Analysis and Design of a Multi-Channel Time-Varying Sliding Mode Controller and its Application in Unmanned Aerial Vehicles

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Abstract: This study introduces a new multi-channel robust nonlinear control algorithm based on the theory of the time-varying sliding mode control (TVSMC) strategy to stabilize the attitude of an unmanned aerial vehicle (UAV) for nuclear decommissioning applications. Since the UAV is subject to constant radiations, its parameters are time-varying and subject to uncertainty all the time. This is especially important in designing sliding mode control as the motion of the control system in the reaching phase can be influenced by environmental disturbances and parameter uncertainties. In this study, a time-varying sliding manifold is proposed to eliminate the reaching phase and to enhance the robust performance. Therefore, a novel type of time-varying sliding surface is introduced based on the initial condition as slope-varying manifold. Then, a procedure for determining the control parameters is investigated. Furthermore, chattering phenomenon can be avoided using two techniques known as boundary layer and continuous SMC. Finally, to highlight the robust performance of the proposed methods, a quadrotor UAV subject to external disturbances and uncertainties is simulated.

Keywords: Sliding mode control, Slope-varying, Time-varying manifolds, Reaching time, Lyapunov stability, Boundary layer, Continuous SMC, Quadrotor UAV.

1. INTRODUCTION

Sliding mode control (SMC) has been recognized as one of the most promising robust nonlinear control methodologies because of its inherent advantages of strong stability, insensitivity to plant parameter variations and environmental disturbances. These properties make it a suitable choice for autonomous operation of robots in hazardous environment with degraded sensors and actuators. The sliding mode control law is designed in such a way that the plant’s state trajectory is attracted to a predetermined (user-selected) manifold in the state space and, once intercepted \( \sigma \), to maintain the system’s trajectory on the switching manifold for all subsequent time. A sliding mode exists if, near the switching surface, the tangent or velocity vectors of the state trajectory point towards the switching manifold [R.A. DeCarlo and Drakunov (2011)]. If the state trajectory intersects the conventional sliding manifold, the magnitude of the state remains within an \( \epsilon \)-neighborhood of \( \sigma \).

Despite the popularity of the conventional sliding mode control (CZMC) technique it has two major drawbacks: sensitivity of the motion of the control system in the reaching phase and the chattering phenomenon. The former is addressed first by introducing the Integral Sliding Mode Control (ISMC) [Matthews and DeCarlo (1988)]. To improve the robust performance further, double integral SMC (DISMC) has been proposed in [S.-C. Tan and Tse (2008)]. Another approach proposed in the literature to tackle the reaching phase robustness problem is to use time-varying sliding mode control (TVSMC) [S.-B. Choi and Jayasuriya (1994)]. The major disadvantage of this method is that the insensitivity of the system to uncertainties and disturbances cannot be guaranteed continuously. This is addressed by introducing the continuous time-varying sliding manifold in [Bartoszewicz (1995)]. Although the technique is proven to be effective in numerous applications [Sheng and Liu (2013)], the finite reaching time to the sliding manifold cannot be assured in this approach and the switching time must be designed using a complicated optimization method.

Chattering drawback can be happened due to the actuators’ unmodeled dynamics or switching delays. The chattering phenomenon in SMC is mitigated in most of the cases by introducing smooth approximation of the switching element rather than using a discontinuous signum function (known as boundary layer) [X. Zhang and Sun (2013)]. Though the boundary layer method is simple to implement, it has some major drawbacks. First, the invariance property is lost. Second, it does not assure the finite reaching time to the switching manifold. On the
that the proposed SVSMC method is applied to the initial cated optimization methods. It is necessary to mention without using fuzzy rules or time-consuming and compli- procedure is proposed to determine the required parameters varying sliding mode control (SVSMC) are introduced via Hokamoto (2017). In this paper, a new continuous slope- between chattering and robust performance [H. Nemati and Sano (2016)]. Generally, there is a delicate balance be- implemented the boundary layer as a promising method Recently, many published papers have employed and im- change with the system’s states [C. Kunusch and Mayoski (2012)]. In [Y. Jin and Hou (2008)], three types of TVSMC algorithms have been introduced for attitude stabilization of a rigid spacecraft. Recently, there has been much attention concentrated in designing flight controllers for quadrotor UAVs based on various SMC schemes. In [Xiong and Zhang (2016)], position and attitude of a quadrotor UAV have been stabilized based on the discrete-time sliding mode control. Attitude regulation of a quadrotor UAV is addressed in [Yang and Yan (2016)] based on fuzzy sliding mode control in the presence of inertial uncertainties and external disturbances. In [S. Li and Zheng (2017)] a hierarchical control strategy based upon the ISMC has been introduced for the position and attitude tracing of a quadrotor UAV. In [Xiong and Zhang (2017)] the global fast dynamic terminal sliding mode control technique has been employed to design a flight controller for a quadrotor UAV. This paper could suppress the chattering phenomenon. However, the obtained results still exhibits some abrupt jumps in the controllers. Second- order sliding mode control based on the super-twisting al- gorithm (STA) has been used for altitude control of a quadrotor UAV in [F. Munoz and Lozano (2017)]. How- ever, the system’s trajectory speed is very slow when the states are far away from the origin in STA [Moreno (2014)] and it cannot endure uncertainties and disturbances that change with the system’s states [C. Kunsch and Mayoski (2012)].

Recently, many published papers have employed and implemented the boundary layer as a promising method to suppress the chattering drawback [B. Sumantri and Sano (2016)]. Generally, there is a delicate balance between chattering and robust performance [H. Nemati and Hokamoto (2017)]. In this paper, a new continuous slope-varying sliding mode control (SVSMC) are introduced via rotating switching manifolds. Furthermore, a simple procedure is proposed to determine the required parameters without using fuzzy rules or time-consuming and complicated optimization methods. It is necessary to mention that the proposed SVSMC method is applied to the initial

\[
\begin{align*}
\ddot{\phi} & = \frac{J_{yy} - J_{zz}}{J_{xx}} \dot{\phi} \psi - J_{zz} \dot{\phi} \\
\dot{\psi} & = \frac{J_{yy} - J_{zz}}{J_{xx}} \dot{\phi} \theta + J_{zz} \dot{\phi} \\
\dot{\phi} & = \frac{J_{yy} - J_{zz}}{J_{xx}} \dot{\theta} + J_{zz} \dot{\theta}
\end{align*}
\]

where \([\phi \, \theta \, \psi]^T\) are Euler angles and known as roll (rotation around \(x\)-axis), pitch (rotation around \(y\)-axis) and yaw (rotation around \(z\)-axis). \(J\) is an inertia matrix \(J = \text{diag}[J_{xx}, J_{yy}, J_{zz}]\) of the quadrotor and \([u_2 \, u_3 \, u_4]^T\) presents the total moments acting on the quadrotor in the body frame. \(J_r\) denotes the propellers’ inertia and \(\Omega_r\) represents the relative propeller’s speed.

3. SLIDING MODE CONTROL DESIGN

The quadrotor UAV model developed in the previous section can be reformulated as a sixth-order nonlinear dynamical system:

\[
\begin{align*}
\dot{x}_1 & = x_2 \\
\dot{x}_2 & = F(x_1, x_2) + G(x_1, x_2)u + D(x_1, x_2, t) \\
y & = x
\end{align*}
\]
Fig. 2. Slope-varying sliding manifolds based on initial conditions

where $\mathbf{x} \in \mathbb{R}^6$ represents the system state vector as $\mathbf{x} = [\mathbf{x}_1 \mathbf{x}_2]^T$ in which $\mathbf{x}_1 = [\phi \dot{\phi} \psi]^T$ and $\mathbf{x}_2 = [\phi \dot{\phi} \psi]^T$. $\mathbf{f}(\mathbf{x}_1, \mathbf{x}_2) = [F_1 F_2 F_3]^T$ and $\mathbf{G}(\mathbf{x}_1, \mathbf{x}_2) = [G_1 G_2 G_3]^T$ are two nonlinear functions describing system dynamics, and $\mathbf{u} \in \mathbb{R}^3$ is the control input to be designed. $\mathbf{y}$ denotes system’s output and $\mathbf{D}(\mathbf{x}_1, \mathbf{x}_2, t)$ is the time-varying external disturbance or parametric uncertainties acting on the UAV dynamic model. In the following, the design methodology of the proposed technique is compared with conventional sliding mode control (CSMC).

3.1 Slope-Varying Sliding Mode Control (SVSMC)

To enhance the performance of Conventional Sliding Mode Control (CSMC), in this subsection, a novel continuous time-varying switching surface is introduced. Since system’s trajectory can be influenced by external disturbances or parameter variations in the reaching phase, one of the methods to increase the robust performance of the SMC technique is to eliminate the reaching phase via rotating sliding manifolds. Figure 2 shows a procedure whereby the proposed sliding surface rotates over time based on initial conditions and converges to the desired sliding manifold. This method mainly suggests that the slope-varying sliding surface ($\sigma_{SV}$) can be selected in the second and fourth quadrants of the phase plane where $\sigma_{SV}(i) < 0$. Main features of the proposed slope-varying sliding mode control (SVSMC) approaches are

- Simplicity of the proposed approach.
- The proposed time-varying function can be combined with various SMC algorithms such as terminal SMC, non-singular terminal SMC, higher-order SMC, twisting and super-twisting algorithms.
- The proposed approach shows a robust performance for all time instances of the reaching phase further to the sliding manifold.
- It is not necessary to determine switching parameters using time-consuming and complicated algorithms. The proposed approach is able to determine its parameters quickly and easily.

The proposed slope-varying sliding manifold is defined as:

$$\sigma_{SV} = \tilde{x}_2 + \Lambda \mathbf{f}(t) \tilde{x}_1 \tag{3}$$

where $\sigma_{SV} = [\sigma_{1,SV} \sigma_{2,SV} \sigma_{3,SV}]^T$ is a proposed sliding surface vector, $\tilde{x}_1 = x_1 - x_{1d}$ and $\tilde{x}_2 = x_2 - x_{2d}$ are perturbations from desired points ($x_{1d} = [\phi_d \dot{\phi}_d \psi_d]^T$, $x_{2d} = [\dot{\phi}_d \dot{\phi}_d \psi_d]^T$). $\mathbf{f}(t)$ is a vector including nonlinear time-varying functions as $\mathbf{f}(t) = [f_1(t) f_2(t) f_3(t)]^T$, $\Lambda = \text{diag}[\lambda_1 \lambda_2 \lambda_3]$ contains positive constants. These constants ($\lambda_i$; $i = 1, 2, 3$) are typically limited by three factors Slotine and Li (1991): the frequency of the lowest unmodeled structural resonant mode ($\nu_s$), the largest neglected time delay ($T_d$), and the sampling rate ($\nu_s$) as follows:

$$\lambda_i \leq \frac{2\pi}{3\nu_r} ; \quad \lambda_i \leq \frac{1}{3T_d} ; \quad \lambda_i \leq \frac{1}{5\nu_s} \tag{4}$$

It is essential to emphasize that this method can be mainly suggested for $\tilde{x}_2|_{t=0} < 0$. If the initial condition could not guarantee the aforementioned condition, the following remark can be employed.

**Remark 1.** Without loss of generality, slope of the switching manifold ($\Lambda$) can be redefined as $-\Lambda$ for the first and third quadrants of the phase plane. Then, the proposed slope-varying sliding surface in Eq. (3) can be rewritten as

$$\sigma_{SV} = \tilde{x}_2 - \Lambda \mathbf{f}(t) \tilde{x}_1 \tag{5}$$

The design procedure of a nonlinear vector, $\mathbf{f}(t)$, is introduced in the following. The initial value of $\mathbf{f}(t)$ must be defined such that the initial states lie on the sliding manifold. i.e.,

$$\sigma_{SV}(0) = 0 \Rightarrow \mathbf{f}(0) = -\frac{\tilde{x}_2(0)}{\Lambda} \tilde{x}_1(0) \tag{6}$$

Then, the nonlinear vector $\mathbf{f}(t)$ must be chosen such that the slope-varying sliding manifold reaches the desired manifold. Here, the following nonlinear function is proposed

$$f_i(t) = f_i(0) + \left(1 - f_i(0)\right) \tanh \alpha_i t ; \quad i = 1, 2, 3 \tag{7}$$

where $\alpha_i$ is a positive constant and will be determined later.

To ensure the attractiveness of the proposed sliding manifold, the following positive definite function of $\sigma_{SV}$ can be considered as a Lyapunov function

$$V = \frac{1}{2} \sigma_{SV}^T \sigma_{SV} \tag{8}$$

Taking the derivative of Eq. (8) with respect to time results in

$$\dot{V} = (\sigma_{1,SV} \dot{\sigma}_{1,SV}) + (\sigma_{2,SV} \dot{\sigma}_{2,SV}) + (\sigma_{3,SV} \dot{\sigma}_{3,SV}) \tag{9}$$

According to the Lyapunov’s direct method, the negative definiteness of $\dot{V}$ implies that the equilibrium state at the origin is stable i.e.,

$$\sigma_{i,SV} \dot{\sigma}_{i,SV} = -\mu_i |\sigma_{i,SV}| \quad ; \quad i = 1, 2, 3 \tag{10}$$

where the parameter $\mu_i$ is a positive constant which must be greater than the magnitude of the disturbance. Substituting Eq. (2) into Eq. (10) results in

$$F_i + G_i u_{i+1} - \tilde{x}_{2d,i} + f_i(t) \lambda_i \tilde{x}_{1,i} + f_i(t) \lambda_i \tilde{x}_{2,i} = -\mu_i \text{sign}(\sigma_{i,SV}) \tag{11}$$

Therefore, for the nonlinear dynamical system in Eq. (2) with its nominal performance and the slope-varying sliding manifold defined in Eq. (3), the proposed slope-varying sliding mode controller $u_{i+1,SV}$ can be designed as
\[ u_{i+1,SV} = -G_i^{-1} \left[ \mu_i \ \text{sign}(\sigma_{i,SV}) + f_i(t)\lambda_i\ddot{x}_{2,i} + F_i + \dot{f}_i(t) \lambda_i\ddot{x}_{1,i} - \dot{x}_{d2,i} \right] \]

then the system’s states move toward the sliding surface and the motion is confined to it. As it can be seen from Eq. (12), the proposed sliding mode control law can be divided into two parts: nominal \((u_n)\) and switching \((u_{sw})\) parts as

\[ u_{i+1,SV,n} = -G_i^{-1} f_i(t)\lambda_i\ddot{x}_{2,i} + F_i + \dot{f}_i(t) \lambda_i\ddot{x}_{1,i} - \dot{x}_{d2,i} \]

\[ u_{i+1,SV,sw} = -G_i^{-1} \mu_i \ \text{sign}(\sigma_{i,SV}) \]

(13)

According to Eqs. (12) and (13), \(\text{sign}(\sigma_{SV})\) is a discontinuous signum function. Signum function can switch the control signal at an infinite frequency, and thereby excite the unmodeled fast dynamics or undesired oscillations known as chattering. To solve this problem simply, two techniques can be employed. In the first technique, one may approximate the discontinuous function with a hyperbolic switching function known as Boundary Layer (BL) as:

\[ u_{i+1} = -G_i^{-1} \left[ \mu_i \ \tanh(\sigma_{i,SV}) + f_i(t)\lambda_i\ddot{x}_{2,i} + F_i + \dot{f}_i(t) \lambda_i\ddot{x}_{1,i} - \dot{x}_{d2,i} \right] \]

or Continuous SMC technique (Cnt.) H. Nemati and Hokamoto (July 2014)

\[ u_{i+1} = -G_i^{-1} \mu_i (\sigma_{i,SMC}) + f_i(t)\lambda_i\ddot{x}_{2,i} + F_i + \dot{f}_i(t) \lambda_i\ddot{x}_{1,i} - \dot{x}_{d2,i} \]

(14)

(15)

where \(\gamma_i\) and \(\beta_i\) are positive odd integers. Though the continuous approximation may not guarantee the robust performance of the system in the boundary layer, continuous SMC approach can be utilized. Sliding mode control techniques using boundary layers are still considered as a promising method to alleviate the chattering phenomenon. Likewise, conventional sliding mode controller can be defined as

\[ u_{i+1} = -G_i^{-1} \mu_i \ \text{sign}(\sigma_{i,SMC}) + \lambda_i \ddot{x}_{2,i} + F_i - \dot{x}_{d2,i} \]

(16)

Reaching time in CSMC can be estimated using

\[ t_{r,i} = \frac{\sigma_{i,SMC}(0)}{\mu_i} \]

(17)

the minimum value of \(\alpha t_r\) must be computed such that \(\tanh\alpha t_r = 1\). This implies that the proposed approach guarantees the finite reaching time to the desired sliding manifold. In MATLAB, \(\tanh 5.3 = 1\) can be achieved if the error tolerance is set to \(10^{-4}\). As a consequence, the magnitude of the parameter \(\alpha_i\) can be obtained using the following relation:

\[ \alpha_i = \frac{5.3 \mu_i}{\sigma_{i,SMC}(0)} \]

(18)

Eq. (18) clearly shows the applicability of the designed parameter \(\alpha_i\) in a continuous time.

3.2 Robust Stability Analysis

In order to assess the effect of external disturbances and uncertainties we analyse the robust stability of the proposed technique in this section. To analyse the robust stability of the system we assume the external disturbance \(D\) exists in derivation of the control law.

Remark 2. Since equation (3) is valid under all circumstances even in the presence of uncertainties, the robust stability of the proposed algorithm is always guaranteed.

Remark 3. In conventional sliding mode control, the robust stability analysis needs to be carried out for both reaching and sliding phases. However, as the proposed slope-varying SMC approach does not have any reaching phase, it is sufficient to analyse the robust performance of the system only in the sliding phase.

Two types of matched disturbances are considered in this paper: 1) time-varying external disturbances such as sinusoidal wind gust, and 2) structural uncertainty. Time-varying external disturbance can be modeled as an acceleration by adding it to the dynamical equation in Eq. (1). The second type of disturbances can be modeled using the following remark.

Remark 4. The structural uncertainty is assumed to be available in the first component of the inertia matrix as \(\Delta J_{xx}\). Therefore, this uncertainty can be modeled as

\[ D_1 = \left( J_r \Omega_r \dot{\theta} - (J_{yy} - J_{zz}) \dot{\psi} \dot{\psi} - u_2 \right) \frac{\Delta J_{xx}}{J_{xx} + \Delta J_{xx}} \]

\[ D_2 = -\frac{\Delta J_{xx}}{J_{yy}} \dot{\psi} \]

\[ D_3 = \frac{\Delta J_{xx}}{J_{zz}} \dot{\theta} \]

Next, the robust performance of the proposed SVSMC is analyzed against uncertainties and disturbances. One
can consider the nonlinear dynamical equation (2) where 
\( \mathbf{D}(\mathbf{x}, \mathbf{u}, t) = [D_1 \ D_2 \ D_3]^T \) denotes external disturbances or uncertainties acting on the UAV dynamic model. This function is unknown but bounded as \( |D_i| < M_i \) (\( i = 1, 2, 3 \)). Taking the time-derivative of the Lyapunov candidate for SVSMC along the uncertain system in Eq. (2), yields

\[ \dot{V}_i = \sigma_{i,SV}(\ddot{x}_{2,i} + \lambda_i f_i(t)\dot{x}_{2,i} + \lambda_i \dot{f}_i(t)\ddot{x}_{1,i}) \]

\[ = \sigma_{i,SV}(F_i + G_i u_{i+1} + D_i + \lambda_i \dot{f}_i(t)\ddot{x}_{2,i} + \lambda_i f_i(t)\dot{x}_{1,i}) \quad (20) \]

Equation (20) can be rewritten using Eq. (11) in the form of:

\[ \sigma_{i,SV}(F_i + G_i u_{i+1} + D_i + \lambda_i \dot{f}_i(t)\ddot{x}_{2,i} + \lambda_i f_i(t)\dot{x}_{1,i} + \ddot{x}_{2,i} - \ddot{x}_{2,i}) \leq \sigma_{i,SV}(-\mu_i \text{sign}(\sigma_{i,SV}) + M_i) \quad (21) \]

Noticably, if \( \mu_i > M_i \) is satisfied, then the Lyapunov stability \( \dot{V}_i < 0 \), is sufficiently ensured. As a result, one can simply conclude the following remark:

**Remark 5.** As expressed in Eq. (13), sliding mode control laws contain two parts in which the switching part \( (u_{\text{sm}}) \) can guarantee the robust performance of the plant in the presence of external disturbances and modeling uncertainties.

4. RESULTS AND DISCUSSION

This section is dedicated to simulation of the time-varying sliding mode control approaches for stabilizing the attitude of a quadrotor UAV. Simulations are developed utilizing the MATLAB software. Physical parameters of an AR Drone Parrot 2.0 are assumed as \( J_{xx} = J_{yy} = 1.8 \times 10^{-3} \) kg m\(^2\), \( J_{zz} = 4.7 \times 10^{-3} \) kg m\(^2\) and \( J_r = 1.8 \times 10^{-5} \) kg m\(^2\). To investigate the effectiveness of the proposed controllers, the following mission is addressed subject to disturbances as \( \mathbf{D}(t) = 10^{-1} [3 \sin(t) \ 2 \sin(t) \ \cos(t)]^T \) rad/s\(^2\). The mission task is to set Euler angles from initial conditions as \([ \phi(0) \ \theta(0) \ \psi(0)] = [30 \ 0 \ 0]\) deg to desired conditions as \([ \phi_d \ \theta_d \ \psi_d] = [-30 \ -45 \ 60]\) deg. Initial and desired conditions for Euler rates are both selected as \([ \dot{\phi}(0) \ \dot{\theta}(0) \ \dot{\psi}(0)] = [\dot{\phi}_d \ \dot{\theta}_d \ \dot{\psi}_d] = [0 \ 0 \ 0]\) rad/s. The uncertainty in a first component of the inertia matrix of the quadrotor is also applied for this mission as \( J_{xx}' = 5.4 \times 10^{-2} \) kg m\(^2\). Sliding gains are selected as \( \lambda_1 = \lambda_2 = \lambda_3 = 1 \) and \( \mu_1 = 1 \). Fractional exponents of the continuous SMC are assumed as \( \gamma_1 = \gamma_2 = \gamma_3 = 7 \) and \( \beta_1 = \beta_2 = \beta_3 = 17 \).

Yaw tracking of the quadrotor (as an example) subject to disturbances and uncertainty based on the CSMC, SVSMC-BL and SVSMC-Cnt methods are shown in Figs. 3 and 4. Figs. 3 and 4 represent that Euler angles start from their initial conditions and converge to the predetermined desired values. Furthermore, as it can be clearly seen from Figs. 3 and 4, the perturbation of the yaw angle around the desired condition based on CSMC and SVSMC-BL is higher than that based on the SVSMC-Cnt. Time responses of control torques are illustrated in Fig. 5 based upon the CSMC, SVSMC-BL and SVSMC-Cnt, respectively. Fig. 5 displays that the control effort in SVSMC-BL and SVSMC-Cnt during transient phase is higher than that in CSMC. On the other hand, the proposed slope-varying controllers consume higher energy to retain the robust performance. In addition, this figure demonstrates that the control effort for CSMC, SVSMC-BL and SVSMC-Cnt in the steady-state phase are very similar. The comparison between CSMC, SVSMC-BL and SVSMC-Cnt proves that the SVSMC-Cnt has better robust performance rather than SVSMC-BL and CSMC in the presence of environmental disturbances and uncertainties. Generally, boundary layer technique has a major drawback not to guarantee the robust performance of the system in the boundary layer thickness. Moreover, Table 1 displays the root-mean-square (rms) value of roll torque \( (u_2) \) and roll error \( (\ddot{x}_1) \), as an example, based on the aforementioned control approaches in the presence of external disturbances and inertia uncertainty. Please note that the rms values in Table 1 is very high because the magnitude of both disturbances and uncertainties are really large in the present simulation. The effectiveness of the SVSMC-Cnt in robust performance and disturbance rejection is represented in Table 1.

<table>
<thead>
<tr>
<th>Approaches</th>
<th>Roll error (deg)</th>
<th>Roll torque (N.m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSMC</td>
<td>59.8109</td>
<td>0.0013</td>
</tr>
<tr>
<td>SVSMC-BL</td>
<td>52.9289</td>
<td>0.0015</td>
</tr>
<tr>
<td>SVSMC-Cnt</td>
<td>44.6545</td>
<td>0.0018</td>
</tr>
</tbody>
</table>

**Table 1. Root-Mean-Square Values of the Proposed Controllers**
5. CONCLUSION

In this paper, an effective implementation of a novel approach for attitude stabilization of a quadrotor has been developed based on the concept of time-varying sliding mode control. Since conventional sliding controllers may be influenced by disturbances and uncertainties in the reaching phase, a new SVSMC strategy is proposed via rotating the initial manifold to improve the robust performance subject to external disturbances and uncertainties. The obtained results prove that the SVSMC-Cnt has better robust performance than conventional SMC and SVSMC-BL against uncertainties and disturbances.

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