

Preface

Variable structure systems (VSS) and its main mode of operation sliding mode control (SMC) are recognized as one of the most efficient tools to deal with uncertain systems due to their robustness and even insensitivity to perturbations [1–3].

The main advantages of VSS/SMC methodology are:

- theoretical insensitivity with respect to the matched perturbations;
- reduced order of sliding mode dynamics;
- finite-time convergence to zero for sliding mode variables.

However, the development of the VSS/SMC theory has shown their main drawbacks: the chattering phenomenon, namely high-frequency oscillations appearing due to the presence of parasitic dynamics of actuators, sensors, and other non-ideality.

During the last decade, one of the main lines in development of the SMC theory was development of the homogeneous higher-order sliding mode controllers (HOSMC) (see [4–6]). At the first stage, the proof of such algorithm was based on the arguments of homogeneity and geometry.

The main driver of development in recent two years is the new Lyapunov-based approaches for HOSMC design and gain selection [7, 8]. Moreover, the development of Lyapunov function approaches allows to design continuous sliding mode algorithms [9–13].

Different properties of SMC algorithms are investigated, like properties of HOSMC for wider classes of homogeneous systems, as well as properties of SMC for stochastic systems [14] and properties of SMC in frequency domain [15, 16]. Different adaptive algorithms were recently developed [17, 18]. These new algorithms were actively used to both ensure the tracking in different control problems and implement it for control in different real-life systems.

This book is an attempt to reflect the recent developments in VSS/SMC theory and reflect the results which are presented. The book consists of three parts: in the first part (i.e., Chaps. 1–7), new VSS/SMC algorithms are proposed and its properties are analyzed; in the second part (i.e., Chaps. 8–13), the usage of VSS/SMC techniques for solutions of different control problems is given; in the

third part (i.e., Chaps. 14–16), applications of VSS/SMC to real-time systems are exhibited.

Part I: New VSS/SMC Algorithms and Their Properties (Chaps. 1–7)

In Chap. 1 “Lyapunov-Based Design of Homogeneous High-Order Sliding Modes” by Prof. Jaime A. Moreno, the author provides a Lyapunov-based design of homogeneous high-order sliding mode (HOSM) control and observation (differentiation) algorithms of arbitrary order for a class of single-input-single-output uncertain nonlinear systems. First, the authors recall the standard problem of HOSM control, which corresponds to the design of a state feedback control and an observer for a particular differential inclusion (DI), which represents a family of dynamic systems including bounded matched perturbations/uncertainties. Next, the author provides a large family of zero-degree homogeneous discontinuous controllers solving the state feedback problem based on a family of explicit and smooth homogeneous Lyapunov functions. The author shows the formal relationship between the control laws and the Lyapunov functions. This also gives a method for the calculation of controller gains ensuring the robust and finite-time stability of the sliding set. The required unmeasured states can be estimated robustly and in finite time by means of an observer or differentiator, originally proposed by Prof. A. Levant. The author gives explicit and smooth Lyapunov functions for the design of gains ensuring the convergence of the estimated states to the actual ones in finite time, despite the non-vanishing bounded perturbations or uncertainties acting on the system. Finally, it is shown that a kind of separation principle is valid for the interconnection of the HOSM controller and observer, and the author illustrates the results by means of a simulation on an electromechanical system.

In Chap. 2 “Robustness of Homogeneous and Homogeneizable Differential Inclusions” by Dr. Emmanuel Bernuau, Prof. Denis Efimov, and Prof. Wilfrid Perruquetti, the authors study the problem of robustness of sliding mode control and estimation algorithms with respect to matched and unmatched disturbances. Using the homogeneous theories and locally homogeneous differential inclusions, two sets of conditions are developed to verify the input-to-state stability property of discontinuous systems. The advantage of the proposed conditions is that they are not based on the Lyapunov function method, but more related to algebraic operations over the right-hand side of the system.

In Chap. 3 “Stochastic Sliding Mode Control and State Estimation” by Prof. Alex S. Poznyak, the author deals with the SMC technique applied to stochastic systems affected by additive as well as multiplicative stochastic white noise. The existence of a strong solution to the corresponding stochastic differential inclusion is discussed. It is shown that this approach is workable with the gain control parameter state-dependent on norms of system states. It is demonstrated that under such modification of the conventional SMC, the exponential convergence of the averaged squared norm of the sliding variable to a zone (around the sliding surface) can be guaranteed, of which the bound is proportional to the diffusion parameter in the model description and inversely depending on the gain parameter.

The behavior of a standard super-twist controller under stochastic perturbations is also studied. For system quadratically stable in the mean-squared sense, a sliding mode observer with the gain parameter linearly depending on the norm of the output estimation error is suggested. It has the same structure as deterministic observer based on “the Equivalent Control Method.” The workability of the suggested observer is guaranteed for the group of trajectories with the probabilistic measure closed to one. All theoretical results are supported by numerical simulations.

In Chap. 4 “Practical Stability Phase and Gain Margins Concept” by Prof. Yuri Shtessel, Prof. Leonid Fridman, Dr. Antonio Rosales, and Dr. Chandrasekhara Bharath Panathula, the authors present a new concept of chattering characterization for the systems driven by finite-time convergent controllers (FTCC) in terms of practical stability margins. Unmodeled dynamics of order two or more incite chattering in FTCC-driven systems. In order to analyze the FTCC robustness to unmodeled dynamics, the novel paradigm of tolerance limits (TL) is introduced to characterize the acceptable emerging chattering. Following this paradigm, the authors introduce a new notion of Practical Stability Phase Margin (PSPM) and Practical Stability Gain Margin (PSGM) as a measure of robustness to cascade unmodeled dynamics. Specifically, PSPM and PSGM are defined as the values that have to be added to the phase and gain of dynamically perturbed system driven by FTCC so that the characteristics of the emerging chattering reach TL. For practical calculation of PSPM and PSGM, the harmonic balance (HB) method is employed, and a numerical algorithm to compute describing functions (DFs) for families of FTCC (specifically, for nested, and quasi-continuous higher-order sliding mode (HOSM) controllers) was proposed. A database of adequate DFs was developed. A numerical algorithm for solving HB equation using the Newton–Raphson method is suggested to obtain predicted chattering parameters. Finally, computational algorithms to that identify PSPM and PSGM for the systems driven by FTCC were proposed. The algorithm of a cascade linear compensator design that corrected the FTCC, making the values of PSPM and PSGM to fit the prescribed quantities, is suggested. In order to design the flight-certified FTCC for attitude for the F-16 jet fighter, the proposed technique was employed as a case study. The prescribed robustness to cascade unmodeled actuator dynamics was achieved.

In Chap. 5 “On Inherent Gain Margins of Sliding-Mode Control Systems” by Prof. Igor Boiko, the author defines notion of inherent gain margin of sliding mode control systems. It is demonstrated through analysis and examples that an inherent gain margin depends on the sliding mode control algorithm and not on the plant. This property makes the inherent gain margin a characteristic suitable for comparison of different control algorithms. Analysis of the first-order sliding mode, hysteresis relay control, twisting algorithm, and suboptimal algorithm is presented.

In Chap. 6 “Adaptive Sliding Mode Control Based on the Extended Equivalent Control Concept for Disturbances with Unknown Bounds” by Prof. Tiago Roux Oliveira, Prof. José Paulo V.S. Cunha, and Prof. Liu Hsu, the authors propose an adaptive sliding mode framework based on extended equivalent control to deal with disturbances of unknown bounds. Nonlinear plants are considered with a quite

general class of (non)smooth disturbances. The proposed adaptation method is able to make the control gain large when the disturbance grows and decrease it if the latter vanishes, allowing for a minimized chattering occurrence. Global stability of the closed-loop system is demonstrated using the proposed adaptive sliding mode control law. Simulations are presented to show the potential of the new adaptation scheme in this adverse scenario of possibly growing or temporarily large disturbances.

In Chap. 7 “Indirect Adaptive Sliding-Mode Control Using the Certainty-Equivalence Principle” by Dr. Alexander Barth, Prof. Markus Reichhartinger, Prof. Kai Wulff, Prof. Johann Reger, Prof. Stefan Koch, and Prof. Martin Horn, the authors address the design of adaptive sliding mode controllers. The presented controllers compensate uncertainties acting on the input channel of the considered system and are characterized by a possible separation into a structured and an unstructured part. The latter class of uncertainty may affect the system in terms of an external disturbance, whereas a structured uncertainty typically occurs in the case of uncertain plant parameters. The presented controller design methodology enhances standard sliding mode controllers by an additional control action generated from an adaptation mechanism. Applying the certainty equivalence principle, it is possible to systematically handle both classes of uncertainties. The controller design is introduced step by step and demonstrated in detail for systems designated to be controlled by the super-twisting algorithm. The deviation of the adaptive part of the controller is thoroughly demonstrated by deriving three different types of adaptation laws. The requirement to enhance sliding mode controllers by the presented adaptive scheme is underpinned by a simulation scenario demonstrating cascaded feedback loops used for speed and current control of a DC motor. Experimental results obtained by a laboratory test-rig consisting of a motor with unbalanced load demonstrate the applicability of the discussed controller design method.

Part II: The Usage of VSS/SMC Techniques for Solutions of Different Control Problems (Chaps. 8–13)

In Chap. 8 “Variable Structure Observers For Nonlinear Interconnected Systems” by Dr. Mokhtar Mohamed, Prof. Xing-Gang Yan, Prof. Sarah K. Spurgeon, and Prof. Zehui Mao, the authors are concentrated on observer design for nonlinear interconnected systems in the presence of nonlinear interconnections and uncertainties. An approach to deal with nonlinear interconnections is proposed by separating the interconnections to linear and nonlinear parts based on an appropriate transformation. Using the structure property of the interconnected systems, novel variable structure dynamics are designed to observe the state variables of the interconnected systems asymptotically with low conservatism. A simulation example and a case study are presented to demonstrate the effectiveness and the feasibility of the developed results.

In Chap. 9 “A Unified Lyapunov Function for Finite Time Stabilization of Continuous and Variable Structure Systems with Resets” by Dr. Harshal B. Oza, Prof. Yury V. Orlov, and Prof. Sarah K. Spurgeon, the authors present a unified

Lyapunov function for finite-time stabilization of continuous and variable structure systems with resets. This chapter aims to uniformly stabilize a perturbed dynamics of the double integrator in the presence of impacts due to the constraints on the position variable. A non-smooth transformation is proposed to first transform the system into a variable structure system that can be studied within the framework of a conventional discontinuous paradigm. Then, a finite-time stable continuous controller is utilized, and stability of the closed-loop dynamics is proven by identifying a new set of Lyapunov functions. The chapter thus contributes to the VSS and SMC theory by the developing mathematical tools for the finite-time stability analysis of such systems in the presence of impacts.

In Chap. 10 “Robustification of Cooperative Consensus Algorithms in Perturbed Multi-Agents Systems” by Prof. Alessandro Pilloni, Prof. Alessandro Pisano, and Prof. Elio Usai, the authors exploit the integral sliding mode design paradigm in the framework of multi-agent systems. Particularly, it is shown how to redesign standard distributed algorithms for estimating the average value and the median value of the agent's initial conditions in spite of perturbations acting on the agent's dynamics. Constructive Lyapunov-based analysis is presented along with simulation results corroborating the developed treatment.

In Chap. 11 “Finite-Time Consensus for Disturbed Multi-Agent Systems with Unmeasured States via Nonsingular Terminal Sliding-Mode Control” by Dr. Xiangyu Wang and Prof. Shihua Li, the authors study the finite-time output consensus problem for leader–follower higher-order multi-agent systems with mismatched disturbances and unmeasured states. This problem is solved by using a feedforward–feedback composite control method which combines the integral-type non-singular terminal sliding mode control approach and a finite-time observer technique together. The main contributions include three aspects: Firstly, in the presence of mismatched disturbances and unmeasured states, the finite-time output consensus is realized by utilizing the distributed active anti-disturbance control for the first time. Secondly, the results extend the applicable scope of the distributed active anti-disturbance control from state feedback to output feedback. Thirdly, the disturbances considered in this chapter are allowed to be faster time-varying or have higher-order forms, which are not limited to slow time-varying types any more.

In Chap. 12 “Discrete Event-Triggered Sliding Mode Control” by Prof. Abhisek K. Behera and Prof. Bijan Bandyopadhyay, the authors present a discrete event-triggered SMC strategy for linear systems. Generally, in the event-triggered control, the state is continuously monitored to generate the possible triggering instant, which may incur additional cost and complexity. To overcome this, a discrete event-triggered SMC is proposed which evaluates event periodically and also guarantees the robust performance of the system. The discrete-time SMC is designed considering the triggering rule that ensures the stability with the discrete event-triggering strategy.

In Chap. 13 “Fault Tolerant Control Using Integral Sliding Modes” by Prof. Christopher Edwards, Dr. Halim Alwi, and Dr. Mirza Tariq Hamayun, the authors consider so-called integral sliding modes (ISM) and demonstrate how they can be employed in the context of fault-tolerant control. Two distinct classes

of problems are considered: Firstly, a fault-tolerant ISM controller is designed for an over-actuated linear system; secondly, an ISM scheme is retrofitted to an existing feedback control scheme for an over-actuated uncertain linear system with the objective of retaining the preexisting nominal performance in the face of faults and failures. The chapter includes with a case study describing the implementation of an LPV extension of one of the ISM schemes on a motion simulator configured to represent a Boeing 747 aircraft subject to realistic fault scenarios.

Part III: Applications of VSS/SMC to Real-Time Systems (Chaps. 14–16)

In Chap. 14 “Speed Control of Induction Motor Servo Drives Using Terminal Sliding-Mode Controller” by Prof. Yong Feng, Dr. Minghao Zhou, Prof. Fengling Han, and Prof. Xinghuo Yu, the authors apply a non-singular terminal sliding mode control method for the servo system of induction motors. The non-singular terminal sliding mode controllers for speed, flux, and currents are presented, respectively. The switching signals in the controller are softened to generate the continuous output signals of the controllers using the equivalent low-pass filters. Therefore, both the chattering is attenuated and the singularity is eliminated, which means that the controllers can be used in the practical applications.

In Chap. 15 “Sliding Modes Control in Vehicle Longitudinal Dynamics Control” by Prof. Antonella Ferrara and Dr. Gian Paolo Incremona, the authors present recent developments produced at the University of Pavia on application of sliding mode control to the automotive field. Specifically, the chapter focuses on the use of advanced SMC schemes to efficiently solve traction control and vehicle platooning control problems. A slip ratio SMC scheme is described, analyzed, and assessed in simulation. Then, the vehicle platooning control problem is introduced as an extended case of the previously described problem. A vehicle longitudinal dynamics control scheme, based on a suboptimal second-order SMC, is presented and coupled with the slip rate control scheme which allows to generate the correct traction control. The validation in simulation on a realistic scenario of the overall scheme is also discussed.

In Chap. 16 “Sliding Mode Control of Power Converters with Switching Frequency Regulation” by Dr. Víctor Repecho, Dr. Domingo Biel, Dr. Josep M. Olm, and Prof. Enric Fossas, the authors introduce a hysteresis band control loop that provides fixed switched frequency in sliding mode controlled systems while keeping the beneficial properties of sliding motion. The proposal is exemplified in DC-to-DC and DC-to-AC power converters carrying out regulation and tracking tasks, respectively, in the face of load disturbances and input voltage variations.

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