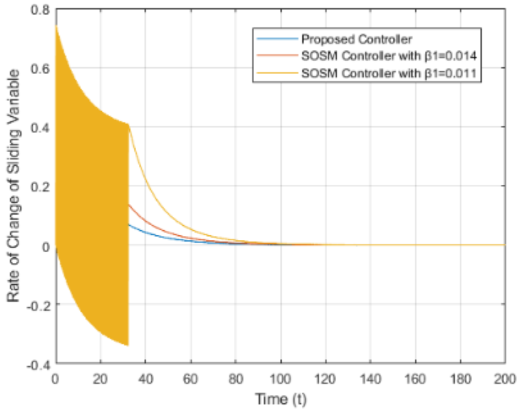

Fig. 9 Rate of Change of Sliding Variable of the Proposed Controller, SOSM Controller with $\boldsymbol{\beta_1 = 0.014}$ and SOSM Controller with $\boldsymbol{\beta_1 = 0.011}$

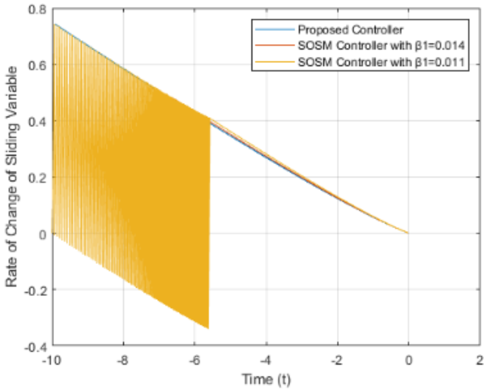

Fig. 10 Error Convergence of the Proposed Controller, SOSM Controller with $\boldsymbol{\beta_1 = 0.014}$ and SOSM Controller with $\boldsymbol{\beta_1 = 0.011}$

Figure 6 depicts the system responses for the proposed controller and the conventional second order sliding mode controller. It is obvious that the proposed controller responds faster than the conventional second-order sliding mode controller with a fixed slope. The proposed controller, the traditional second-order sliding mode controller with $\beta_1 = 0.014$ and the traditional second-order sliding mode controller with $\beta_1 = 0.011$ have rise times of 34 S, 52 S, and 60 S, respectively, and settling times of 66 S, 83 S, and 92 S. The time required for the response to achieve the steady-state value in the system with the proposed controller is 79 S, whereas it is 100 S for the typical second-order sliding mode controller $\beta_1 = 0.014$ and 105 S for the typical second-order sliding mode controller $\beta_1 = 0.011$. The percentage overshoot is zero in all cases. The proposed controller achieves a faster response than the typical second-order sliding mode controller by exerting significantly higher control effort during the first phase, as shown in Figure 7. The IAE indices for the proposed controller and the conventional second-order sliding mode controller with $\beta_1 = 0.014$ and the traditional second-order sliding mode controller with $\beta_1 = 0.011$ are 150, 230, and 310, respectively, whereas the ITAE indices are 30000, 48500 and 62000, confirming the faster response of the system with the proposed controller. Figure 10 shows how the proposed technique achieves faster error convergence. Table 2 summarizes the performance measures for the responses.

Table 2 Performance Comparison

Parameter	**SOSM with β1=0.011**	**SOSM with β1=0.014**	**Proposed Controller**
Rise Time	60 S	52 S	34 S
Peak Time	105 S	100 S	79 S
Peak Overshoot	0	0	0
Settling Time	92 S	83 S	66 S
IAE	310	230	150
ITAE	62000	45800	30000

According to the simulation results, the proposed controller responds more quickly than a traditional second order sliding mode controller. Stability, robustness, and tracking accuracy are not compromised in order to boost dynamic performance.

4. Conclusion

A new second-order sliding mode control based on the fuzzy logic controller is developed in this paper. It is demonstrated that by rotating the sliding line in the phase plane using a fuzzy logic control, the dynamic response of the controller may be improved. The efficiency of the proposed method is proven using simulation results for a dynamic uncertain system. A ship steering model is used to compare the proposed controller to a traditional second-order sliding mode controller with a fixed sliding surface. The simulation findings reveal that the proposed controller has a quick dynamic reaction, which can be interpreted as lowering the reaching mode time and hence boosting the dynamics when compared to a second order sliding mode controller with a fixed sliding surface. Furthermore, the proposed control mechanism is relatively basic, requires little computing time, and is straightforward to implement.

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