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Reaching Conditions for Discrete-time Sliding Mode Control: Analysis and Design

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Abstract

Sliding mode control (SMC) is a robust control method widely used in engineering due to its ability to handle uncertainties and disturbances effectively. In discrete-time sliding mode control (DSMC), system trajectories are constrained to sliding surfaces in the state space, leading to improved performance and stability. This paper provides an overview of DSMC, focusing on its applications, advantages, and limitations. It discusses the use of DSMC in various engineering fields such as robotics, aerospace, and automotive systems, highlighting its robustness and effectiveness in practical scenarios. The paper also addresses the challenges and limitations of DSMC, including issues such as chattering, high control effort, and sensitivity to model uncertainties. Furthermore, the paper explores recent advances in DSMC and potential future research directions, suggesting that the development of advanced reaching laws could further enhance the performance and applicability of DSMC in real-world applications.

Keywords: Sliding mode control (SMC), discrete time sliding mode control (DTSMC), robust control

INTRODUCTION

Discrete-time sliding mode control is a robust strategy used to stabilize dynamic systems in the presence of uncertainties. It ensures that the system's movements converge to a predetermined sliding surface and remain there despite disturbances. The effectiveness of this method depends heavily on the design of reaching laws, which determine when the control system should switch between different modes. The concept of reaching laws in sliding mode control was introduced by Vadim Utkin in the late 1960s and early 1970s. Initially, simple first-order reaching laws were used, followed by higher-order laws for faster convergence. Non-switching laws were later introduced to further reduce chattering, and adaptive laws were developed to handle uncertainties, enhancing the robustness of the control system. Reaching laws are crucial for achieving desired performance, such as quick convergence, robustness, and reduced chattering. These laws can be designed in different ways, including fixed or adaptive approaches. Fixed laws are based on the system's dynamics and performance requirements, while adaptive laws adjust parameters based on real-time measurements to enhance performance in varying conditions.

The discrete-time system involves designing a sliding surface to guide the system to a desired trajectory despite uncertainties, possibly using novel control laws. An external trajectory generator based on a switching type reaching law selects trajectories based on system state, ensuring the system follows the desired path. However, a limitation is that the sliding variable can lead to bounded errors in variables. Control parameters are

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crucial to maintain quasi-sliding-mode existence, helping the system stay close to the desired trajectory [1]. The paper introduces a new reaching law for discrete-time sliding-mode control, which uses a combination of a power function, exponential term, perturbation estimation, and difference function to adjust control gains and adapt to changes in the system's behaviour. This reaching law is designed to improve control performance by reducing chattering (rapid switching of control signals) and ensuring a smaller width of the quasi-sliding-mode domain (QSMD), which is the region around the sliding surface where the system's behaviour is close to sliding mode. The paper also includes theoretical analyses of the system dynamics during the reaching and sliding phases, considering different control gain values. The effectiveness of the proposed method is demonstrated through numerical simulations and experimental tests using a piezoelectric actuator [2]. The paper introduces an adaptive reaching law combined with a sliding mode controller for robust control. The adaptive reaching law dynamically adjusts the control strategy based on the system's state and uncertainties, ensuring robust performance in the face of varying conditions. A simulation example is provided to verify the effectiveness of the proposed method, demonstrating its ability to stabilize the system and accurately track desired trajectories. Additionally, the paper compares the proposed method with other reaching laws, such as the disturbance compensator reaching law (DCRL), novel dead zone reaching law (NDZRL), and novel exponential reaching law (NERL), showing its superiority in terms of control quality and robustness. However, a limitation of the proposed method is the potential complexity of implementing the adaptive reaching law in real-time systems, which may require significant computational resources and could introduce additional delays in the control loop [3]. The paper proposes a novel reaching law for discrete-time sliding mode control, developed using methods like quadratic optimization, pole placement, and dead-beat design. This reaching law is part of a nonlinear sliding mode controller that accounts for model uncertainty and disturbances, aiming to improve control performance. It is designed to eliminate chattering, enable fast convergence with minimal control signal usage, and ensure that supply orders are both non-negative and upper-bounded. Additionally, the paper introduces the concept of quasi-sliding mode, where the system's state remains close to the sliding hyperplane without necessarily crossing it, providing a flexible approach to control [4]. The paper presents a novel approach called multi-power reaching law-based sliding-mode control (SMC) for uncertain discrete-time systems. This method adapts control gains based on different stages of the convergence process, leading to faster convergence and improved control accuracy. The function kh(x) is described as monotonically decreasing with respect to x in the region (0,), indicating its behaviour for positive values of x. Additionally, the paper discusses the computation of the difference between s(k+1) and s(k) based on control parameters and the sign function, which likely plays a role in the control algorithm's implementation. The function g(x) is introduced, satisfying certain conditions and used to derive expressions related to sliding-mode control, suggesting its importance in the control design process [5].

The paper introduces a new sliding mode controller with disturbance compensation for sampled data systems, aiming to eliminate chattering and reduce disturbance effects. It uses a reference sliding variable profile generated by a non-switching reaching law for stability and robustness. However, the controller's performance may be affected by modelling inaccuracies and parameter variations. The control scheme ensures that the plant closely follows the reference, limiting disturbance effects to a single time step. While a disturbance compensation method is proposed to further improve robustness, its effectiveness in dynamic or uncertain environments may be limited. Overall, the controller shows promising results in simulations compared to conventional methods [6]. The paper proposes a reaching law for uncertain discrete time systems to ensure limited sliding variable rate of change and asymptotic convergence to zero. The reaching law is utilized to design a control strategy for inventory management systems with multiple suppliers and limited warehouse capacity. The control strategy guarantees that suppliers are not forced to send more goods than they are capable of and that warehouse capacity is never exceeded. The strategy also ensures that consumers' demand is always fully satisfied. The proposed reaching law approach is proven to satisfy all the desirable properties of the system and is an alternative solution to time-varying sliding hyperplanes in variable structure systems [7]. The paper proposes a novel reaching law for discrete-time sliding-mode control. The reaching law is based on an

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exponential term that dynamically adapts to the variation of the switching function. The proposed reaching law guarantees a smaller width of the quasi-sliding-mode domain (QSMD) and decreases the reaching time. The ultimate magnitude of the QSMD in the proposed method is of the order O(T^3). The reaching steps for the system to converge to the sliding surface are obtained and the system dynamics in and out of the QSMD are theoretically analysed. Numerical simulations and experimental investigations on a piezoelectric actuator validate the effectiveness of the proposed method [8]. Excessive chattering, a rapid and high-frequency switching of the control signal near the sliding surface, is a significant issue in Delta-Operator Sliding Mode Control (DSMC) when using a non-smooth reaching law. This phenomenon degrades system performance and can lead to wear on mechanical components due to the discontinuity in the control law. As the system state approaches the sliding surface, the control signal switches rapidly between its upper and lower bounds, causing oscillations in the system output and making stabilization challenging. To address this, various approaches have been proposed, such as using a smoothing function, incorporating a dead-zone in the control signal, or adopting a different reaching law for smoother control action near the sliding surface. These strategies aim to reduce the effects of chattering while maintaining system stability and performance [9]. The paper proposes a sliding mode controller (SMC) for discrete-time systems, employing an adaptive reaching law based on a negative power term that adjusts to variations in the switching function. This controller aims to expedite the system trajectories' entry into the desired quasi sliding mode domain (QSMD) while minimizing chattering. Compared to traditional controllers, the proposed scheme achieves similar reaching times but with lower chattering amplitudes. The controller's parameters are set as follows: a=0.8, d=0.0099, g=0.05, and l=5. Numerical examples on a second-order system with time-varying uncertainties demonstrate the effectiveness of the proposed controller [10].

FUNDAMENTALS OF SLIDING-MODE CONTROL (SMC)

Principles and Applications

Sliding-mode control (SMC) ensures stability and robustness by guiding the system state to a specific surface. Quasi-sliding mode reduces errors and control effort by allowing the system to stay close to this surface. Discrete-time sliding-mode control, stemming from electronic and digital systems, adapts SMC to discrete-time dynamics. Researchers aim to improve control by handling input limits and reducing errors in system states [1]. Sliding-mode control is a robust and nonlinear technique that is insensitive to disturbances. It guides the system state to a predefined sliding surface, ensuring stability. In this approach, there are two phases: reaching, where the system approaches the surface, and sliding, where it stays on the surface. This method, called Discrete Sliding Mode Control (DSMC), is effective for dynamic systems with uncertainties [2]. Sliding mode control is robust against uncertainties and disturbances. The discrete-time version is popular in digital control systems. However, it lacks invariance, requiring extra effort to handle uncertainties. To simplify design and understand system behavior, the adaptive reaching law method is used [3]. Sliding mode control guarantees system stability by directing it to a predefined hypersurface. Discrete-time sliding mode control provides both robustness and computational efficiency [4]. Multi-power reaching law-based sliding-mode control is proposed for uncertain discrete-time systems. The control gains are adaptively adjusted using a multi-power function to achieve faster convergence. Theoretical analysis of sliding-mode dynamics and reaching steps is provided. Simulation results demonstrate reduced reaching steps and improved control accuracy [5]. Sliding mode control constrains a system to a predefined surface, reducing its dimensions and making it robust against disturbances. To achieve this, the control signal must switch with high frequency, which is crucial for its effectiveness [6]. Sliding mode control ensures stability and robustness in control systems. The reaching law approach avoids the need for complex Lyapunov-based proofs of stability. Discrete-time sliding mode controllers provide good robustness [7]. Sliding mode control guides the system state trajectory onto a specific surface, ensuring robust regulation. The design of Discrete Sliding Mode Control (DSMC) emphasizes discrete-time control with robustness. Quasi-Sliding Mode (QSM) and Quasi-Sliding Mode Domain (QSMD) are regions where quasi-sliding mode motion occurs, allowing for smoother control. The reaching law approach is used to reduce chattering and improve tracking accuracy in sliding mode control [8]. Sliding mode control ensures system stability despite disturbances. The delta-operator framework improves numerical stability in this control

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method. The sliding mode band (QSMB) is essential for system trajectory convergence. Continuous and discrete sliding mode control use different reaching laws [9]. Sliding mode control is studied in both continuous and discrete domains. Discrete Sliding Mode Control (DSMC) focuses on reducing chattering and improving system performance. The adaptive reaching law is a useful tool for effectively controlling discrete systems [10].

REACHING CONDITIONS IN DISCRETE-TIME SLIDING MODE CONTROL

Influence on System Behavior

In discrete-time sliding mode control, the rate of change of the sliding variable is limited during the reaching phase for smooth convergence. The reaching law-based control strategy determines how quickly the system reaches the sliding surface, affecting the duration of the reaching phase [1]. The reaching law in sliding mode control adjusts control gains to reduce chattering and smooth out the system's operation. It also helps steer the system towards the sliding surface, ensuring stability. Moreover, the reaching law simplifies the design of the Discrete Sliding Mode Control (DSMC) system while maintaining its robustness [2, 3]. In discrete-time sliding mode control, a reaching law is used to achieve fast convergence without chattering. The reaching law chosen is of the non-switching type, which ensures robustness and faster convergence, improving control performance [4]. The multi-power reaching law improves convergence and accuracy, while the single power law reduces steps with better accuracy. Both methods enhance control performance. Multi-power functions and perturbation estimation also boost convergence and accuracy. Reaching law methods in sliding mode control include non-switching, observed-based, power, and generalized approaches [5]. In discrete-time sliding mode control, reaching conditions include compensating for disturbances and updating controls to ensure stability. The goal of discrete-time SMC is to minimize the bandwidth of quasi-sliding mode to improve control performance [6]. The reaching law in discrete-time systems limits the rate of change of the sliding variable, ensuring smooth convergence. This law guarantees that the variable converges asymptotically to zero, indicating stability. Designing control strategies based on reaching law simplifies the stability analysis, bypassing the need for complex Lyapunov-based proofs [7, 8]. Delta-operator based reaching laws ensure that system trajectories in discrete-time sliding mode control converge to their continuous-time counterparts. The Quasi-Sliding Mode Band (QSMB) confines system trajectories near the sliding surface, and the delta-operator facilitates a smooth transition between discrete and continuous time models [9, 10].

DESIGN CONSIDERATIONS IN SLIDING MODE CONTROL

Key Aspects for Effective Control System Implementation

An adaptive reaching law for robust control of discrete-time systems without needing a boundedness assumption on the system state. This law adjusts control gains to reduce chattering, where the control signal rapidly switches between values. The reaching law, featuring a power function and exponential term, enhances adaptability and control performance. Theoretical analysis includes studying the decrement band and Quasi-Sliding Mode Domain for stability. Validation is done through simulations and experiments, showing improved stability and performance [1–3]. Designing a sliding mode control system, consider the reaching law for smooth transitions and reduced chattering. Fast convergence helps the system reach its target swiftly. Limiting the sliding variable's rate of change prevents abrupt control signal changes. Including multiple suppliers with varying lead times and losses ensures adaptability. Keeping the control signal non-negative and bounded maintains system stability [4]. The multi-power reaching law improves the convergence rate and control accuracy of the system. It achieves this by enhancing the system's ability to reach the desired sliding surface more quickly and accurately. Additionally, the stability analysis of the system includes considerations of its dynamics and the steps involved in crossing the sliding surface [5]. A new sliding mode controller has been developed for sampled data systems, which includes compensation for disturbances. The controller uses a reference sliding variable profile that is generated using a non-switching reaching law. This reaching law is responsible for determining how the system approaches the sliding surface, which is essential for maintaining stability and robustness in the presence of disturbances [6, 7]. The delta-operator framework improves control design by enhancing numerical stability. Calculating the Quasi-Sliding

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Mode Band (QSMB) is crucial for delta-operator-based controls, defining where system trajectories stay near the sliding surface. Discrete Sliding Mode Control (DSMC) and Continuous Sliding Mode Control (CSMC) use different reaching laws and stability analysis due to their discrete and continuous natures. Robust control is vital for uncertain systems, ensuring stability and performance despite uncertainties [8, 9]. Designing a controller with an adaptive reaching law for DSMC systems involves selecting parameters for control signal and system response. The adaptive law allows adjustment based on the system's response for robust performance. Estimating disturbances with historical data involves analyzing past disturbances for future prediction. The design aims for a balanced controller in DSMC systems, considering convergence, chattering reduction, and robustness. Overall, careful parameter selection and disturbance estimation are crucial for effective DSMC system design [10].

Consider the following uncertain system with parameter uncertainty and external disturbance,

$$\dot{x} = [Ax + \Delta Ax]x + Bx\,u + d \quad (1)$$

where $x \in Rn$ and $u \in R$ denote the state vector and the control input, respectively. Ax and Bx are system matrices with appropriate dimensions. The parameter uncertainty and the external disturbance are represented by ΔAx and d, respectively. The system model (1) can be discretized with a sample period of T by the first-order Euler approximation [3].

$$x(k + 1) = Ax(k) + Bu(k) + T[\Delta Ax(k) + d(k)] \quad (2)$$

where $A = (I + TAx)$, $B = TBx$, $\Delta A = \Delta Ax$, I is an identity matrix

The following switching function is employed in reaching law method:

$$s_k = c_{xk}, \quad (3)$$

where $C \in R1\times n$ is the gain vector of the switching function. The control objective is to drive the system trajectory to converge onto the sliding surface S defined in (4) and also move toward the origin along the sliding surface [8]

$$S = \{x_k |\, c_{xk} = 0\} \quad (4)$$

System (1) is said to be in a QSM within the ΔΩ neighborhood of the specified sliding surface (4) if a motion of this system satisfies [8–10]

$$|s(k)| \le \Delta\Omega \quad (5)$$

for all $k > k*$, where $k*$ is a constant integer, and Δ in (5) is regarded as width of the QSMD. With Δ vicinity of the switching function (4), the reaching condition for (2) is said to be satisfied. A discrete-time system is said to satisfy the reaching condition of QSMD if, for all $k \ge 0$, the following conditions are satisfied

$$-\Delta\Omega \le s(k + 1) < s(k), \text{ if } s(k) > \Delta\Omega \quad (6)$$

$$s_k \le s(k + 1) < \Delta\Omega, \text{ if } s_k < -\Delta\Omega \quad (7)$$

$$|s(k + 1)| \le \Delta\Omega, \text{ if } |s_k| \le \Delta\Omega \quad (8)$$

The proposed adaptive reaching law is as follows:

$$s_k+1 = \alpha sk - \frac{\delta}{\varphi(k)}\,\text{sgn}(s_k) + C(dk - 2dk-1 + dk-2) \quad (9)$$

$$\varphi(k) = \gamma + (1 - \gamma)(|\, s_k| + 1)-l, \quad (10)$$

$0< \alpha < 1$, $0 < \gamma < 1$, $l > 0$ and $\delta > \xi$. Substituting (2) into (3) and comparing with (9), the controller designed for (2) can be derived as

$$uk = (C\Delta)^{-1}[\alpha s\,k - \frac{\delta}{\varphi(k)}\,\text{sgn}(s_k) - C\Delta x\,k - C(2dk-1 - dk-2)] \quad (11)$$

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When the proposed controller (11) is applied to the system (2) the system trajectory starting outside the QSMD will move monotonically towards the QSMD.

If s_k is outside the boundary of QSMD, Case 1: When $s_k > \Delta > 0$, $\varphi \in (\gamma, 1)$ and $\delta > \xi$, it can be obtained that

$$s_k+1 = \alpha s\ k - \frac{\delta}{\varphi(k)} \operatorname{sgn}(s_k) + C(dk - 2dk{-}1 + dk{-}2)$$

$$< s_k - \frac{\delta}{\varphi(k)} + \xi k < s\ k \quad (12)$$

Since $s_k > \Delta$, it can be calculated that $s_k+1 > 0$.

Case 2: $s_k < -\Delta < 0$,

$$s_k+1 = \alpha s\ k - \frac{\delta}{\varphi(k)} \operatorname{sgn}(s_k) + C(dk - 2dk{-}1 + dk{-}2)$$

$$< s_k + \frac{\delta}{\varphi(k)} + \xi k < s\ k \quad (13)$$

Since $s_k < -\Delta$, it can be calculated that $s_k+1 < 0$.

The inequality,

$$||D_k|| \leq ||(C\Delta)^{-1}|| \cdot ||C|| \cdot (||dk{-}2|| + ||2dk{-}1||) + \bar{d} \leq ||(C\Delta)^{-1}|| \cdot ||C|| \cdot 3\bar{d} + \bar{d} \quad (14)$$

represents a bound on the norm of the matrix D_k in the context of a control system. Here, D_k is a matrix related to the system dynamics, and $\|.\|$ denotes the matrix norm. The inequality indicates that the norm of D_k is bounded above by a function of the norms of matrices C and C', as well as the norms of the vectors d_{k-2} and d_{k-1}, and a constant D_k. This bound ensures that the influence of D_k on the system dynamics remains within certain limits, which is important for stability and performance of the control system.

RESULTS AND ANALYSIS

The results of the study demonstrate the effectiveness of the proposed control method in improving system performance. Simulation results show that the system converges to the Quasi-Sliding Mode Boundary (QSMB) within a short time frame of 15 seconds. Despite initial chattering due to discontinuity in the control signal, the proposed method successfully reduces system trajectory time within the desired Quasi-Sliding Mode Dynamics (QSMD), resulting in a significant decrease in chattering levels. An adaptive reaching law, part of the proposed method, is introduced to maintain these reduced chattering levels while achieving the desired results. This adaptive law also leads to a reduction in the width of the QSMD and the bounds of state trajectories, indicating improved system performance. Experimental verification further validates the effectiveness of the proposed method, demonstrating smaller QSMD width and faster reaching speeds compared to existing methods. The proposed method is a control strategy based on sliding mode control with an adaptive reaching law which incorporates an adaptive reaching law and other components, emerges as a superior approach. It not only reduces chattering and reaching time but also ensures a smaller QSMD width, faster convergence rate, and superior robustness and control accuracy compared to existing methods. Experimental verification confirms the method's effectiveness, making it a promising approach for improving system performance in discrete-time disturbed systems.

Discussion And Future Directions

The field of control systems should prioritize real-time implementation and experimental validation of proposed strategies to ensure their practical feasibility and effectiveness in real-world scenarios. This includes thorough testing and comparison of novel reaching laws, such as the enhanced power reaching law, against existing methods to demonstrate improvements in control performance. Additionally, wise adjustment of control gains to mitigate chattering and enhance overall system performance is crucial,

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as previous methods have often lacked such adjustments, leading to suboptimal control strategies. By addressing these aspects through rigorous experimentation and validation, researchers can contribute to enhancing control strategies across various domains, showcasing their versatility and applicability in diverse scenarios.

Furthermore, future research should focus on advancing adaptive control strategies for uncertain discrete-time systems by exploring the application of the multi-power reaching law in different domains. Understanding the impact of proposed reaching laws in diverse scenarios will be essential for ensuring robustness and adaptability across various applications. Analysing the scalability and adaptability of systems in real-world settings will also be crucial for determining practical implications and limitations. Finally, exploring enhancements to increase the reaching speed in systems, especially in complex industrial applications, will be vital for improving overall performance and efficiency. By addressing these key areas, future research can contribute significantly to the advancement of adaptive control strategies, paving the way for more effective and reliable control systems in the future.

CONCLUSIONS

This review article illuminates the advancements and potential of sliding-mode control strategies, particularly emphasizing their analysis within and outside the quasi-sliding mode domain (QSMD). The strategies exhibit remarkable efficiency, evidenced by their ability to guide trajectories across the sliding surface swiftly with specific parameters. Their stability and dependability are further underscored by the switching function's ability to remain within the QSMD once engaged, complemented by delta-operator stability analysis aligning with continuous-domain counterparts, establishing a robust theoretical foundation. The introduction of novel reaching laws and quasi-sliding mode band calculations offers ingenious solutions to traditional control challenges. Validation through simulation results, especially in mitigating the chattering-reaching time dilemma, provides compelling evidence of their practical effectiveness. The methods' validation through simulations and experiments on a piezoelectric actuator underscores their robustness and suitability for real-world applications. Moreover, the adaptive reaching law's capacity to estimate unknown system parameters and external disturbances enhances the adaptability and robustness of these control strategies. Lastly, the review highlights the superior performance of the novel discrete sliding mode control (DSMC) controller over established methods like NERL, NDZRL, and DCRL in terms of robustness and control accuracy. Overall, this review article not only sheds light on the current advancements in sliding-mode control strategies but also sets the stage for future research and development in this promising field.

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