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

WITH the recent rapid developments in industrial technology, the modern industrial systems have become more and more complex requiring a greater attention to be paid on the stabilizability, the robustness, the reliability, and the optimization issues. The recent developments in sliding mode control and observation techniques serve as powerful tools in this respect. The use of sliding mode control offers a number of advantages: insensitivity to external disturbances, system reduction, high accuracy, and finite time convergence. However, there are still several remaining issues that should be solved before it can be extensively used in the industry in the near future, that is, chattering effect, requirement of an accurate model of the system, relative higher complexity and higher implementation cost compared to existing linear controllers. This “Special Section on Sliding Mode Control and Observation for Complex Industrial Systems—Part I” of the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS presents to the industrial electronics community the most recent advances with topics, such as applications of sliding mode control in industrial electronics (power grid, uninterruptible power supply, robot manipulators, etc.), design and implementation issues of sliding mode control and observation techniques.

It is our pleasure to present this Special Section. Due to the high number of good papers submitted, this Special Section will be divided into two parts.

In item 1) of the Appendix, a hybrid active–passive linear heave compensation system with a nonlinear cascade controller is designed to reduce the adverse effect of the unexpected vessel heave variation on the response of the underwater payloads. An adaptive extended disturbance observer is constructed to estimate and separately compensate the external perturbations. Sliding mode control is designed for the outer position tracking loop in order to compensate the disturbance estimation error while the backstepping technique is employed in the inner pressure control loop.

In item 2) of the Appendix, a novel state/model-free variable-gain discrete sliding mode control strategy is presented to suppress the unmolded position-dependent dynamics and disturbances in the nanopositioning wafer stage. To balance the tradeoff between the robustness and the chattering, the gain of the switching control term is designed to be variable. The proposed scheme facilitates a rapid implementation without either a parameter model or a state observer, and excellent tracking performance with the optimal controller parameters.

In item 3) of the Appendix, a modeling approach of complex microgrids and its sliding mode control design is presented in a decentralized way. Second-order sliding mode control scheme based on suboptimal algorithm is designed for DGUs, taking unknown load dynamics, nonlinearities, and unavoidable modeling uncertainties into account.

In item 4) of the Appendix, a novel sliding mode control approach is proposed for a class of nonlinear systems, where a nonlinear sliding surface is designed using implicit function theory. Then, the proposed method is applied to solve the tracking control problem of a two-wheeled mobile robot, which can be transferred to a stabilization problem for the corresponding tracking error system.

A kernel independence criterion based on independent component analysis algorithm for fault monitoring is proposed in item 5) of the Appendix. Given kernel independence criterion in Regeneration Hilbert space, an exact objective function is given. The proposed approach is compared with the conventional kernel-independent component analysis in view of calculation accuracy and computational efficiency.

A new event-triggered sliding mode control algorithm is proposed in item 6) of the Appendix to solve the load frequency control problem of multiarea interconnected power systems. The prescribed $H\infty$, or energy-to-energy, perfor-mance is utilized to test the effectiveness of the corresponding disturbance attenuation. Sufficient conditions for the stability analysis of the considered system are derived. Load frequency control problem is also addressed in item 7) of the Appendix, due to the fact that it causes frequency oscillations among interconnected power systems. An adaptive supplementary control method based on sliding mode technique and adaptive dynamic programming strategy is proposed for the power system frequency regulation taking disturbances and parameter uncertainties into account.

In item 8) of the Appendix, direct yaw-moment control strategies are proposed for in-wheel electric vehicles by using sliding mode and nonlinear disturbance observer techniques. A second-order sliding mode controller is designed by taking the derivative of the controller as a new control to tackle the chattering problem. The derived sliding mode control and a nonlinear disturbance observer are combined as a composite control to avoid the large control gains. The proposed method is compared with a traditional discontinuous first-order sliding mode controller.

A dc voltage incipient sensor fault isolation method is proposed in item 9) of the Appendix for single-phase three- level rectifier devices in high-speed railway electrical traction systems. By combination of sliding mode technique with nonlinear parametrization adaptive estimation technique, a new

---

Digital Object Identifier 10.1109/TIE.2017.2714038

incipient fault isolation method is developed for the considered systems. The isolable sufficient conditions are derived using new functions.

In item 10) of the Appendix, a robust finite-time anti-sway tracking control method is developed for three-dimensional overhead crane systems using sliding mode technique. The proposed sliding mode based robust finite-time anti-sway tracking control method is designed by considering variation in payload weight, the initial sway angles, and parameter uncertainties due to the payload weight uncertainty.

An integral sliding mode controller is developed for a general type of underwater robots in item 11) of the Appendix. An adaptive multi-input and multioutput extended state observer is designed to estimate the unmeasurable linear and angular velocities and the unknown external disturbances. An adaptive gain update algorithm is introduced to estimate the upper bound of the uncertainties. Finally, the proposed control method is applied to solve the tracking problem of the underwater robot.

In item 12) of the Appendix, an adaptive integral sliding mode control method with time-delay estimation is proposed. Parameter variations and disturbances are estimated via time-delay estimation approach. Integral sliding surface is designed to eliminate the reaching phase and an adaptive gain dynamics is employed to high tracking accuracy.

In item 13) of the Appendix, a high-performance sliding mode control is proposed to control the output voltage of the four-leg inverter with fixed switching frequency for uninterruptible power supply applications. The proposed control achieves chattering reduction, robustness, regulation, and dynamic response of the considered system. Practical implementation of the proposed method on a real test bench is also discussed.

For the three-dimensional gliding motion of a dolphin-like gliding robot, the work in item 14) of the Appendix presents a sliding mode observer-based heading control scheme. To regulate the gliding direction, a pair of flippers are used via differential actions, rather than actuators commonly used in traditional underwater gliders. Based on a dynamic model, including a sliding mode observer, a backstepping controller, and a solver for action commands of the flippers, a framework of the control algorithm is established.

To this end, the overview of all 14 papers of the Special Section—Part I has been completed. The Guest Editors hope that this Special Section will increase the interest of both the scientific and industrial communities in this very dynamic area and will attract more attention to producing new ideas and algorithms for future research applications.

ACKNOWLEDGMENT

There are numerous individuals without whose help this Special Section would not have been completed. First, the Guest Editors would like to express their gratitude to all the authors for contributing their research work to this Special Section, and they believe that their contributions will be of great interest to the IEEE industrial electronics community. Next, the Guest Editors would also like to thank the anonymous reviewers for their valuable comments and helpful suggestions that have contributed to the improvement of the papers included in this Special Section. In particular, they would like to express their sincere acknowledgment to the present and the past Editors-in-Chief of the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, Prof. L. G. Franquelo and Prof. C. Cecati, for providing the opportunity to organize this Special Section as well as their enthusiastic support. Finally, they also thank the Journal Administrators, S. McLain and S. Jacobs, for providing their professional assistances in preparing this Special Section.

LIGANG WU, *Guest Editor*
Department of Control Science and Engineering
Harbin Institute of Technology
Harbin 150000, China

SUDIP K. MAZUMDER, *Guest Editor*
Department of Electrical and Computer Engineering
University of Illinois
Chicago, IL 60607 USA

OKYAY KAYNAK, *Guest Editor*
Department of Electrical and Electronics Engineering
Bogazici University
Istanbul 81030, Turkey

APPENDIX
RELATED WORK

1) S. Li, J. Wei, K. Guo, and W.-L. Zhu, “Nonlinear robust prediction control of hybrid active–passive heave compensator with extended disturbance observer,” *IEEE Trans. Ind. Electron.*, vol. 64, no. 8, pp. 6684–6694, Aug. 2017.
2) M. Li, K. Yang, Y. Zhu, H. Mu, and C. Hu, “State/model-free variable-gain discrete sliding mode control for an ultra precision wafer stage,” *IEEE Trans. Ind. Electron.*, vol. 64, no. 8, pp. 6695–6705, Aug. 2017.
3) M. Cucuzzella, G. P. Incremona, and A. Ferrara, “Decentralized sliding mode control of islanded AC microgrids with arbitrary topology,” *IEEE Trans. Ind. Electron.*, vol. 64, no. 8, pp. 6706–6713, Aug. 2017.
4) J. Mu, X.-G. Yan, S. K. Spurgeon, and Z. Mao, “Generalised regular form based SMC for nonlinear systems with application to a WMR,” *IEEE Trans. Ind. Electron.*, vol. 64, no. 8, pp. 6714–6723, Aug. 2017.
5) Y. Zhang, W. Du, and X.-G. Li, “Observation and detection for a class of industrial systems,” *IEEE Trans. Ind. Electron.*, vol. 64, no. 8, pp. 6724–6731, Aug. 2017.
6) X. Su, X. Liu, and Y.-D. Song, “Event-triggered sliding-mode control for multi-area power systems,” *IEEE Trans. Ind. Electron.*, vol. 64, no. 8, pp. 6732–6741, Aug. 2017.
7) C. Mu, Y. Tang, and H. He, “Improved sliding mode design for load frequency control of power system integrated an adaptive learning strategy,” *IEEE Trans. Ind. Electron.*, vol. 64, no. 8, pp. 6742–6751, Aug. 2017.
8) S. Ding, L. Liu, and W. X. Zheng, “Sliding mode direct yaw-moment control design for in-wheel electric vehicles,” *IEEE Trans. Ind. Electron.*, vol. 64, no. 8, pp. 6752–6762, Aug. 2017.

9) K. Zhang, B. Jiang, X.-G. Yan, and Z. Mao, “Incipient voltage sensor fault isolation for rectifier in railway electrical traction systems,” *IEEE Trans. Ind. Electron.*, vol. 64, no. 8, pp. 6763–6774, Aug. 2017.
10) D. Chwa, “Sliding-mode-control-based robust finite-time antisway tracking control of 3-D overhead cranes,” *IEEE Trans. Ind. Electron.*, vol. 64, no. 8, pp. 6775–6784, Aug. 2017.
11) R. Cui, L. Chen, C. Yang, and M. Chen, “Extended state observer-based integral sliding mode control for an underwater robot with unknown disturbances and uncertain nonlinearities,” *IEEE Trans. Ind. Electron.*, vol. 64, no. 8, pp. 6785–6795, Aug. 2017.
12) J. Lee, P. H. Chang, and M. Jin, “Adaptive integral sliding mode control with time-delay estimation for robot manipulators,” *IEEE Trans. Ind. Electron.*, vol. 64, no. 8, pp. 6796–6804, Aug. 2017.
13) M. Pichan and H. Rastegar, “Sliding-mode control of four-leg inverter with fixed switching frequency for uninterruptible power supply applications,” *IEEE Trans. Ind. Electron.*, vol. 64, no. 8, pp. 6805–6814, Aug. 2017.
14) J. Yuan, Z. Wu, J. Yu, and M. Tan, “Sliding mode observer-based heading control for a gliding robotic dolphin,” *IEEE Trans. Ind. Electron.*, vol. 64, no. 8, pp. 6815–6824, Aug. 2017.

Ligang Wu (M’10–SM’12) received the B.S. degree in automation, the M.E. degree in navigation guidance and control, and the Ph.D. degree in control theory and control engineering from Harbin Institute of Technology, Harbin, China, in 2001, 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, 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 Harbin Institute of Technology as an Associate Professor and was promoted to Professor in 2012. He has published 6 research monographs and more than 120 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 in 2015 and 2016. He currently serves as an Associate Editor for a number of journals, including the IEEE TRANSACTIONS ON AUTOMATIC CONTROL, IEEE/ASME TRANSACTIONS ON MECHATRONICS, *Information Sciences*, *Signal Processing*, and *IET Control Theory and Applications*. He is also an Associate Editor for the Conference Editorial Board, IEEE Control Systems Society.

Sudip K. Mazumder (SM’03–F’16) received the M.S. degree in electrical power engineering from Rensselaer Polytechnic Institute, Troy, NY, USA, in 1993, and the Ph.D. degree in electrical and computer engineering from Virginia Polytechnic Institute and State University, Blacksburg, VA, USA, in 2001.

He is the Director of the 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 also serves as the President of NextWatt LLC, a small business organization that he set up in 2008. He has over 24 years of professional experience and has held R&D and design positions in leading industrial organizations and has served as 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, energy storage; wide-bandgap (GaN/SiC) power electronics; and optically triggered wide-bandgap power semiconductor devices. His research has attracted over 40 sponsored research projects from leading federal agencies and industries, and yielded close to 200 peer-reviewed publications in prestigious tier-one international journals and conference proceedings, 8 patents, 10 book chapters, and 1 (pending) book, and more than 70 invited/plenary/keynote lectures and presentations.

Prof. Mazumder has been the Chair of 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 University of Birmingham, Birmingham, U.K., in 1972.

From 1972 to 1979, he held various positions within industry. In 1979, he joined the Department of Electrical and Electronics Engineering, Bogazici University, Istanbul, Turkey, where he is currently a Full Professor. He has served as the Chairman of the Computer Engineering and the Electrical and Electronic Engineering Departments and as 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. He has held Visiting Professor/Scholar positions at various institutions in Japan, Germany, USA, and Singapore. He is the author of 3 books, has edited 5 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 as 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 in 2002–2003 and the Vice President (for conferences) of the IEEE Computational Intelligence Society in 2004–2005.