Modeling, Analysis, and Advanced Control in Motion Control Systems—Part III

PRECISION, agility, robustness, efficiency, and intelligence are now becoming the design indexes for modern motion control systems. High control performance, intelligent functions, or efficiency improvements advance the level of motion control products or systems and bring a lot of benefits for companies. The difficulties for the control research academics and practicing engineers lie in various factors, such as nonlinearities, friction, complex internal dynamics, time-varying parameters in the system dynamics, external disturbances in the working environment, and complex work tasks. These make the control design a very challenging work. To employ advanced control algorithms and schemes, time-/frequency-domain modeling, system identification, observation for unmeasured states, estimation for pivotal parameters, and the corresponding analyses are often necessary.

The main objectives of this "Special Section on Modeling, Analysis, and Advanced Control in Motion Control Systems" of the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS are to build a platform for research academics and practicing engineers of the industrial electronics and industrial informatics communities to present their most recent findings related to digital control systems in motion control systems.

This part of the Special Section consists of 17 papers which cover different applications on motion control systems, such as motor systems [items 1) through 4) in the Appendix], flywheel rotors [item 5) in the Appendix], pneumatic muscle actuators [item 6) in the Appendix], multimass systems [item 7) in the Appendix], transportation systems including unmanned surface vehicles (USVs) [item 8) in the Appendix], wheeled mobile robots [item 9) in the Appendix], unmanned aerial vehicles [item 10) in the Appendix], car vehicles [items 11) through 14) in the Appendix], oil well sonic logging systems [item 15) in the Appendix], and general motion systems [items 16) and 17) in the Appendix].

Topics of interest of this Special Section include various advanced modeling, analysis, and control techniques for motion control systems with simulation and/or experimental verifications, particularly, modeling [items 8) and 15) in the Appendix], estimation or identification for uncertainty/disturbance or parameter of motion control systems [items 1) through 3), 7), 9), 10), 13), and 16) in the Appendix], adaptive/intelligent control design for motion control systems [items 1), 2), 4) through 7), 10), 14), and 16) in the Appendix], etc.

Item 1) in the Appendix provides a comprehensive overview on disturbance/uncertainty estimation and attenuation (DUEA) techniques in permanent-magnet synchronous motor (PMSM) drives. First, various disturbances and uncertainties showing different characteristics and appearing in different control loops in ac motor drives are revisited. Second, this paper has paid attention to the design of various DUEAs for different ac servo systems. It also provides in-depth analysis of the relationship between these advanced control methods in the context of PMSM systems. Third and most important, the similarities and differences in disturbance attenuation of DUEA and other promising methods such as internal model control and output regulation theory have been analyzed in detail. The extensive applications of DUEAs in different ac motor drives are also categorized and summarized in this paper.

Item 2) in the Appendix provides a novel disturbance-observer-based nonlinear triple-step controller to attenuate the influence of cogging torque in low-speed condition for a permanent magnet dc motor. Considering that the cogging torque is a fast time-varying disturbance and changes harmonically, a reduced-order nonlinear observer is designed to estimate it. Based on the nonlinear reduced-order observer, a triple-step nonlinear method is applied to derive a speed tracking controller. Experimental results show that tracking errors are substantially reduced at low speeds by the disturbance-observer-based nonlinear triple-step controller.

Without any extra test pulses needed, a novel rotor estimation method on the basic of "inductance rectangle" for doubly salient electromagnetic motor is proposed in item 3) in the Appendix. The rotor position estimation is in the field building process which is prior to the startup, so the influence of flux saturation is eliminated since there is no current in armature windings during this process. With the estimated accurate rotor position, a new antireverse startup strategy with the consideration of boundary sector is investigated. Various experiments are provided to confirm the effectiveness.

Item 4) in the Appendix considers the contouring control design problem for an industrial *X–Y* linear-motor-driven stage system. Based on the global task coordinate frame, combining iterative learning control with adaptive robust control together, a kind of learning adaptive robust control method is developed to suppress parametric uncertainties and disturbances. The learning adaptive robust controller is synthesized in a serial structure. Comparative experimental results verify that the closed-loop system shows excellent transient/steady contouring performances with robustness to parametric variations and external disturbances.

Item 5) in the Appendix emphasizes the study of the stable suspension of rotor suspended by superconducting magnetic bearing (SMB) and active magnetic bearing (AMB) for the superconducting attitude control and energy storage flywheel. The

Digital Object Identifier 10.1109/TIE.2016.2635618

rotor's dynamic model is established by linearizing the suspension forces of both SMB and AMB within the neighborhood of equilibrium point; the decoupling control method is introduced to make the radial translation and tilting of rotor decouple and displacement cross-feedback control method is adopted to suppress the high-speed rotor's gyroscopic effects. This control method first takes superconducting magnetic suspension stiffness into consideration. Simulations of rotor's vibration have been done when the rotor speeds up to 50 000 r/min; the results can prove that the linearization of suspension force of SMB and AMB is reasonable and the cross-feedback control method is effective to suppress the whirling of the high-speed discal rotor.

Item 6) in the Appendix develops a novel controller based on adaptive servomechanism to achieve precise tracking for pneumatic muscle actuators whose model has nonlinear and time-varying characteristics. Due to the proposed adaptive servomechanism, it is proved that the control design can fulfill the tracking task and ensure that the trajectory of the closed-loop system stays in a significantly small bounded range around the reference trajectory. Extensive experimental results on pneumatic muscle actuators illustrate the effectiveness of the proposed controller. Meanwhile, both the tracking accuracy and bandwidth have been substantially enhanced as well as achieves better performance than nonadaptive and PID controllers and other existing controllers. Hence, the present adaptive servomechanism controller has promising application potential in flexible robots widely used in rehabilitation, intelligent manufacturing, national defense, and so on.

For those drive control systems with elastic coupling between motors and driven devices, the mechanical resonances cannot be neglected. Usually, it is difficult to damp high frequency torsional vibration while simultaneously the dynamic performance could be well ensured. Item 7) in the Appendix considers the motion control system of a multimass mechanism with variable moment of inertia. A new control structure is proposed for such mechanism consisting of a filter damping higher resonance frequencies and an adaptive speed controller. The filter provides a compromised filtering effect in a range of resonance frequency variation. A neural adaptive controller is designed to realize active damping of lower resonance frequencies. Experimental comparison results between the proposed controller and the constant parameter PI controller with the same constant antiresonance filter show the advantages of this proposed solution.

Item 8) in the Appendix presents an original nonlinear modeling scheme for the water-jet propulsion USV system. The main idea of this work is to utilize both the offline quasi-linear parameter-varying model structure and online active modeling technique to approach the real behavior of an USV system. By doing this, the imprecision of the fixed offline model structure due to the unstructured and time-varying model errors can be improved clearly. This will be useful to design a controller with improved motion performance. This work has also presented some real tests and result analysis has shown its superiority to several other traditional modeling methods.

Item 9) in the Appendix presents a robust tracking control scheme for wheeled mobile robots with skidding, slipping, and input disturbance. Considering the existing skidding and slipping, a desired disturbance observer-based virtual velocity control law is designed. By using the nonlinear disturbance observer, the robust tracking control scheme is developed considering the prescribed tracking performance requirement. In the tracking control scheme design, the prescribed performance function method is employed to guarantee the desired tracking performance. Experiment results on a wheeled mobile robot are carried out to demonstrate its properties.

Unmanned aerial vehicle-based aerial manipulator has received more and more attention due to its superior mobility in 3-D space. Item 10) in the Appendix addresses the parameter estimation and control design for an aerial manipulator. An online parameter estimator is designed considering the multirotor and robotic arm with unknown payload. Then, an adaptive sliding mode controller is developed to guarantee that the end effector of the robotic arm asymptotically tracks the desired trajectory. Simulation results and load-carrying experimental results using a custom-made aerial manipulator are provided to verify the effectiveness of the proposed scheme.

The driving force allocation and control problem for electric vehicles with multiple driving motors are studied in item 11) in the Appendix. For electric vehicles with four in-wheel-motors (IWMs), as the IWM is attached to tire, disturbances, and complex tire dynamics inevitably influence the output force. In this paper, a global-local control structure is proposed. A global controller coordinates wheel and vehicle motions to generate reference driving forces and a local controller controls the generated force commands. Vehicle start-off simulation and experimental results on an instantaneous split-friction road are shown to verify the effectiveness of the proposed method.

Item 12) in the Appendix proposes a novel 3-D dynamic stability controller using model predictive control, where the control modes of the controller are divided into yaw stability control mode, yaw-roll stability control mode, and rollover prevention control mode to achieve precision control of vehicle in different situations and to mitigate an adverse effect of time delay on vehicle stability control. The controller is applied to the Carsim vehicle model, which is a nonlinear vehicle model and is very close to the real vehicle. Simulation results and hardware-in-the-loop results show that the proposed controller can achieve a seamless integration of lateral stability and rollover prevention in complicated steering maneuvers.

The authors of items 13) and 14) in the Appendix deal with the control of an intake valve for camless engines. Item 13) in the Appendix focuses on the sensorless control design. A velocity estimator is designed based on the inversion of electromagnetic actuator model. Then, a position observer is built to estimate the valve position by taking the coil current as input signal and the estimated valve velocity as output signal. For the control of actuator, under the cascaded structure, PD feedback plus feedforward compensation for the stationer error is developed. Comparative experimental results with an extended Kalman filter-based sensorless control method are provided to show the advantages of the proposed methods.

To minimize the regulation energy for intake valves of camless engines, item 14) in the Appendix studies the control method based on the resonance concept of a new generation of actuators. The new actuator consists of a piezo part and a hydraulic one. The regulator employs a cascade structure. The controller includes feedforward actions and an external resonance control part. The controller parameters change adaptively with changes in the velocity of the revolution of the engine. Experimental results of trajectory tracking in engine applications demonstrate the effectiveness of the proposed actuator solution.

Item 15) in the Appendix focuses on a control system design for the oil well sonic logging device. The removal of ringing is desirable for acoustic logging as too much ringing can interfere with the processing of formation data. Compared to the existing approach uses a strong passive damper, the proposed method here is based on the active ringing damping in which a control signal is injected to compensate the transmitter motion vibration. The method does not require the addition of extra sensors. An iterative technique is used to adapt the ringing braking signal by learning the control patterns in the past cycles. Simulation and experimental results demonstrate the effectiveness and robustness of the proposed method in the ringing braking.

Most of the repetitive control design requires the exact knowledge of the plant model and the period of the external signal. In many control systems, disturbances are not periodic, but aperiodic. In item 16) in the Appendix, an extended state observer (ESO)-based repetitive controller is designed to compensate periodic signals, aperiodic disturbances, and uncertainties of the controlled plant with relative degree equal or greater than zero. It provides a simple design solution applicable for a wide variety of plants. The simulation and experimental comparison studies show that the ESO-based repetitive controller has superior performances in the presence of various disturbances and system uncertainties.

Learning from demonstration method is proposed for generating a trajectory resembling a demonstration rather than trajectory planning by sophisticated engineers. Item 17) in the Appendix presents a new learning from the demonstration method to improve the adaptability using motion templates for trajectory generation. It learns the spatiotemporal features from human demonstrations and represents movements as feature templates. The generated trajectory maintains the spatial–temporal features of demonstrations while satisfying task specifications and environmental constraints. Experiments results show the effectiveness of this method for generating different kinds of motion primitives using a wheeled mobile robotics platform.

SHIHUA LI, *Guest Editor*
School of Automation
Southeast University
Nanjing 210096, China

LENNART HARNEFORS, *Guest Editor*
Corporate Research
ABB
SE-721 78 Västerås, Sweden

MAKOTO IWASAKI, *Guest Editor*
Department of Electrical and Mechanical Engineering
Nagoya Institute of Technology
Nagoya 466-8555, Japan

ACKNOWLEDGMENT

The Guest Editors would like to thank all the authors and the numerous anonymous reviewers for contributions to this Special Section. They would also like to thank Prof. C. Cecati, the former Editor-in-Chief of the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, for giving them the chance to organize this Special Section, and Prof. L. Franquelo, Prof. H. Gao, and Mrs. S. McLain for their professional guidance, support, and assistance during the entire preparation of this Special Section.

APPENDIX
RELATED WORK

1) J. Yang, W.-H. Chen, S. Li, L. Guo, and Y. Yan, "Disturbance/uncertainty estimation and attenuation techniques in PMSM drives—A survey," *IEEE Trans. Ind. Electron.*, vol. 64, no. 4, pp. 3273–3285, Apr. 2017.
2) H. Chu, B. Gao, W. Gu, and H. Chen, "Low speed control for permanent magnet DC torque motor using observer-based nonlinear triple-step controller," *IEEE Trans. Ind. Electron.*, vol. 64, no. 4, pp. 3286–3296, Apr. 2017.
3) X. Zhou, B. Zhou, J. Yu, L. Yang, and Y. Yang, "Research on initial rotor position estimation and anti-reverse startup methods for DSEM," *IEEE Trans. Ind. Electron.*, vol. 64, no. 4, pp. 3297–3307, Apr. 2017.
4) C. Hu, Z. Hu, Y. Zhu, and Z. Wang, "Advanced GTCF-LARC contouring motion controller design for an industrial X-Y linear motor stage with experimental investigation," *IEEE Trans. Ind. Electron.*, vol. 64, no. 4, pp. 3308–3318, Apr. 2017.
5) J. Tang, K. Wang, and B. Xiang, "Stable control of high-speed rotor suspended by superconducting magnetic bearings and active magnetic bearings," *IEEE Trans. Ind. Electron.*, vol. 64, no. 4, pp. 3319–3328, Apr. 2017.
6) L. Zhu, X. Shi, Z. Chen, H. Zhang, and C. Xiong, "Adaptive servomechanism of pneumatic muscle actuators with uncertainties," *IEEE Trans. Ind. Electron.*, vol. 64, no. 4, pp. 3329–3337, Apr. 2017.
7) S. Brock, D. Luczak, K. Nowopolski, T. Pajchrowski, and K. Zawirski, "Two approaches to speed control for multi-mass system with variable mechanical parameters," *IEEE Trans. Ind. Electron.*, vol. 64, no. 4, pp. 3338–3347, Apr. 2017.
8) J. Han, J. Xiong, Y. He, F. Gu, and D. Li, "Nonlinear modeling for a water-jet propulsion USV: An experimental study," *IEEE Trans. Ind. Electron.*, vol. 64, no. 4, pp. 3348–3358, Apr. 2017.
9) M. Chen, "Disturbance attenuation tracking control for wheeled mobile robots with skidding and slipping," *IEEE Trans. Ind. Electron.*, vol. 64, no. 4, pp. 3359–3368, Apr. 2017.
10) H. Lee and H. J. Kim, "Estimation, control and planning for autonomous aerial transportation," *IEEE Trans. Ind. Electron.*, vol. 64, no. 4, pp. 3369–3379, Apr. 2017.
11) Y. Wang, H. Fujimoto, and S. Hara, "Driving force distribution and control for electric vehicles with four in-wheel-motors: A case study of acceleration on split-

friction surfaces," *IEEE Trans. Ind. Electron.*, vol. 64, no. 4, pp. 3380–3388, Apr. 2017.
12) L. Li, Y. Lu, R. Wang, and J. Chen, "A 3-dimentional dynamics control framework of vehicle lateral stability and rollover prevention via active braking with MPC," *IEEE Trans. Ind. Electron.*, vol. 64, no. 4, pp. 3389–3401, Apr. 2017.
13) P. Mercorelli, "A motion sensorless control for intake valves in combustion engines," *IEEE Trans. Ind. Electron.*, vol. 64, no. 4, pp. 3402–3412, Apr. 2017.
14) P. Mercorelli and N. Werner, "An adaptive resonance regulator design for motion control of intake valves in camless engine systems," *IEEE Trans. Ind. Electron.*, vol. 64, no. 4, pp. 3413–3422, Apr. 2017.
15) X. Song, Y. Zhao, and J. Dykstra, "Active damping of acoustic ringing effect for oil well sonic logging system," *IEEE Trans. Ind. Electron.*, vol. 64, no. 4, pp. 3423–3432, Apr. 2017.
16) H. M. Sayem, Z. Cao, and Z. Man, "Model free ESO-based repetitive control for rejecting periodic and aperiodic disturbances," *IEEE Trans. Ind. Electron.*, vol. 64, no. 4, pp. 3433–3441, Apr. 2017.
17) X. Yin and Q. Chen, "Trajectory generation with spatio-temporal templates learned from demonstrations," *IEEE Trans. Ind. Electron.*, vol. 64, no. 4, pp. 3442–3451, Apr. 2017.

Shihua Li (M'05–SM'10) was born in Pingxiang, China, in 1975. He received the Bachelor's, Master's, and Ph.D. degrees in automatic control from Southeast University, Nanjing, China, in 1995, 1998, and 2001, respectively.

Since 2001, he has been with the School of Automation, Southeast University, where he is currently a Professor and the Director of the Mechatronic Systems Control Laboratory. He has authored or coauthored more than 200 technical papers and two books. His main research interests include modeling, analysis, and nonlinear control theory with applications to mechatronic systems.

Prof. Li is the Vice Chairman of the IEEE CSS Nanjing Chapter. He serves as an Associate Editor or Editor of the *International Journal of Robust and Nonlinear Control*, *IET Power Electronics*, *International Journal of Control, Automation and Systems*, *International Journal of Electronics*, and *Journal of Power Electronics*, and as a Guest Editor of the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, *International Journal of Robust and Nonlinear Control*, and *IET Control Theory and Applications*.

Lennart Harnefors (SM'93–M'97–SM'09) received the M.Sc., Licentiate, and Ph.D. degrees in electrical engineering from the Royal Institute of Technology (KTH), Stockholm, Sweden, and the D.Sc. degree in industrial automation from Lund University, Lund, Sweden, in 1993, 1995, 1997, and 2000, respectively.

Between 1994 and 2005, he was with Mälardalen University, Västerås, Sweden, where he became a Professor of electrical engineering in 2001. Between 2001 and 2005, he was, in addition, a part-time Visiting Professor of electrical drives with Chalmers University of Technology, Göteborg, Sweden. Since 2005, he has been with ABB, where he is currently a Senior Principal Scientist with Corporate Research, Västerås. Since 2011, he has been, in addition, with KTH as a part-time Adjunct Professor of power electronics. His research interests include analysis and control of power electronic systems, in particular, grid-connected converters and ac drives.

Prof. Harnefors is an Associate Editor of the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS and *IET Electric Power Applications*.

Makoto Iwasaki (M'92–SM'09–F'14) received the B.S., M.S., and Dr. Eng. degrees in electrical and computer engineering from Nagoya Institute of Technology, Nagoya, Japan, in 1986, 1988, and 1991, respectively.

Since 1991, he has been with Nagoya Institute of Technology, where he is currently a Professor and the Head of the Department of Electrical and Mechanical Engineering. He was a Japanese Government Research Fellow with Chemnitz University of Technology, Chemnitz, Germany,from 1997 to 1998 and from 2002 to 2003, and with the Technical University of Munich, Munich, Germany, from 1997 to 1998. His current research interests include applications of motion control theory and soft-computing techniques for motor/motion control.

Dr. Iwasaki is a Member of the Institute of Electrical Engineers of Japan and the Japan Society for Precision Engineering. For his professional society contributions to the IEEE, he has been elected as an Administrative Committee Member of the IEEE Industrial Electronics Society (IES) from 2010 to 2016, a Technical Editor for the IEEE/ASME TRANSACTIONS ON MECHATRONICS from 2010 to 2014, and an Associate Editor of the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS since 2014. He served as the Chair of the Technical Committee on Motion Control of the IEEE IES and as the General Chair for the IEEE IES International Conference on Mechatronics (ICM2015).