Preface

It is well known that linear dynamical systems cannot adequately describe many phenomena commonly observed in the real world. With the advancement of science and technology, practical systems are becoming more complex in order to complete more advanced tasks. With the increasing requirements for system performance, linear system theory based study cannot satisfy the practical requirements, and the mathematical equations used to model real physical and engineering systems have become more and more complex. In reality, there are many factors which will affect system performance. To describe and explore various natural phenomena, it is necessary to consider these factors and thus to investigate complex systems as a means to model real systems more accurately. This book systemises aspects of the authors' recent achievements in the area of variable structure control alongside with some fundamental knowledge in the area.

This book focuses on the study of complex control systems in which the complexity mainly stems from nonlinearities, uncertainties, time-delay, faults and/or coupling among subsystems. It provides rigorous theoretical solutions to the problem of control of complex systems but has potential application in practical systems. It should be emphasised that many theoretical studies on control systems often assume that all system states are available for control design. This assumption is not valid for real systems in many cases. To implement such control schemes, a pertinent way forward is to construct an appropriate dynamical system which is called an observer, to estimate the state variables. Unfortunately, the traditional separation principle for linear control systems usually does not hold for the nonlinear counterpart, which implies that for nonlinear systems, the properties of a state feedback control law may not be achieved when the control law is implemented with the estimated states. In connection with this, this book focuses on output feedback control design: both static output feedback and dynamical output feedback strategies, including reduced order dynamical output feedback strategies, are proposed to control complex systems such that the closed-loop systems have the desired performance.

Variable structure control techniques have been extensively studied, and widely applied to theoretical research and practical engineering systems due to their high robustness. Specifically, as one special case of variable structure controllers, sliding mode controllers are completely robust to matched uncertainties. Moreover, the sliding motion is determined by reduced order dynamics, which facilitates the reduction of the effects of mismatched uncertainties on the whole systems when compared with other methods. A key development in this book considers variable structure control for complex systems based on only output information, using mainly the Lyapunov direct method and sliding mode techniques, with the objective of enhancing the robustness against uncertainties, reduction of conservatism and enlargement of the admissible systems. Rigorous stability analysis and design methodologies are provided from a theoretical perspective for this theme. Nonlinearities appear in all the considered systems throughout the book. Both the matched and mismatched uncertainties covered in this book are nonlinear and bounded by nonlinear functions. Since the considered systems are complex and all the results are rigorous, the conditions developed for all the main results in this book are sufficient. As there is no general way to obtain the design parameters for an output feedback controller, trying to determine 'easy' test conditions with low conservatism, by separating possible known information from the system and then employing them in the design to reduce the effects of factors such as uncertainties and time-delay on the system, is one of the main targets throughout this book. The book also presents novel contributions to deal with nonlinear uncertainties for time-delay systems by combining the Lyapunov–Razumikhin approach and variable structure techniques for different cases when delay is known and unknown respectively. It is shown that for interconnected systems, decentralised control schemes are available to cancel/reduce the effects of the interconnections on the whole system performance, under certain conditions. One of the characteristics of this monograph is that many examples and case studies with simulations are given to help readers understand the developed theoretical results and the proposed approaches.

The first two chapters present fundamental knowledge used in later developments. Chapter 1 develops some preliminary ideas regarding variable structure control. Specifically, the basic concepts and fundamental methodologies for sliding mode control and decentralised control are provided. Some of them are clarified for the first time based on the authors' understanding as a result of the authors' many years of research work in the areas. Several practical examples are given to show the potential application of complex systems. This helps readers understand the main methods used in the book intuitively from both mathematical and practical points of view. Chapter 2 presents some preliminary mathematical results and some results developed by the authors.

Chapter 3 considers static output feedback control design for both nonlinear systems and interconnected systems. For a class of fully nonlinear systems, a variable structure control based on Lyapunov methods is designed to drive and maintain the system in a 'small' region of the origin. Then, in the region, the nonlinear system is linearised and a sliding mode control is designed to stabilise the system asymptotically. Both controllers combined together stabilise the system globally. For interconnected systems, decentralised control schemes are developed and output variables embedded in the nonlinearity are separated and used in the control design to reduce conservatism. Case studies relating to a mass–spring system, coupled inverted pendulums and a flight control system are provided to illustrate the developed control methodologies.

Chapter 4 considers dynamical output feedback control design for systems with mismatched uncertainties/disturbances such that the corresponding closed-loop systems are asymptotically stable. Compared with Chap. 3, all the uncertainties involved in this chapter are bounded by nonlinear functions of the system state variables instead of the output variables. The bounding functions are assumed to be known and thus it is possible to use them for control design and system analysis to reduce the effects of uncertainties. In Sect. 4.2, a sliding surface is designed which is independent of the designed observer, and then a sliding mode control is synthesised based on the estimated states from the designed observer and the system outputs. The controller design and the observer design are separated. The designed control can be implemented with any appropriate observer but the developed approach requires that the considered system is minimum phase. In Sect. 4.3, a dynamical compensator is designed first. A sliding surface is then designed for the augmented system formed by the considered system and error dynamics. It is not required that the nominal system is minimum phase. Applications to control of the High Incidence Research Model (HIRM) aircraft are given in Sect. 4.4. Both longitudinal and lateral aircraft dynamics based on different trim values of Mach number and height are employed in the simulation study.

Chapter 5 continues to consider dynamical output feedback controller design. It focuses on large-scale interconnected systems and uses reduced order compensators to form the feedback loop which is particularly important for large-scale systems as it may avoid 'the curse of dimensionality'. In Sect. 5.2, sliding mode dynamics are established and the stability is analysed using an equivalent control approach and a local coordinate transformation. A robust decentralised output feedback sliding mode control scheme is synthesised such that the interconnected system can be driven to the predesigned sliding surface. This approach allows both the nominal isolated subsystem and the whole nominal system to be nonminimum phase. In Sect. 5.3, a similar structure is introduced to identify a class of nonlinear large-scale interconnected systems. By exploiting the system structure of similarity, the proposed nonlinear reduced order control schemes allow more general forms of uncertainties. Specifically, based on a constrained Lyapunov equation, the effect of matched uncertainties is canceled completely. The study shows that a similar structure can simplify the analysis and reduce the amount of computation. Numerical simulation examples and a case study on river pollution control are provided to illustrate the results developed.

Chapters 6 and 7 consider complex systems with time-delay. A Lyapunov–Razumikhin approach is employed to deal with time-delay throughout the two chapters. All the developed results are suitable for time-varying delay and there is no limitation to the rate of change of the time-varying delay as with the Lyapunov–Krasovskii approach. Chapter 6 requires that the time-delay is known and thus the time-delay can be used in the design to reduce conservatism. Therefore the controllers are delay dependent. Chapter 7 removes the assumption that the time-delay is known but the results obtained are usually conservative when compared with Chap. 6. In Chap. 6, both static and dynamical output feedback control schemes are presented for complex time-delay systems; decentralised static output feedback sliding mode controllers are designed to stabilise complex interconnected time-delay systems where delay exists in both the interconnections and the isolated subsystems. In Chap. 7, local stabilisation is considered for affine nonlinear control systems with uncertainties involving time-varying delay. It is not assumed that the nominal system is either linearisable or partially linearisable. Section 7.4 focuses on the stabilisation problem for a class of large-scale systems with nonlinear interconnections. A decentralised static output feedback variable structure control is synthesised and a set of conditions is developed to guarantee that the considered large scale interconnected systems are stabilised uniformly asymptotically. Section 7.5 provides some examples to demonstrate the results developed in Sects. 7.2–7.4. Numerical simulation examples and a case study on a mass–spring system are provided to demonstrate the theoretical results.

Chapter 8 considers fault detection and isolation (FDI) for nonlinear systems with uncertainties using particular sliding mode observers for which the design parameters can be obtained using LMI techniques. In Sect. 8.2, a sliding mode observer based approach is presented to estimate system faults using bounds on the uncertainties, and as a special case, a fault reconstruction scheme is available where the reconstructed signal can approximate the fault signal to any accuracy. Section 8.3 considers sensor FDI for nonlinear systems where a nonlinear diffeomorphism is introduced to explore the system structure and a simple filter is presented to 'transform' the sensor fault into a pseudo-actuator fault scenario. Both fault estimation and reconstruction are considered. Case studies on a robotic arm system and a mass–spring system demonstrate the effectiveness of the proposed FDI schemes.

Chapter 9 provides a decentralised strategy for the excitation control problem of multimachine power systems which are formed from an interconnected set of lower order subsystems through a network transmission. Both mismatched uncertainties in the interconnections and parametric uncertainties in the direct axis transient short circuit time constants, which affect the subsystem input distribution matrix, are considered. The proposed approach can deal with interconnection terms and parametric disturbances with large magnitude. The results obtained hold in a large region of operation if the control gain is high enough. This allows the operating point of the multimachine power system to vary to satisfy different load demands. Simulations based on a three-machine power system are presented to illustrate the proposed control scheme.

Chapter 10 makes some concluding remarks. Several specific examples are presented to show the complexity of the systems considered in this book. Some comments offer suggestions for future work. Finally, Appendixes A to D provide some results (with rigorous proofs), which are used in the book, and Appendix E presents notation and the parameters of the multimachine power system considered in Chap. 9.

The book aims to disseminate recent results in the area of variable structure control of complex systems. It is suitable for scientists and engineers in academia and industry who are interested in either variable structure techniques or complex systems including nonlinear control, decentralised control, time-delay systems, robust control and fault detection and isolation. It is particularly valuable to have a combined set of references at the end of the book for ease of access to many important theoretical and practical applications. It contains many case studies and numerical examples with simulations to help readers understand and apply the developed theoretical results. The analysis and design methodologies are also useful for both undergraduate and postgraduate students in the field of nonlinear control systems design. We believe mathematicians and control engineers will find this book useful.

Last but not least, we would like to point out that this book only attempts to present part of the authors' recent achievements in the area of complex variable structure control, which is obviously built on many other previous results. Although we have tried to cover most of the recent important ideas and results in the area, the exposition is far from a complete overview of the associated subjects. The bibliography includes only the literature which has been actually used in the book. We sincerely apologise for any serious omissions, large or small.

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April 2016

http://www.springer.com/978-3-319-48961-2

Variable Structure Control of Complex Systems
Analysis and Design
Yan, X.-G.; Spurgeon, S.K.; Edwards, C.
2017, XXII, 350 p. 41 illus., 23 illus. in color., Hardcover
ISBN: 978-3-319-48961-2