Sliding Mode Control and Observation for Complex Industrial Systems—Part II

THIS Guest Editorial is for the special section on "Sliding Mode Control and Observation for Complex Industrial Systems—Part II," and it is the continuation of the previous part; see item 1) in the Appendix. The previous part of the special section (Part I) includes 14 papers, whereas this part (Part II) has 11 papers included. To facilitate the review of these 11 papers in Part II, we classify them into two categories according to their contents and focuses, i.e., seven papers are focused on the "control design of power electronics" (see items 2)–8) in the Appendix); and four papers are focused on the "control design of vehicle systems" (see items 9)–12) in the Appendix). Following is a brief review for each of these 11 papers.

The work in item 2) in the Appendix shows that the switching surface controllers are of minimum-switching and bang-bang natures for dc–dc converters and have the fastest analytically possible response time. Since such controllers remain drawbacks for the current limitation, the sensitiveness against small parameters and the computation burden nonlinear switching surface, a switched affine model of boost converters is used to reformulate its time response and to characterize its equilibrium states. With a piecewise linear switching surface, a constrained near optimal controller is proposed to guarantee the controller's robustness. For arbitrary switching surface controllers, a general condition for the existence of sliding mode and a novel method to check finite time reaching are presented. The proposed method is validated on an experimental setup with a boost converter prototype and a TMS320F2812 processor board.

Based on a higher order sliding mode observer, a robust control scheme is presented in item 3) in the Appendix for sensor fault-resilient control, and the applications in dc servomotor drive is provided, such as the antennae control for satellite tracking, radio telescopes, and conveyor belt systems. The incipient sensor faults and detects are considered in contrast to the earlier works on abrupt faults. A robust output tracking controller is developed based on fractional integral terminal sliding mode surface, and the faster and finite-time convergence of the error trajectory is ensured. With the estimated speed, whenever the residual crosses the threshold, various slopes of incipient faults are considered in the control system. In the presence of most common faults, the closed-loop performance is experimentally validated on a DC motor-based industrial mechatronic drives unit.

In item 4) in the Appendix, a new direct sliding mode voltage controller is designed based on parabolic modulation, and then, the application to buck converter is provided. The sliding mode controller is designed with simple control structure and good operating performance and can help to achieve constant-switching-frequency operation of a switching converter. It is validated on a buck converter that the proposed parabolic-modulation approach can achieve constant switching frequency in the continuous conduction mode and quasi-constant switching frequency in the discontinuous conduction mode. The inherent input disturbances can be rejected via the sliding mode controller, and superior reference tracking performance can be implemented. Besides, seamless mode transition between continuous conduction mode and discontinuous conduction mode can be also achieved.

In item 5) in the Appendix, a detailed second-order sliding mode control is presented to regulate active magnetic bearings systems throughout a wide operating speed range. Since the unavoidable imperfections in manufacturing, rotor mass imbalance is a common problem to rotating machines. To stabilize the inherently unstable system, a linear controller is designed as the first component. Meanwhile, to handle the model uncertainties of the system as well as the exogenous harmonic disturbances, a second-order sliding mode control is presented in second component. Additionally, compared to the conventional linear controller, the effectiveness and superiority of the proposed control techniques is demonstrated from simulation and experimental results.

In item 6) in the Appendix, a discrete-time sliding mode observer is designed for equivalent capacitor voltages control in modular multilevel converters. The communication complexity in applications is reduced with several series-connected submodules. In the voltage control loops, the observed voltages of the equivalent capacitors are used for simpler implementation. A new discrete time control methodology is presented to design the observer and ensure the transient and steady-state observer performances. Simulation results under distinct conditions are provided to demonstrate the effectiveness of the proposed methodology. For the equivalent capacitor voltages of the proposed control system, the effectiveness of the designed discrete-time sliding mode observer is also validated by experimental results.

In item 7) in the Appendix, a state-machine structure of second-order sliding mode control is proposed for three-level buck dc–dc converters without sensing currents. Comparing with the existing methods of balancing the flying capacitor voltage, the proposed control approach tackles the strongly coupled problem of output voltage and flying capacitor voltage, and the insensitivity to parameter variations can be ensured. For the output voltage, fast startup without overshoots, fast load

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disturbances rejection and robustness against parameter uncertainties, and balance of the flying capacitor voltage can be achieved using the controller without sensing the current of flying capacitor.

The work in item 8) in the Appendix presents a novel sliding mode control strategy of an islanded inverter-based microgrid to perform the exact finite-time restoration among voltages and frequencies. Distributed tracking consensus algorithms are designed to achieve voltage and frequency restoration in the secondary control layer of an islanded inverter-based microgrid. The presented control problem is attacked from a cooperative-based control perspective inspired to the tracking consensus paradigm. To enhance the robustness and convergence properties of the system with respect to the existing solutions, *ad hoc* chattering-free sliding mode based distributed algorithms are designed. The restoration is achieved while dispensing with the knowledge of the distributed generators' models and parameters. Besides, a simple set of tuning rules are derived for the performance of the control system. Simulations on a realistic inverter-based microgrid modelization illustrate the effectiveness of the proposed methodology.

In item 9) in the Appendix, a new model-free adaptive integral sliding mode-constrained control scheme is presented for autonomous four-wheeled mobile vehicle (4WMV) parking systems. For 4WMV, online identification for the object model is presented based on a data-driven technique, and a compact-form dynamic linearization-based observer formulation is used. In the autonomous 4WMV parking system, an integral sliding mode controller a dynamic antiwindup compensator is provided to solve integral saturation and actuator saturation problems. The advantage of this control scheme lies in that only the body angle and steering angle of the vehicle is utilized. The designed model-free sliding mode control scheme is compared with the PID control algorithm with coordinate compensation, and the simulation results show that the designed control scheme possesses a better control performance for the autonomous 4WMV parking system.

By using the sliding mode control strategy, the robust stability of a type of multiagent system with time delay and uncertainties is ensured in item 10) in the Appendix, while the insensitiveness to the parameter change and interference is implemented. Considering the conditions that the system is with fixed structure, every agent being only influenced by single time-delay and each agent being affected by multiple time delay, an improved sliding mode control law is synthesized. Lyapunov functions and the linear matrix inequality (LMI) approach are based to derive the robust stability of the sliding motion. Experiments on each condition are conducted to prove the effectiveness of the conclusion.

Considering a nonrecursive higher order sliding mode observer, the work in item 11) in the Appendix is concerned with the finite- and fixed-settling time differentiators. The estimation in fixed convergence time is achieved, which is independent of initial conditions of the differentiation errors. The corresponding convergence/settling times are also estimated. Against the Levant recursive sliding mode differentiators' performance, the finite- and fixed-time higher order ones are compared via a hypersonic missile control. The designed double-layer adaptive algorithm can avoid the overestimation of the control gains that mitigates control chattering. The simulation is carried out under the case during the missile's terminal phase of flight. For both the differentiators and the controller, the robustness and the high-accuracy output tracking performance are demonstrated in the presence of matched and unmatched external disturbances and missile model uncertainties.

For single input–single output dynamical systems, the authors in item 12) in the Appendix discuss constrained a quasi-sliding mode control problem based on the prescribed performance control technique. The goal of the work is to maintain the tracking error trajectory in a predefined convergence zone. The zone is described by a performance function in the presence of the uncertainties. A quasi-sliding mode control with a new sliding variable is designed in the discrete-time domain to achieve the goal. Meanwhile, the transient response of the system can be adjusted without producing the offset error in the steady state, by using a modified convergence zone. Finally, an experiment example on a piezo-actuated positioning system shows that the proposed method has good response and gives much better performance than the widely used PID controller in term of tracking accuracy.

We have made an overview for all the 11 papers included in the second part of the special section, and we hope that the selected contributions will increase the interest of researchers in related fields and push forward the research frontier of sliding mode control and observation for complex industrial systems.

LIGANG WU, *Guest Editor*
Harbin Institute of Technology
Harbin 150000, China

SUDIP K. MAZUMDER, *Guest Editor*
University of Illinois
Chicago, IL 60607 USA

OKYAY KAYNAK, *Guest Editor*
Bogazici University
Istanbul 81030, Turkey

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APPENDIX
RELATED WORK

1) D. Xu, Y. Shi, and Z. Ji, "Model-free adaptive discrete-time integral sliding-mode-constrained-control for autonomous 4WMV parking systems," *IEEE Trans. Ind. Electron.*, vol. 64, no. 12, pp. 834–843, Jan. 2018.
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6) A. Ghasemian and A. Taheri, "Constrained near-time-optimal sliding-mode control of boost converters based on switched affine model analysis," *IEEE Trans. Ind. Electron.*, vol. 64, no. 12, pp. 887–897, Jan. 2018.
7) R. Ling, Z. Shu, Q. Hu, and Y.-D. Song, "Second-order sliding-mode controlled three-level buck DC-DC converters," *IEEE Trans. Ind. Electron.*, vol. 64, no. 12, pp. 898–906, Jan. 2018.
8) A. Pilloni, A. Pisano, and E. Usai, "Robust finite-time frequency and voltage restoration of inverter-based microgrids via sliding-mode cooperative control," *IEEE Trans. Ind. Electron.*, vol. 64, no. 12, pp. 907–917, Jan. 2018.
9) S. K. Kommuri, J. J. Rath, and K. C. Veluvolu, "Sliding-mode-based observer–controller structure for fault-resilient control in dc servomotors," *IEEE Trans. Ind. Electron.*, vol. 64, no. 12, pp. 918–929, Jan. 2018.
10) M. V. Basin, P. Yu, and Y. B. Shtessel, "Hypersonic missile adaptive sliding mode control using finite- and fixed-time observers," *IEEE Trans. Ind. Electron.*, vol. 64, no. 12, pp. 930–941, Jan. 2018.
11) M. L. Nguyen, X. Chen, and F. Yang, "Discrete-time quasi-sliding-mode control with prescribed performance function and its application to piezo-actuated positioning systems," *IEEE Trans. Ind. Electron.*, vol. 64, no. 12, pp. 942–950, Jan. 2018.

Ligang Wu (M'10–SM'12) received the B.S. degree in automation from Harbin University of Science and Technology, Harbin, China, in 2001 and the M.E. degree in navigation guidance and control and the Ph.D. degree in control theory and control engineering, both from Harbin Institute of Technology in 2003 and 2006, respectively.

From January 2006 to April 2007, he was a Research Associate in the Department of Mechanical Engineering, The University of Hong Kong, Hong Kong. From September 2007 to June 2008, he was a Senior Research Associate in the Department of Mathematics, City University of Hong Kong. From December 2012 to December 2013, he was a Research Associate in the Department of Electrical and Electronic Engineering, Imperial College London, London, U.K. In 2008, he joined the Harbin Institute of Technology as an Associate Professor and was then promoted to Professor in 2012. He has published six research monographs and more than 130 research papers in international refereed journals. His current research interests include sliding mode control, switched systems, stochastic systems, computational and intelligent systems, multidimensional systems, and flight control.

Prof. Wu was the winner of the National Science Fund for Distinguished Young Scholars in 2015. He received the China Young Five Four Medal in 2016 and was named as a Thomson Reuters Highly Cited Researcher for the period 2015–2017. He is currently an Associate Editor for a number of journals, including the IEEE TRANSACTIONS ON AUTOMATIC CONTROL, the IEEE/ASME TRANSACTIONS ON MECHATRONICS, *Information Sciences*, *Signal Processing*, and *IET Control Theory and Applications*. He is also an Associate Editor of the Conference Editorial Board of the IEEE Control Systems Society.

Sudip K. Mazumder (SM'03–F'16) received the M.S. degree in electrical power engineering from the Department of Electrical Power Engineering, Rensselaer Polytechnic Institute, Troy, NY, USA, in 1993 and the Ph.D. degree in electrical and computer engineering from the Department of Electrical and Computer Engineering, Virginia Tech, Blacksburg, VA, USA, in 2001.

He is currently the Director of Laboratory for Energy and Switching-Electronics Systems and a Professor in the Department of Electrical and Computer Engineering, University of Illinois, Chicago, IL, USA. He is currently the President of NextWatt LLC, a small business organization that he set up in 2008. He has more than 24 years of professional experience and has held R&D and design positions in leading industrial organizations and was the Technical Consultant for several industries. His current research interests include switching-sequence and switching-transition based control of power-electronics systems and interactive-power networks; power electronics for renewable energy, micro/smart grids, and energy storage; wide-bandgap (GaN/SiC) power electronics; and optically triggered wide-bandgap power semiconductor devices. His research has attracted more than 40 sponsored-research projects from leading federal agencies and industries and has yielded close to 200 peer-reviewed publications in prestigious tier-one international journals and conferences, eight patents, 10 book chapters, one (pending) book, and more than 70 invited/plenary/keynote lectures and presentations.

Prof. Mazumder has been the Chair for the IEEE Power Electronics Society Technical Committee on Sustainable Energy Systems since 2015. He also serves as the Co-Chair for the IEEE Power Electronics Society Subcommittees on Distributed Generation and Renewable Energy and Power Semiconductors and as a Committee Member for the IEEE PELS Standards Subcommittee.

Okyay Kaynak (SM'90–F'03) received the Ph.D. degree in electronic and electrical engineering from the Department of Electronic and Electrical Engineering, University of Birmingham, Birmingham, U.K., in 1972.

From 1972 to 1979, he held various positions within the industry. In 1979, he joined the Department of Electrical and Electronics Engineering, Bogazici University, Istanbul, Turkey, where he is currently a Full Professor. He was the Chairman of the Computer Engineering and the Electrical and Electronic Engineering Departments and the Director of the Biomedical Engineering Institute, Bogazici University. He is currently the UNESCO Chair on Mechatronics and the Director of the Mechatronics Research and Application Center, Bebek, Istanbul. He has held Visiting Professor/Scholar positions at various institutions in Japan, Germany, the USA, and Singapore. He is the author of three books, has edited five books, and is the author or coauthor of more than 300 papers that have appeared in various journals and conference proceedings. His current research interests include the fields of intelligent control and mechatronics.

Prof. Kaynak is serving or has served on the Editorial or Advisory Boards of a number of scholarly journals and was the Editor-in-Chief of the IEEE/ASME TRANSACTIONS ON MECHATRONICS during 2013–2016. He is currently an Associate Editor of the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS and the IEEE SENSORS JOURNAL. He is active in international organizations and has served on many committees of the IEEE. He was the President of the IEEE Industrial Electronics Society during 2002–2003 and the Vice President (for conferences) of the IEEE Computational Intelligence Society during 2004–2005.