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Survey

Sliding-mode variable structure control for complex automatic systems: a survey

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Abstract: Automatic systems (ASs) can automatically control the work of controlled objects without unattended participation. They have been extensively used in industry, agriculture, automobiles, robots and other fields in recent years. However, the performance of the controller cannot meet the work requirements under complex environmental conditions. Therefore, improving the control performance is one of the difficult problems that automated systems should solve. Sliding-mode variable structure control has the advantages of fast response, insensitivity to uncertainty and interference and easy implementation; thus, it has been extensively used in the field of complex control systems. This article analyses and explains the research status of motors, microgrids, switched systems, aviation guidance, robots, mechanical systems, automobiles and unmanned aerial vehicles (UAVs) and prospects for the application of sliding-mode variable structure control in complex ASs.

Keywords: sliding-mode control; automatic system; complex environment; application; studies

1. Introduction

Automatic systems (ASs) are systems that can be operated or managed by means of advanced technology without manual intervention. Since ancient times, humans have created countless kinds of Ass. The technical level of ASs has gradually improved with the growth of human knowledge.

Compared with traditional systems, the research scope of ASs has obviously expanded. Various types of systems have emerged, including motors [1,2], microgrids [3], switched systems [4], aviation guidance [5], robots [6], mechanical systems [7], automobiles [8,9] and unmanned aerial vehicles (UAVs) [10], which may be applied to ASs now or in the near future. However, in the actual application process, many controlled objects are difficult to describe accurately, such as the tracking control of a linear motor positioner [11,12], satellite attitude control [13] and robot control [14]. Strong coupling exists amongst variables, time-varying parameters, uncertain internal and external interference and other factors. Consequently, various forms of uncertainty and nonlinear forms are inevitably existing in the mathematical modelling of systems, and the use of traditional control models is evidently unable to meet the actual need.

ASs are complex systems created by the integration of machinery, control, computer and other technologies. Control system is undoubtedly one of the key technologies to develop ASs. With the continuous development of modern science and technology, ASs have experienced long-term professional technical research, and a lot of in-depth research in process control [15], automatic control [16] and intelligent control [17] have been studied. ASs could achieve the purpose of normal operation under complex environmental conditions by means of adopting effective technology or combining a variety of technologies. As a kind of intelligent control, the remarkable progresses of sliding-mode control (SMC) technology have taken ASs to reach a higher level in recent years.

The sliding mode of SMC can be designed and is unaffected by object parameters and disturbances, which makes SMC have the advantages of rapid response, strong robustness to uncertain parameters and external interference and no need for real-time system identification. Therefore, it has been widely used in the field of complex system control, humans can create highly applicable ASs in various complex environments in accordance with SMC technology, and an extended and detailed discussion on the development trends of SMC in ASs application is a need.

In this paper, the development trend of ASs is described by summarizing the main achievements in several complex fields. The rest of this paper is organized as follows: Introduction of SMC is presented in Section 2. Section 3 compares SMC, model predictive control (MPC) and PID control. Section 4 analyses the SMC used in eight complex ASs: electric motors, microgrids, switched systems, aviation guidance, robots, mechanical systems, automobiles and UAVs. It also indicates the development direction of SMC in the application of complex ASs at last. A comprehensive description is formed in the field of ASs which contains SMC, and its application in complex environment in this paper.

2. SMC

2.1 Basic thought

Sliding-mode variable structure control emerged in the 1950s, it was based on Relay control and Bang-Bang control. After more than 60 years of development, sliding-mode control (SMC) has become a general design method for automatic control systems. Sliding-mode variable structure control is essentially a type of nonlinear control, its nonlinearity is represented by discontinuity of control and its control structure changes with time. It can change purposefully in accordance with the current state of systems (such as deviation and its derivatives) in the dynamic process. SMC has formed a relatively complete theoretical system. It has been widely used in various industrial control objects because of its good control performance for nonlinear systems, applicability for multi-input multi-output systems, and establishment of good design standards for discrete time systems.

2.2 Fundamentals

Sliding-mode variable structure control refers to the variable structure control with sliding mode. Sliding mode is the state when the system is restricted to motion in some domain of the switched hyperplane. Generally, the initial state of the system does not exist in the domain. It can drive the state trajectory to a certain domain of the switching hyperplane by the action of the variable structure controller and the state trajectory can remain in this domain within a certain time range. The process involved above is called reachability. The state trajectory of the system moves on the sliding mode and finally tends to the origin, which is called sliding mode motion.

Consider the following single input linear systems [18]:

$$\dot{x}(t) = Ax(t) + Bu(t) \tag{1}$$

where $x(t) \in R^n$ and $u(t) \in R$ denote the state and output of the system respectively. A is the system matrix and B is the input matrix. The state feedback controller of linear system is usually designed as:

$$u(t) = Kx(t) \tag{2}$$

where the state feedback matrix K can be constructed by pole placement or linear two linear regulator. Obviously, the controller of Eq (2) is fixed, but in sliding-mode variable structure control systems, the controller structure varies with the change of switching functions. Generally speaking, the sliding-mode variable structure controller is:

$$u(t) = \begin{cases} u^{+}(t), & S(t) > 0 \\ u^{-}(t), & S(t) < 0 \end{cases} \tag{3}$$

where $S(t)$ is the switching function. When $S(t) = 0$, the system reaches the sliding surface. $u^{+}(t)$ and $u^{-}(t)$ represent the left and right controllers of the sliding surface respectively. It can be seen that the variable structure control is mainly reflected in:

$$u^{+}(t) \neq u^{-}(t) \tag{4}$$

It can be seen that the essence of sliding-mode variable structure control is to make the closed-loop control system have different structures through switches, and to make systems have good dynamic quality such as asymptotic stability. The response of the sliding-mode variable structure control systems consists of the reaching stage, the sliding stage and the steady stage. Therefore, the sliding-mode variable structure control systems need to meet the following three conditions:

a) The reachability condition is satisfied, that is, the system state is driven to the sliding surface in finite time.
b) There are sliding modes, which $S(t)\dot{S}(t) < 0$.
c) The sliding mode has good dynamic properties such as asymptotic stability.

3. SMC, MPC and PID

SMC, MPC and PID control have similar control background and are important branches of Process Control. [19] evaluated the controller on the Twin Rotor Mimo System (TRMS). Tables 1 and 2 compared SMC, MPC and PID controllers on settling times (ts), rise times (tr), integral of the absolute error (IAE) and integral of the squared error (ISE), including perturbation and without perturbation. It also estimated the state of yaw control and pitch control of TRMS. It can be seen that the application of the MPC control minimizes the control effort compared to the SMC and PID controllers, and that the SMC control has better performance rates and better response to disturbances. From the perspective of applicability, there are two significant differences. The first difference is that PID and MPC control are suitable for linear system with accurate mathematical model. The discontinuous control of SMC will have absolute advantage if the applied system has low requirements for the model. Moreover, most ASs applied in complex environment are mostly nonlinear and time-varying uncertain systems. The second difference is that PID control method is mainly through setting and adjusting K_P, K_I, K_D three PID parameters for adjusting the system performance. Compared with adjusting three parameters of PID, SMC is more real-time when the parameters, structure uncertainty, coupling and interference of the controlled object change. The realization of MPC is to establish the model of the optimization problem and solve the optimization problem in order to obtain the output of the controller. MPC needs to solve the optimization problem iteratively in each time step. However, the solution of the optimization problem is often time-consuming, and the action of the controller may have stronger requirements for real-time, which is a main disadvantage of model predictive control at present. SMC only needs to design the switching hyperplane of system and make the system state constraint to switching hyperplane by means of sliding mode controller, so the system can get the desired performance. It can also overcome system uncertainty and unknown response to external interference, which is the inherent shortcomings of PID and MPC control. Therefore, SMC is more suitable for complex ASs.

Table 1. Yaw control results on real equipment.

Scenario	Without perturbation				With perturbation		
	Ts [s]	Tr [s]	IAE	ISE	Ts [s]	IAE	ISE
MPC	24.4	4.7	2.9	1.5	28.5	2.5	1.9
SMC	14.2	1.4	1.7	0.8	23.2	1.9	1.0
PID	52.4	7.1	4.8	3.3	35.6	6.2	3.4

Table 2. Pitch control results on real equipment.

Scenario	Without perturbation				With perturbation		
	Ts [s]	Tr [s]	IAE	ISE	Ts [s]	IAE	ISE
MPC	26.7	11.2	1.9	1.3	24.1	3.6	2.5
SMC	17.8	2.5	1.2	0.8	10.6	2.9	0.6
PID	14.69	1.6	2.6	1.8	29.2	6.2	3.6

4. Application studies

4.1 Application of SMC in electric machines

Electric machine control refers to the motor control of starting, accelerating, running, decelerating and stopping. Different requirements and purposes exist in accordance with the type of motor and the usual occasion of the motor. The motor realises its fast start, rapid response and prompt response through motor control, and its purpose is to achieve high efficiency, torque output and overload capacity. Domestic and foreign scholars have applied advanced SMC methods to servo motor, induction motor and synchronous motor (SM) systems to guarantee the stability of the motor control systems.

4.1.1 Servo motor systems

A servo motor drive system has the benefits of simplified transmission system and compact structure. The servo motor continuously rotates in a single direction, which prevents the frequent start and stop of the motor in forward and reverse rotational directions. The stability of the system is affected by the uncertainty in the middle mechanical mechanism of the servo motor. In [20], a nonlinear adaptive sliding-mode observer (SMO) was developed and applied to motor control. The observer was structured in an adaptive speed observer and an adaptive magnetic flux observer. The former was robust to the changes in motor load torque. It was persuasive, and the load torque could converge to a true value under suitable conditions. The latter adopted singular perturbation technology, which was simple in design and easy to implement in industrial applications. In [21], aiming at the magnetic saturation problem of motor systems, an improved SMC strategy based on the exponential arrival law was proposed. The strategy enhanced the robustness of the systems, realised a stable and fast response and effectively solved the flutter problem of a drive system. Paper [22] designed a model-following SMC method in a switched reluctance motor, which provided stable speed tracking for cruise and enhanced the cruiser's ability to withstand load torque interference and anti-inductance deviation. Article [23] also proposed nonsingular terminal SMC (NTSMC), which could realise intelligent control of a turbine system without identifying the model of the wind turbine, improve the speed adjustment of the wind turbine rotor and eliminate the sliding-mode observation estimation error.

4.1.2 Induction motor systems

An induction motor is a complicated nonlinear system with time-varying parameters. The proportional-integral (PI) regulator used in indirect field-oriented control (IFOC) is weak against uncertain disturbances, such as load mutations, and the PI parameters are difficult to tune. In addition, IFOC is sensitive to the changes in rotor time constant, which greatly weakens the robustness of the induction motor servo system against parameter changes. In response to the problems of IFOC, many scholars have adopted corresponding improvement strategies. [24] studied the continuous time T-S fuzzy system with two kinds of multiplicative gain changes, which was applied to induction motor. According to the linear matrix inequality, the filter analysis conditions were proposed. Through the results of these conditions, a non-fragile H_∞ filter was designed. The filter could ensure the stability of the system without adding additional variables or strict LMI design conditions. A better decoupling method was also provided so that the filter system error has a specified H_∞ performance with respect to the change of filter gain. [25] studied the problem of peak-to-peak filtering, which applied to the networked nonlinear DC motor quantization system. The DC motor system was composed of nonlinear armature resistance. A T-S fuzzy system was also designed based on Fuzzy Lyapunov function. Two static quantizers were used to quantify the measurement output signal and the performance output signal. Newly designed filter eliminated the system uncertainty, and the filtering error system also achieved asymptotic stability. In [26], a sliding-mode artificial neural network control method driven by an induction motor was proposed and implemented in a feedback control system. The SMC training algorithm effectively reduced the number of parameters to be adopted by the drive system to ensure the stability of the system. In [27], a new type of adaptive SMO was designed and applied to the sensorless field-oriented control (FOC) of induction motors. When the switch gain was set adequately large, the accuracy of the rotor flux and speed of the induction motor was high. The robustness against the changes in electrical parameters was strong. In [28], a new type of super-twisting sliding-mode direct torque and flux controller, which adjusted the response by changing the proportional gain of the controller, was provided. It presented fast response speed, strong anti-interference capability, high accuracy and improved running time. No vibration characteristics occurred, and the control scheme has been successfully applied to induction motor drives. In [29], a backstepping-based induction motor speed observer was designed using the sliding switching function of a sliding-mode controller, and the stability of the observer structure was analysed using Lyapunov theory, which effectively improved the robustness of the observer control structure. It guaranteed a trouble-free operation of an electric drive system and has been successfully applied in industrial applications. In [30], a cascaded PI second-order SMC method was suggested. The PI controller and second-order SMC separately controlled a brushless doubly fed induction motor (DFIM) powered by a matrix converter. The sliding mode surface was selected as $S_{sl} = X_1 + \lambda_1 X_2$ in order to achieve zero steady-state error tracking of current i_{cd}^*, where $X_1 = i_{cd} - i_{cd}^*$,$X_2 = \int i_{cd} - i_{cd}^* \, dt$,$\lambda_1$ is the sliding mode coefficient to adjust the current loop bandwidth. A second-order sliding mode differentiator was used in order to get the derivative of i_{cd}^* accurately. The outer and inner rings demonstrated a strong anti-interference capability and excellent robust tracking performance and effectively prevented chattering.

4.1.3 Synchronous motor (SM) systems

When an SM is running, as the temperature and other environmental factors change, parameter perturbation will occur, which will affect the performance of a speed control system. The existence of uncertain factors, such as load disturbance, will further affect the speed control. The robustness of the system has a negative effect. In response to the above problems, [31] designed an improved flux linkage observer based on a sliding-mode compensator for closed-loop sensorless operation. This observer would not affect the estimation accuracy of the rotor position and could accurately compensate for DC offset and position error, which caused by a filter and higher harmonics. It rapidly realised the dynamic response of a permanent magnet SM (PMSM) drive system. In [32], a SMO and a disturbance observer (DO) were cascaded and used in a PMSM. The SMO was used for speed estimation, and the DO was used for torque estimation. The DO updated the operating point of the controller. A state feedback controller was also designed to realise sensorless operation of the PMSM and improve the robust speed control of the PMSM. In [33], two schemes for suppressing the torque pulsation of an open-end winding PMSM were introduced. One was the zero-sequence back-EMF observer (ZCBO) algorithm based on adaptive SMC in consideration of dead time, and the other was a predictive current control scheme based on ZCBO. Both schemes could evidently suppress torque ripple. In [34], a SMO with delay suppression was designed with respect to the real-time rotor position of a PMSM controlled using the vector control algorithm. The SMO selected a new hyperbolic function as the switching function. According to the boundary layer (BL) theory, the switching function should meet the following requirements: the function was continuous; the upper and lower limits of saturation function were 1 and -1 respectively; the slope in BL is nonlinear; no time delay feature. After four conditions of the switching function were met, the vibration of the SMO could be reduced, the position estimation error of a low-pass filter could be eliminated, and the PMSM rotor position estimation accuracy could be improved. Paper [35] designed a new sensorless scheme for PMSM under sliding-mode current control, which could achieve low- and zero-speed conditions without injecting high-frequency signals and using machine models, ensuring the controllability of PMSM.

4.2 Application of SMC in microgrids

The traditional voltage control strategy for microgrids mainly adopts dual closed-loop PI control, which is simple and easy to implement. Nevertheless, the control effect is poor for a complex system. When the microgrid system has external disturbances or parameter changes, the robustness of the control cannot be guaranteed. How to develop a controller to make the system have good effects and robustness is the concern of this article. SMC has recently been widely used in the control of microgrids, and many results have been achieved. In [36], a solution based on distributed SMC was introduced into an autonomous renewable power grid to control the local execution of each multi renewable energy agent, the sliding surface of complete system can be expressed as a matrix: $S = (\mathcal{L}+I)\left[s_1 \cdot \quad \cdot \quad \cdot s_{n_a}\right]^T$, which achieves a progressive global consensus. Two schemes based on distributed averaging integrator (DAI) and distributed sliding-mode control (DSMC) are compared for damping factor. The results showed that DSMC was not affected by damping factor and had constant convergence time. The transient response was rapidly converged. This article [37] firstly introduced and applied a robust adaptive sliding-mode controller (RASMC) to the AC reference voltage source of an adjustable micro-electro-mechanical system (MEMS) to ensure that MEMS can function under the condition of parameter changes and interference. The precise output voltage increased the robustness of the system. In [38], the full-order sliding-mode method was used in an AC microgrid, distributed observers were assigned to distributed generators, and a backstepping nonlinear controller was designed for the observers. Voltage regulation and frequency recovery were realised, and the problem of distributed secondary control of the AC microgrid was solved.

4.3 Switched systems

The switching system is a hybrid system, which composed of a series of continuous, discrete subsystems and rules for coordinating the switching between these subsystems. Different from the general system, the switching rules play an important role in the operation process of the switching system, and different switching rules will result completely different dynamic characteristics. Specially, the stability of its subsystems is not equivalent to the stability of the whole system. The switching system comes from the actual control system and could solve plenty of practical problems. In [39], the concept of dissipation was introduced into sliding mode dynamics to analyse the dissipation of continuous-time nonlinear switched stochastic systems. The switching function of the system was $\sigma(t,i) = G(i)x(t) - \int_0^t G(i)\big(A(i) + B(i)K(i)\big)x(\theta)\,d\theta$, for each $i \in \mathrm{N}, G(i) \in R^{m\times n}$ and $K(i) \in R^{m\times n}$ are real matrices to be designed later on. The average residence time method and the piecewise

Lyapunov function were used to derive the sufficient conditions of LMI to ensure the strict dissipation of sliding mode dynamics. The trajectories of system can be driven onto the sliding surface $\sigma(t,i) = 0$ in a finite time by the SMC law

$$u(t) = K(i)x(t) - \rho(t,i)sign\big(\sigma(t,i)\big),$$

$$\rho(t,i) = \varrho + \phi(i)\|x(t)\| + \left\|\big(B^T(i)X(i)B(i)\big)^{-1}B^T(i)X(i)E(i)\right\| \|\omega(t)\|,$$

with ϱ being a positive constant. New SMC could drive the system trajectory to reach the predetermined sliding surface in a finite-time. Paper [40] proposed a switching control law method to avoid the stick-slip problem of pneumatic system actuators. This method converted the closed-loop system into a piecewise-affine (PWA) system with sliding mode, and found fourth-order piecewise polynomial Lyapunov function through LMI convex optimization, effectively improve the stability of the pneumatic system in the presence of dry friction. Paper [41] used the average residence time technique and the positive diagonal dominant Lyapunov function to construct a new switch surface function in nonlinear discrete-time SMC switching system with repetitive scalar, which reduced the adverse effects caused by the nonlinear repetitive scalar. Using the weighted H_∞ gain, the transient performance of the system was optimized. SMC law could force the trajectory of the closed-loop system to reach the predetermined sliding surface within a finite-time. Article [42] constructed an integral sliding function and established an adaptive SMC (ASMC) SMC in a class of uncertain switching systems with a state delay and nonlinear input. ASMC could drive the trajectory of the closed-loop system to reach and stay on the predetermined sliding surface and robustness of the closed-loop system was significantly improved. In [43], a mode switching SMC with fuzzy nonlinear gain was proposed. The controller redesigned the mode of switching strategy, by adding hysteresis control, which adopted the exponential reaching law $\dot{s} = -\varphi sgn(s) - \omega s$, where $\varphi(\varphi > 0)$ and $\omega(\omega > 0)$ were exponential approach law parameters, which ensured the dynamics of the sliding mode process and reduced the high-frequency jitter of the electrodynamic system. Compared with the conventional PID control, the response curve of the proposed scheme was smoother and the response time was shorter. New system enhanced the tracking performance of different types through improving the tracking response speed. Paper [44] combined the switch second-order sliding mode(S-SOSM) control and the SMC to form a new robust controller. SMC controlled the inner loop of the robot system, and S-SOSM controlled the outer loop. S-SOSM algorithm could counteract the effects of state-related non-modeling dynamics, eliminate the influence of time-varying external disturbances. The new controller effectively reduced jitter, speeded up the response and improved the trajectory tracking performance of the system. In [45], a SMC rule for nonlinear stochastic semi-Markov switching systems (SMSSs) was designed. A sufficient condition that depended on the residence time was obtained through the random semi-Markov Lyapunov function, which guaranteed the random stability of the sliding mode dynamics. The rule ensured the reachability of sliding mode dynamics in a finite-time. Paper [46] designed a switch surface based on the time-delay system model event trigger scheme for fuzzy SMC network control system. The new system adjusted by semi-Markov process could realise the accessibility of the sliding surface and has been successfully applied to a single-link robotic arm system. Article [47] combined the observer and the second-order discrete-time adaptive sliding mode function to form a robust adaptive SMC method, which compensated for external disturbances. Network predictive control (NPC) method was used to compensate for communication constraints.

New method solved the problem of switching network control with external interference. In [48], SMC was applied to discrete singular switched systems with time-varying delays. The system constructed a new sliding surface function, derived new sufficient conditions through LMIs, ensured the accessibility of the sliding surface and reduced vibration. In [49], an appropriate finite-time SMC law was constructed in accordance with the random semi-Markov Lyapunov function. The integral sliding variable was designed as $s(t) = \mathcal{D}_\mu \hat{x}(t) - \int_0^t \mathcal{D}_\mu(\mathcal{A}_\mu + \mathcal{B}_\mu \mathcal{K}_\mu)\hat{x}(s)\, ds$, where $\mathcal{D}_\mu \epsilon \mathbb{R}^{m \times n}$ were chosen such that $\mathcal{D}_\mu \mathcal{B}_\mu$ were nonsingular. An appropriate SMC law was constructed as $u(t) = \mathcal{K}_\mu \hat{x}(t) + \left(\mathcal{D}_\mu \mathcal{B}_\mu\right)^{-1} \mathcal{D}_\mu \mathcal{L}_\mu \mathcal{C}_\mu \hat{x}(t) - \left(\mathcal{D}_\mu \mathcal{B}_\mu\right)^{-1} \mathcal{D}_\mu \mathcal{L}_\mu z_\Theta(t) - \eta_\mu sgn\big(s(t)\big)$ to ensure that the trajectory of the system reached the predetermined sliding mode surface in a finite-time and to enhance the robustness towards parameter uncertainties as well as external disturbances. Paper [50] combined event trigger mechanism (ETM) and limited information SMC law to avoid event sampling mismatch. The discrete-time level set method was applied to the dynamic quantization policy (DQP), it could avoid the quantizer saturation of SMC without online detection. The newly constructed switching law realised the stability of an uncertain switching system. In [51], the observer H_∞ was designed in a singular half-Markov jumping system. The system used LMI to derive sufficient conditions and obtained the gain matrix of the state feedback controller, which effectively ensured the random stability of the closed-loop system.

4.4 Application of SMC in aviation guidance

With the development of aerospace technology, spacecraft with changeable structure characteristics have appeared. The mass distribution and stiffness characteristics of such spacecraft will change considerably during their deployment. With a single on-orbit configuration and its dynamic characteristics, the design of a control system may cause a large deviation or even instability of the spacecraft. Therefore, research on the control method suitable for the variable structure process has an important engineering value. In recent years, the sliding-mode variable structure controller has developed rapidly. Compared with PID, the controller has stronger robustness. In [52], SMC was applied to the guidance of missiles, and an adaptive sliding-mode guidance law was derived using SMC's excellent robustness to parameter disturbances, which effectively eliminated the controller's chattering. In [53], a nonlinear mid-range missile controller was proposed to intercept theatre ballistic missiles. The controller included a quaternion-based sliding-mode attitude controller that could stably adjust the missiles under uncertain conditions. The posture improved the stability of the system.

4.5 Application of SMC in robotics

In recent decades, the field of robotics has received increasing attention, and related research has made remarkable progress. Robots have been applied to various fields to complete difficult tasks, which introduce high requirements for the design of control schemes. In [54], a novel sliding-mode tracking control scheme was utilised to realise trajectory tracking of incomplete mobile robots, and it has been successfully applied in vision-based mobile robot systems. Paper [55] designed a global nonsingular terminal sliding-mode (NTSM) controller. Depending on the Lyapunov stability criterion, NTSMC converged to zero in the sliding mode when t equals 3nite, which eliminated the singularity of conventional terminal SMC. The controller has been successfully applied to the control of a rigid manipulator with n degrees of freedom. In [56], a back propagation neural network and SMC were combined to form a new closed-loop system. A neural network SMC method, which effectively eliminated the interference of a robot fish's roll angle, was also proposed. In [57], an improved robust super-twisting sliding-mode controller (RSSMC), which used a novel arrival law to eliminate the disturbance problem of a four-wheeled autonomous mobile robot (FAMR), was proposed. The disturbance of linear growth on sliding surface can be solved by employing $\mu_{i=1,2} > 0$. The newly proposed method was applicable for trajectory tracking control of very universal systems which subjected to external disturbances and uncertainties states, including the linear systems and nonlinear ones. Moreover, the "ideal modelling" assumption was not necessary during the derivation of the proposed RSSMC method, the controller improved the control of the FAMR's accuracy and tracking performance. Article [58] combined the reverse thrust (BS) design technology with adaptive equivalent SMC and proposed a bionic visual navigation control system. A fuzzy logic position strategy was designed to compensate for the swing of cone sleeves in autonomous aerial refueling (AAR), which improved the ability to resist wind interference and the accuracy of receiver position estimation. In [59], a robot J6 joint speed control system was regarded as a linear system in a certain extent, and parameter uncertain part was regarded as an equivalent simplified model. An adaptive SMC (ASMC) algorithm was designed in accordance with information concentration (IC) estimator, which effectively estimated the unknown parameters of the equivalent simplified model and improved the stability of the system. Text [60] developed a robust jitter-free SMC in follower robot system and designed five tracking paths of different difficulties to compare robust jitter-free SMC tracking robots with PID tracking robots. From the numerical values, SMC tracking robots consumed less energy. It has a minimal trajectory tracking error during the sharp turns, and could show excellent tracking performance under complex working conditions. In [61], a new type of ASMC was proposed in the robot manipulator system. Its nonlinear sliding mode surface has a fast transient response and high steady-state accuracy and ASMC has good tracking performance and could reduce system chattering effectively. In [62], an adaptive reverse thrust SMC was proposed in a two-link robot, and a manipulator dynamic model based on lagrangian dynamics was established, which considered coupling and nonlinear characteristics. A nonlinear estimation function was designed using Lyapunov theory to improve the robustness of the robot. New control system enabled the manipulator to have a good trajectory tracking ability in a complex environment. Text [63,64] also used the same method to achieve the global optimal control. Paper [65] proposed a simple NTSMC, which designed a novel integral sliding surface and completely eliminated the singularity problem of the controller. The geometric uniformity technology was used to converge the effective time to the sliding surface, improved the stability of the system greatly and solved the global finite-time tracking problem of uncertain robot manipulator. In [66], an integral SMC based on integral control was developed for a dual-arm robot. The low-pass filter minimized the controller jitter and the first-order sliding surface based on cross-coupling error ensured the position synchronization of the dual-arm manipulator. New controller could provide accurate trajectory tracking and has good robustness. Text [67] combined NTSMC and a third-order sliding mode observer (TOSM) to form a robot fault-tolerant control (FTC). A new switching function was designed based on the estimated state of the observer

$$\hat{s} = \hat{e} + {}^{2k_1 e}\Big/_{1+\exp\left(-\mu_1(|e|-\varphi)\right)} + {}^{2k_2|e|^{\alpha} sign(e)}\Big/_{1+\exp\left(\mu_2(|e|-\varphi)\right)},$$

$0 < \alpha < 1, \varphi = \frac{\gamma_2}{\gamma_1}^{1/_{1-\alpha}}$, and k_1, k_2, μ_1, μ_2 were positive constants, the following constraints were satisfied for the system to operate in sliding mode $\hat{s} \doteq 0, \dot{\hat{s}} = 0$. The combined controller ensured fast convergence in a finite-time, enhanced the robustness to system uncertainty, improved the tracking performance of the controller and reduced jitter.

4.6 Application of SMC in mechanical systems

In mechanical system modelling, system uncertainty is generally inevitable due to the unknown system parameters or the input of external interference signals. The controller design is mostly difficult because of the high nonlinearity of mechanical systems. For uncertain nonlinear systems, SMC is an effective robust control method. Bartolini et al. [68–71] conducted a series of studies on sliding-mode variable structure control in complex and uncertain nonlinear mechanical systems by designing a switching function for the second derivative. The systems were extended to a multi-input nonlinear system, and chattering was evidently eliminated using the continuous variable structure control law in time. Second-order SMC has been successfully applied to a manipulator control system with constraints, an unmodelled actuator control system and machinery with Coulomb friction in the system. In [72], a second-order sliding-mode controller was designed to ensure that a two-degree-of-freedom manipulator can achieve stable index tracking and parameter changes. The output signal was smoothed through a second-order filter, which effectively suppressed the manipulator jitter problem. In [73], a smoothing strategy based on a new type of score difference was proposed by describing functional technology, which provided a reasonable range of tracking accuracy for servo systems and eliminated the chattering phenomenon effectively. The new strategy was suitable for a second-order or higher-order unmodelled dynamic DC servo mechanism. Article [74] developed an integrated SMC in the fluid power electro-hydraulic actuator (EHA) system. An EHA system model was established with load interference and measurement noise. The optimal feedback gain derived from H_∞ control and regional pole placement enabled EHA systems to be driven to the quasi-sliding mode surface. In [75], the SMC law was formulated in the uncertain Markov jump linear time-delay system. A generally uncertain transition rate (GUTR) model was established, and linear matrix inequalities (LMIs) were used to ensure the stochastic stability of the system. SMC law could force the state trajectory of time-delay system onto the sliding surface within a finite-time interval. In [76], a saturated adaptive SMC technology was applied to the relative position controller and relative attitude height controller of a quadrotor, and the saturation efficiency and model uncertainty of the autonomous ship control input were evaluated. The performance was estimated and compensated, and the goal of stable landing of the ship was achieved. In [77], H_∞ filters were studied in Itô stochastic systems with Markov switching, and the existing optimization problems of linear matrix inequalities (LMIs) was solved to ensure the existence of finite-time H_∞ filters. In [78], a dissipative global SMO was designed for a nonlinear mechanical system with two degrees of freedom. Although the nonlinear system did not have the attribute of bounded input bounded state, the observer could theoretically converge the global finite time to the actual speed of the system. Article [79] combined reverse thrust (BS) control and SMC to form a new closed-loop controller. The multivariable super-twisting algorithm was used to reduce the controller flutter problem effectively, eliminate the disturbance and realise quadrotors' trajectory tracking under external interference and uncertain conditions. In [80] a sufficient condition for finite-time stochastic bounded degree (FTSB) was established in random singular Markov jump systems

(MJSs), which was based on stochastic functional methods and LMIs, and extended to the FTH∞SB. LMI conditions obtained by the state feedback controller ensured that systems with a partly known transition rates (TRs) were FTSB and FTH∞SB. In [81], a global SMC method was proposed and combined with a state observer to form a new controller, which solved the robustness problem of nonlinear systems with time-delay and input nonlinear uncertainties. The control process of the new method was simple and effectively eliminated the chattering phenomenon in the input process. The stability and global robustness of the entire nonlinear closed-loop system were improved. In [82], a neural network and adaptive NTSMC were combined to form a novel closed-loop control system. An adaptive target-tracking controller was proposed using an adaptive adjustment algorithm, which improved the underdriven autonomous underwater vehicle stability for aircraft target tracking. Paper [83] studied the nonlinear H∞SMC based on Takagi-Sugeno fuzzy observer, and the new controller could ensure the limited time accessibility of the predefined sliding surface. Text [84] designed a complementary sliding-mode controller for the guide vane opening of a 250 megawatt(MW) hydrogenation unit, which effectively reduced the various indicators of a 250 MW DFIM in a hydraulic turbine control system. Overshoot and settling time enabled the system to accelerate response speed and have ideal error-tracking capabilities. Article [85] designed the dynamic output feedback degree of freedom SMC. The system modelled the MJSs which subjected to stochastic communication protocol (SCP) and analysed the random stability of MJSs. The feasibility of control scheme was verified using a motor model. Article [86] combined simple square-wave voltage injection with NTSM observers and designed an overall system delay compensation method for hybrid position observers, eliminating the delay effect of multimode pulse width modulation sensor control, improving the wireless sensor control performance of an internal PMSM driver in rail transit. Paper [87] designed a model-free decentralized SMC and applied it to large-scale systems which subjected to injection attacks. New control scheme was implemented based on the adaptive dynamic programming (ADP) method, and an injection attack of sliding surface was compensated using the integral surface function to realise the optimal control of sliding mode dynamics. The parallel strategy iterative algorithm proposed in the scheme ensured the reachability of each sliding variable. Paper [88] designed a robust station-keeping control algorithm based on SMC for a hovering over-actuated autonomous underwater vehicle (HAUV). As a result, the HAUV could maintain a fixed position and direction underwater, and the robustness of the HAUV to model uncertainty and ocean current interference was improved. In [89], SMC was also used to realize a finite-time projection synchronization of variable-order fractional (VOF) chaotic systems. The finite-time stability analysis of the system was carried out. Assuming that there was a continuous-time positive-definite function $V(t)$ satisfied ${}_0^C D_t^{\varphi(t)} V(t) \leq -\lambda_1 V(t) - \lambda_2 \left| V^{\frac{1}{2}}(t) \right|$, where $\varphi(t) \in [\varphi_0, \varphi_1] \subset (0,1)$ and $\lambda_1, \lambda_2 > 0$.The novelty of [89] was that a new finite-time stability criterion was designed for the VOF control system, which realized the projection synchronization of VOF undisturbed chaotic system.

4.7 *Application of SMC in automotive systems*

With the continuous increase in global car ownership, environmental pollution, energy crisis, traffic accidents and other issues have become increasingly prominent, prompting the development of cars in the direction of safety, energy saving and intelligence. New energy vehicles have superior environmental performance and can relieve energy shortage; hence, they have become a research hotspot. Article [90] proposed a robust linear parameter varying (LPV) controller based on H_∞ control theory and applied it to the electric vehicle FOC framework, which solved the problem of the mechanical speed of electric vehicles due to thermal effects. Article [91] designed adaptive fuzzy SMC and applied it to the power distribution of hybrid electric scooters (HESs). The designed approach minimised the instantaneous cost function, obtained a minimum fuel power distribution of HESs and realised fuel economy of HESs. In [92], the SMC was constructed in accordance with a hidden Markov model, which ensured the reachability of SMC in automotive electronic valve systems. The scheduling protocol between sensor nodes of automotive electronic valve systems was determined by weighted try-once-discard (WTOD) and avoided data conflicts during the transmission of the system from sensors to controllers. In terms of vehicle motion control algorithms, domestic and foreign scholars have conducted research on vehicle arrangement, vehicle antilock braking, path following and automatic driving.

4.7.1 Vehicle platoon problem

In [93], the overall SMC was used for the vehicle-following interaction, and a distributed collaborative braking controller was developed. The transfer function method was utilised to analyse the chord stability of a vehicle platoon, and the distance error amongst vehicles and the speed error were reduced. Consequently, the vehicle energy consumption was effectively reduced, and road traffic congestion was alleviated. In [94], first- and second-order SMC methods were proposed to solve the problems of vehicle traction and platoon. SOSM control kept a vehicle at a safe distance from other vehicles. The new control method stabilised the vehicle under complex load conditions. Traction control improved the security and driving performance of the car.

4.7.2 Vehicle antilock braking system (ABS)

In [95], first-order sliding-mode (FOSM) and integral sliding-mode (ISM) control methods were presented for the wheel slip control (WSC) of electric vehicles. FOSM showed a strong ability to control in-wheel motors (IWM), and ISM demonstrated a strong antiuncertainty capability. The two control methods could be effectively utilised in IWM electric vehicles with WSC. Wen [96] combined optimal sliding-mode (OSM) control with ABS, designed a controller that is unaffected by torque distribution and applied it to nonlinear variable voltage charging control. The control system greatly improved the energy recovery efficiency of electric vehicles in the case of ABS. In [97], combined SMC and electric vehicle ABS (emABS) were integrated to improve the braking effect of battery electric vehicles, and the wheel deceleration and vehicle slip rate based on the SMC algorithm were used. emABS was controlled to improve the braking energy recovery rate. In [98], an improved nonlinear adaptive SMO was designed for the slip rate problem of distributed drive electric vehicles. The wheel slip rate was estimated by observing the changes in the longitudinal braking of the wheels, and the chattering was improved. The problem was equivalent to realising control of wheel slip rate.

4.7.3 Path-following problem

Article [99] combined compound nonlinear feedback control and ISM control to improve the transient performance of a four-wheel independent drive vehicle system, prevent system chattering problems and achieve accurate vehicle path-following control. Paper [100] designed an overall adaptive integral terminal sliding mode control scheme in an automotive electronic throttle system and combined it with an uncertainty observer. The new controller was on a sliding-mode surface to start, which improved the tracking accuracy of the system. In [101], a speed control strategy and a path-following control strategy based on the sliding-mode method were proposed for a self-driving car. The second-order super-twisting SMC (STSMC) provided and tracked the required speed of the vehicle to keep the tires away from road friction. The second-order quasi continuous (QC) path-following controller shortened the direction error and distance error between the vehicle and the path. Article [102] proposed terminal SMC based on the reaching law and combined it with nontime reference path-tracking control to form a new controller that can effectively avoid obstacles when a vehicle is automatically parked. The vehicle reference path-tracking effect was improved, such that the vehicle entered the parking space rapidly and safely.

4.7.4 Automatic drive

In [103], a new adaptive SMC controller was proposed by combining a state observer with SMC. Two nonlinear functions, the specified performance function and barrier function, were applicable to the sliding-mode surface. Lane-keeping stability of autonomous vehicles was realised, and the transient performance of the system was improved. In [104], a dual closed-loop cascade control framework based on SMC was designed to solve a decoupled integrated electro-hydraulic brake system. The outer loop used a conditional ISM controller to ensure stable tracking accuracy; the inner ring adopted SMC, which improved the response speed of the system. The new controller greatly reduced the economic cost and improved the stability of the system. In [105], a sub-OSM controller was proposed for the exploration of vehicle autonomous driving control in environmental characteristics. The controller was implemented in an embedded unit supporting the Robot Operating System and could automatically determine the trajectory of coastal areas and optimise autonomous driving functions. In [106], a feedback controller based on SMC and a path-tracking controller based on the autodriver algorithm were designed. They minimised the transient error between vehicle position and road, accelerated the control speed and improved the system control accuracy.

4.8 Application of SMC in unmanned aerial vehicles (UAVs)

A UAV is a typical underdriven, nonlinear and unstable system. Owing to their small inertial mass, poor anti-interference capability and high flight environment requirements, UAVs have high control system algorithm requirements. Domestic and foreign researchers have applied advanced control methods to the distributed control, tracking capability and fault tolerance control of quadrotor UAVs and other UAVs to ensure that the UAV control system has strong robustness.

4.8.1 Quadrotor UAVs

Article [107] developed a real-time hardware-in-the-loop-simulation platform for underactuated quadrotor drones and proposed a novel adaptive nonlinear sliding-mode controller for quadrotor drones, realising drone progressive adjustment, yaw asymptotic tracking and altitude asymptotic tracking. In [108], a fixed time controller based on sliding-surface was designed for the visual servo control of quadrotor drones, such that the image feature error variables of the drones converge to a stable equilibrium point in a fixed time. The stability of the coupled nonlinear closed-loop system was improved. Paper [109] proposed a vibration-free sliding-mode algorithm combined with the unit quaternion attitude trajectory. The algorithm constitutes a new controller that can perform stable trajectory tracking, such that the quadrotor UAV can be started when the motor is turned off. It can also reduce the deployment time of the drone. Text [110] designed a multi-mode UAV controller based on the super-distortion algorithm. It used the Lyapunov function to analyse the stability of the UAV flight mode and switching flight mode. New controller can achieve a stable flight mode transition under external interference.

4.8.2 Distributed control

In [111], proportional-derivative SMC (SMC PD) and linear quadratic regulator (LQR) SMC were proposed to form a multilayer distributed control system and maintain the geometric structure of the movement process of a UAV group. SMC PD effectively reduced the drone navigation trajectory deviation and shortened the nominal establishment time of the drone group by nearly half. LQC SMC eliminated interference and model uncertainty. Both control methods could achieve single drone modularity and scalability. Article [112] proposed a second-order nonlinear distributed algorithm for various UAV systems and applied it to multiagent systems. The algorithm provided smooth control input signals. A new formation control model was also developed. Trajectory tracking of three formations was realised to avoid the chattering effect.

4.8.3 Navigation tracking

Paper [113] applied first-order SMC to a fixed-wing UAV. Chattering was prevented by smoothing the control discontinuity of the boundary layer close to the switch surface, and the anti-interference capability of the UAV was improved. At the same time, the controller realised accurate heading rate calculation. This article [114] designed a closed-loop guidance law based on the SMC algorithm for the video surveillance of moving targets by using UAVs. The guidance law only measured the azimuth angle and was simple to calculate. It realised video surveillance of moving targets by using a drone. It also made the controller have a good hiding capability. In [115], a sliding-mode surface with PID structure and a neuro-fuzzy structure were combined to form an adaptive sliding-mode controller. The new controller has a new elastic structure that can achieve the best approximation and rapidly restore system performance, such that UAVs can perform stable trajectory tracking in complex situations. Article [116] introduced a drone navigation method, which was based on a real-time SMC algorithm. It prevented the collision problem of multiple drones running at the same time, reduced the target uncertainty and made the drones accurately monitor moving targets on the ground.

4.8.4 Fault tolerance control

In [117], two UAV fault-tolerant control schemes were proposed. The two schemes combined SMC and control distribution based on LPV, without the need to reconfigure the UAV. They could redistribute the signal, and the UAV could maintain a good state-tracking capability under uncertain conditions and failures. In [118], a new strategy based on adaptive SMC was proposed for the motor failure of a coaxial octorotor UAV. The STSMC strategy could readjust the gain in accordance with the detected motor error, monitor the operating status of the system in real time, accelerate the response and ensure the stability of the system.

5. Conclusions

The development of process control has remarkably improved the control performance of autonomous systems. SMC is an effective means to improve the control performance of ASs in complex environments. This article discusses SMC in motors, microgrids and switched systems. A comprehensive analysis of the application directions of aviation guidance, robots, mechanical systems, automobiles and UAVs is performed, and a new direction of SMC in the application and development of complex ASs is indicated. In the future, chattering attenuation NTSMC can be developed to eliminate the instability impact of chattering on wind turbine systems. For the observer controller of an electric drive system, the direction of the controller structure can be improved, and the calculation time can be reduced. For tunable microelectromechanical systems, RASMCs can be utilised to study measurement noise problems and control energy consumption problems. For the voltage regulation of isolated AC microgrids, a distributed sliding-mode controller can be designed for time-varying parameter uncertainties. For solving network control systems with semi-Markovian switchings, the positive dynamics model based on the event-triggered scheme can achieve the stochastic stability of the system. What enhances the robustness of the system is that SMC law based on Lyapunov can ensure the trajectory of the system reaching the predetermined sliding surface. For the roll stability adjustment of robot fish, energy-optimised roll stability control can be designed to enable the robot fish to perform visual tasks, such as target tracking. For FAMR, RSSMC can be used for multimode switching control, such that FAMR has high manoeuvrability for trajectory tracking in complex environments. Discrete-time adaptive global sliding-mode controllers can be applied to uncertain nonlinear systems with time delays in the future. For AUV, the combination of neural network and adaptive NTSMC improves the stability of target tracking. For the antilock braking control system of electric vehicles, the distributed braking force of multimotor systems can be studied to achieve the highest overall efficiency of the vehicles. For automatic driving of cars, the yaw moment based on differential braking can be controlled to improve the tracking performance of automatic driving. For the problem of distributed control of UAVs, the UAV formation can be controlled in hardware format, such that the UAV formation can avoid obstacles when flying.

6. Challenges and prospects

It has attracted the attention of many scholars since Emelyanov and Utkin proposed sliding- mode variable structure control in the 1950 s. At first, it did not attract the attention of the control circles. With the rapid development of nonlinear systems and high technology, this control method has emerged in many complex systems, such as discrete systems, distributed parameter systems, time-delay systems and so on. However, it still faces some challenges and key technical problems. For example, one should analyze the reachability of sliding surface and the stability of sliding mode in complex nonlinear systems, reduce the chattering of the system effectively and track the target quickly and stably. What's more, whether the complexity of the system need to be further reduced for avoiding heavy structural design.

The application of SMC in complex systems could be expanded in the further study. The future research will focus on the following aspects: Firstly, the theory of SMC should be studied more deeply and the nonlinear system could be expressed as linear under certain conditions, which create conditions in order to turn theory into practice. Secondly, combining the technology with a practical problem to create a mature and symbolic model for learning and practice. Thirdly, the research results of this technology ought to be summarized in order to solve more problems related to these fields which based on some current application fields. Fourthly, SMC could be extended to more complex fields to solve other important problems, such as LMI convex optimization problems, time- delay problems and so on. With the depth and improvement of theoretical research as well as the settlement of many difficulties, it can be expected that SMC will have a widespread application prospect in ASs.

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Conflict of interest

The authors declare no potential conflict of interests.

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