Guest Editorial: Special Issue on Type-2 Fuzzy-Model-Based Control and Its Applications

This Special Issue is dedicated to the memory of Prof. Robert John, one of the pioneers of type-2 fuzzy sets and systems, who passed away during the preparation of this Issue.

TYPE-2 fuzzy sets were proposed by Prof. Lotfi A. Zadeh in 1975 as a way to handle membership function uncertainties. Although a small number of articles were published about type-2 fuzzy sets during the subsequent 20 years, it was not until Prof. Jerry Mendel, his students, and other colleagues he collaborated with, including Prof. Robert John (to whom this Special Issue is dedicated), worked on type-2 fuzzy systems (a.k.a., fuzzy logic systems) that the field of type-2 fuzzy sets and systems began to blossom (e.g., as summarized in [1], [2]). Because type-1 fuzzy logic control was already one of the most important and widely studied applications for type-1 fuzzy sets, it was very natural for type-2 fuzzy logic control to emerge [3]. As is well-known, control systems must often be designed to perform well in the face of uncertainties, including external but unmeasurable disturbances that act upon the plant, changing plant parameters due to aging or other effects, incomplete knowledge about parameter values, and specific control mechanisms, such as sampling, eventtriggering, etc. Type-2 fuzzy sets have the potential to better handle such uncertainties because they lead to controllers that provide a greater sculpting capability of the state space (i.e., to more nonlinearity, adaptivity, and variability of the controller structure) than type-1 fuzzy logic controllers. This greater sculpting is provided by more design degrees of freedom that occur in type-2 fuzzy set models. Just as there can be different kinds of type-1 fuzzy logic controllers, there can also be different kinds of type-2 fuzzy logic controllers. The book in [4], which is coedited by five scholars, is an excellent entry into type-2 fuzzy logic controllers; however, each of its four type-2 fuzzy logic controller chapters focuses on the contributions made by its coauthor (and students).This Special Issue, which focuses on type-2 model-based control, adds to what is in [4] and demonstrates the broadening of the type-2 fuzzy logic controller field.

During the past three decades, type-1 fuzzy-model-based (FMB) control strategies have been shown to effectively address the nonlinearity in the control systems. Benefiting from the pioneering concept of parallel distributed compensation (PDC) proposed by Prof. Kazuo Tanaka and his colleagues including Prof. Hua O. Wang [5], the stability analysis of type-1 FMB control systems can now be conducted systematically. The PDC concept lays down the foundation driving the development of type-1 FMB control research. As shown in [5], a wide range of research topics within the type-1 FMB control framework have been investigated through strict mathematical approaches, e.g., the fuzzy observer design, robust fuzzy control, optimal fuzzy control, etc. Under the type-1 FMB control framework, Dr. Hak-Keung Lam has taken it to another level by introducing 1) imperfect premise matching (IPM) concept that advocates that the fuzzy controller can have its own set of premise membership functions and 2) membership function-dependent (MFD) analysis that initiates the use of membership-function in formation in a stability analysis and control design [6]. The monograph [6] summarized in-depth many results in terms of the categories of the FMB control systems, types of Lyapunov functions, types of analysis techniques, and amount of membership-function information and its extraction. In general, type-1 FMB control strategies are very powerful for nonlinear systems. Nevertheless, type-1 fuzzy sets lack the capability of directly handling (modeling) the previously mentioned uncertainties.

A type-2 FMB control framework can be established by adopting type-2 fuzzy sets into type-1 FMB designs. Doing this, the resulting type-2 FMB controller inherits the merits of both type-2 fuzzy sets and the FMB control strategy, and has the unique advantage of directly handling both nonlinearity and uncertainty. However, the big challenges are 1) a type-2 fuzzy model and its modeling method, and a type-2 fuzzy controller under the FMB control framework is lacking; and 2) new analysis techniques have to be developed because the PDC-based analysis cannot be applied when the premise membership functions are of type-2. Since the first successful attempt was made in 2008 [7] to address these issues, the intervaltype-2(IT2) FMB control system, its stability analysis, and control design have gradually been recognized by the fuzzy control community. The IPM concept and the MFD analysis were also investigated through the IT2 fuzzy sets in [8], which are significant concept, and techniques support the stability analysis and control design. Besides the parameter uncertainty, the type-2 fuzzy sets have also demonstrated their potential to deal with the intrinsic uncertainty caused by specific control mechanisms, such as the sample-data control mechanism and event-triggered control mechanism.

Digital Object Identifier 10.1109/TFUZZ.2020.3046933

After the two special issues on type-2 fuzzy set sand systems proposed by IEEE Transactions on Fuzzy Systems in 2007 and 2013, the importance and merit of type-2 fuzzy sets have gained even more attention. Since the significance of type-2 FMB control and related applications has drawn the attention of many researchers, we made a call for another type-2 special issue about this topic. In total, 31 submissions were received and 11 submissions of those were accepted upon the careful evaluations of the reviewers, guest editors, and the editor-in-chief.

The article entitled "Stability analysis for interval Type 2 fuzzy systems by applying homogenous polynomially membership functions dependent matrices and switching technique," by Wang *et al*., uses the homogenous polynomially membership functions dependent matrices for the IT2 fuzzy systems to reduce the conservativeness in the stability conditions. The simulations verify that the method in this paper is less conservative than the existing ones reported in the literature.

The article entitled "Fault estimation for mode-dependent IT2 fuzzy systems with quantized output signals," by Sakthivel *et al.*, presents a fault estimation for mode-dependent IT2 fuzzy systems with quantized output measurements. By offering three illustrative examples, in which two of them are practical models, namely, the tunnel diode circuit system and Rössler system, the availability and feasibility of the proposed design method are explained.

The article entitled "Towards systematic design of general Type-2 fuzzy logic controllers: Analysis, interpretation and tuning," by Sakalli *et al*., provides a new perspective on how the deployment of General Type-2 (GT2) fuzzy sets affects the mapping of a class of fuzzy logic controllers. Also, the systematic design approach for GT2-FLCs is presented. In the article, the analyses, interpretations, and design methods are validated with experimental results conducted on a drone.

The article entitled "Security sliding mode control of interval Type-2 fuzzy systems subject to cyber attacks: The stochastic communication protocol case," by Zhang *et al*., addresses the security control problem of a class of IT2 fuzzy systems via the sliding-mode control strategy. In the paper, sufficient conditions are derived so that the resultant closed-loop interval type-2 fuzzy system is stochastically stable and, at the same time, the state trajectories can be forced into a small domain around the prescribed sliding surface. The proposed control design approach is verified by two examples.

The article entitled "Design on Type-2 fuzzy-based distributed supervisory control with backlash-like hysteresis," by Shen *et al.,* investigates the distributed synchronization control subject to the unknown backlash-like hysteresis by using the smooth function approximation capability of type2 fuzzy logic systems. In the paper, it is guaranteed that the resulting closed-loop signals including system states belong to the corresponding compact sets. The adaptive compensation terms of the optimal approximation errors are adopted in the proposed method. Simulation results demonstrate the effectiveness of the proposed new design method.

The article entitled "Asynchronous event-triggered control for networked interval Type-2 fuzzy systems against DoS attacks," by Li *et al.*, investigates the asynchronous adaptive event-triggered control problem for networked IT2 fuzzy systems subject to nonperiodic denial-of-service (DoS) attacks. Two resilient adaptive event triggered mechanisms are applied independently to both sensor and controller output while resisting nonperiodic DoS attacks. Mismatched membership functions are considered between the dynamic output feedback controller and IT2 fuzzy model, and a slack matrix is introduced to relax the stability conditions. The effectiveness of the developed control approach is illustrated by two examples.

The article entitled "A novel Hammerstein model for nonlinear networked systems based on an interval Type-2 Fuzzy Takagi-Sugeno-Kang system," by Khalifa *et al.*, proposes a novel Hammerstein structure for nonlinear networked systems based on an IT2 Takagi–Sugeno–Kang fuzzy system. The structure of the nonlinear subsystem is learned online based on the type-2 fuzzy clustering and the update algorithms are utilized to assure the model stability and the parameter fast convergence. The simulation results show a higher performance for the proposed model than that of compared models.

The article entitled "Efficient Model predictive control for networked interval Type-2 T-S fuzzy system with stochastic communication protocol," by Dong *et al.*, investigates the efficient model predictive control problem of a class of nonlinear systems in the framework of IT2 T-S fuzzy systems. In the paper, the balance among the computational burden, the control performance, and the initial feasible region has been considered. The effectiveness of the proposed method is verified through simulation examples.

The article entitled "Fault detection filtering design for discrete-time interval Type-2 T-S fuzzy systems in finite frequency domain," by Wang *et al.*, focuses on the problem of fault-detection filtering design for discrete-time IT2 T-S fuzzy systems in the finite frequency domain. By exploiting the information of footprint of uncertainty and lower and upper membership functions of the fuzzy system, a novel MFD finite-frequency fault-detection filtering design approach has been proposed and then applied to the fault detection. The effectiveness of the proposed fault detection methods has been verified through simulation studies.

The article entitled "Aperiodic sampled-data-based control for interval Type-2 fuzzy systems via refined adaptive event-triggered communication scheme," by Li *et al*., devotes to event-triggered stabilization for a class of IT2 fuzzy systems with aperiodic sampling. Benefiting from the merits of the proposed research, the conservatism is significantly reduced for obtaining upper bound for stable sampling interval and achieves obvious superiority over the existing methods for saving communication resource while maintaining the control performance of the system.

The article entitled "Affine transformed IT2 fuzzy event-triggered control under deception attacks," by Han *et al.*, investigates the stabilization of type-2 fuzzy system in the presence of cyberattacks. In this paper, affine membership functions are considered in the controller design. Also, robust adaptive event-triggered control is proposed to avoid unwanted triggering events. The experimental results demonstrate the importance of the proposed approach in terms of state convergence, robustness, and avoiding unwanted triggering events.

To conclude, a wide range of related topics have been collected for the special issue. Especially some of the hot research topics are from the networked control field like the sampled-data control design, event-triggered control design, the dynamic output control design against cyberattacks, such as DoS and deception attacks. From those research outcomes, it demonstrates that type-2 control strategies are effective to address the uncertainties in the control systems. Fault estimation and detection are also hot research topics to be discussed through the IT2 control design. Besides, there are IT2 FMB control designs combined with other types of control frameworks are reported, such as the model predictive control and sliding-mode control. The stability analysis of the hybrid control systems is conducted through the MFD approach, which shows the potential of implementing type-2 control design with other control design frameworks. In addition, the design of the GT-2 FLC is presented in this special issue.

Special thanks to Prof. Jon Garibaldi, the Editor-in-Chief of the IEEE TRANSACTIONS ON FUZZY SYSTEMS, for his support and efforts provided to this special issue. We would like to thank the Journal Editorial Administrator, Clair Morton for her assistance to this special issue. We would also like to thank all the authors who contributed their original works to this special issue and all the anonymous reviewers for sharing their thoughts on the submissions. We hope that this special issue can inspire the researchers in the field and push the research on type-2 FMB control systems to new frontiers.

BO XIAO *Guest Editor*
Imperial College London
London SW7 2AZ, U.K.

HAK-KEUNG LAM *Guest Editor*
King's College London
WC2R 2LS London, U.K.

KAZUO TANAKA *Guest Editor*
University of Electro-Communications
Tokyo 182-8585, Japan

JERRY M. MENDEL *Guest Editor*
University of Southern California
Los Angeles, CA 90089-2564 USA

REFERENCES

[1] J. M. Mendel, *Uncertain Rule-Based Fuzzy Systems: Introduction and New Directions*, 2nd ed. Cham, Switzerland: Springer, 2017.
[2] C. Oscar and M. Patricia, *Type-2 Fuzzy Logic: Theory and Applications*. Berlin, Germany: Springer-Verlag, 2008.
[3] J. M. Mendel and R. I. B. John, "Type-2 fuzzy sets made simple," *IEEE Trans. Fuzzy Syst.*, vol. 10, no. 2, pp. 117–127, Apr. 2002.
[4] J. Mendel, H. Hagras, W.-W. Tan, W.W. Melek, and H. Ying, *Introduction to Type-2 Fuzzy Logic Control*. Hoboken, NJ, USA: Wiley, 2014.
[5] K. Tanaka and H. O. Wang, *Fuzzy Control Systems Design and Analysis: A Linear Matrix Inequality Approach*. Hoboken, NJ, USA: Wiley, 2004.
[6] H. K. Lam, "Stability analysis of polynomial fuzzy model-based control systems using switching polynomial Lyapunov function," in *Polynomial Fuzzy Model-Based Control Systems*. Berlin, Germany: Springer, 2016, pp. 223–258.
[7] H. K. Lam and L. D. Seneviratne, "Stability analysis of interval type-2 fuzzy-model-based control systems," *IEEE Trans. Syst., Man, Cybern. B, Cybern.*, vol. 38, no. 3, pp. 617–628, Jun. 2008.
[8] H. K. Lam, H. Li, C. Deters, E. L. Secco, H. A. Wurdemann, and K. Althoefer, "Control design for interval type-2 fuzzy systems under imperfect premise matching," *IEEE Trans. Ind. Electron.*, vol. 61, no. 2, pp. 956–968, Feb. 2013.

Bo Xiao (member, IEEE) received the Ph.D. degree in Robotics (Control Sciences and Engineering) from the Department of Informatics, King's College London, London, U.K., in 2018.

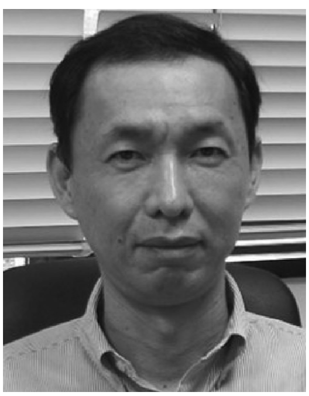
He is currently a Research Associate with Hamlyn Centre for Robotic Surgery and the Department of Computing, Imperial College London, London. During the period 2017 to 2018, he was a Research Fellow with Advanced Robotics Centre and the Department of Biomedical Engineering, National University of Singapore, Singapore. His current research interests include fuzzy model based control systems, interval type-2 fuzzy logic, polynomial control systems, machining learning, reinforcement learning, and their applications in medical robotics.

Dr. Xiao has been the Guest Editor for the IEEE TRANSACTIONS ON FUZZY SYSTEMS, *IET Control Theory and Applications*, *International Journal of System Sciences*, and *Mathematical Problems in Engineering*. He was an active reviewer for a number of peer-reviewed journals.

Hak-Keung Lam (Fellow, IEEE) received the B.Eng. (Hons.) degree in Electronic Engineering and Ph.D. degree in Electronic and Information Engineering from the Department of Electronic and Information Engineering, The Hong Kong Polytechnic University, Hong Kong, in 1995 and 2000, respectively.

From 2000 to 2005, he was with the Department of Electronic and Information Engineering, The Hong Kong Polytechnic University, as a Postdoctoral Fellow and a Research Fellow, respectively. In 2005, he joined, as a Lecturer, with King's College London, where he is currently a Reader. His current research interests include intelligent control, computational intelligence, and machine learning.

Dr. Lam was a Program Committee Member, an International Advisory Board Member, an Invited Session Chair, and a Publication Chair for various international conferences, and a Reviewer for various books, international journals, and international conferences. He is also an Associate Editor for the IEEE TRANSACTIONS ON FUZZY SYSTEMS, the IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS II: EXPRESS BRIEFS, *IET Control Theory and Applications*, the *International Journal of Fuzzy Systems*, *Neurocomputing*, and *Nonlinear Dynamics,* and a Guest Editor and an Editorial Board member for a number of international journals. He is a coeditor of two edited volumes *Control of Chaotic Nonlinear Circuits* (World Scientific, 2009) and *Computational Intelligence and Its Applications* (World Scientific, 2012), and authored or coauthored of three monographs *Stability Analysis of Fuzzy-Model-Based Control Systems* (Springer, 2011), *Polynomial Fuzzy Model Based Control Systems* (Springer, 2016), and *Analysis and Synthesis for Interval Type-2 Fuzzy-Model-Based Systems* (Springer, 2016). He was named as a Highly Cited Researcher.



Kazuo Tanaka (Fellow, IEEE) received the B.S. and M.S. degrees in electrical engineering from Hosei University, Tokyo, Japan, in 1985 and 1987, respectively, and the Ph.D. degree in systems science from the Tokyo Institute of Technology, Tokyo, in 1990.

He is currently a Professor with the Department of Mechanical Engineering and Intelligent Systems, University of Electro-Communications, Chofu, Japan. He was a Visiting Scientist in computer science with the University of North Carolina at Chapel Hill, Chapel Hill, NC, USA, in 1992 and 1993. His research interests include intelligent systems and control, nonlinear systems control, robotics, and brain–machine interface and their applications.

Prof. Tanaka was the Chair of Task Forces on Fuzzy Control Theory and Application and IEEE Computational Intelligence Society Fuzzy Systems Technical Committee. He was also an Associate Editor for *Automatica* and for the IEEE TRANSACTIONS ON FUZZY SYSTEMS, and is on the IEEE Control Systems Society Conference Editorial Board. He is also an International Fuzzy Systems Association Fellow. He was the recipient of the Best Young Researchers Award from the Japan Society for Fuzzy Theory and Systems, in 1990, the Outstanding Papers Award at the 1990 Annual NAFIPS Meeting in Toronto, ON, Canada, in 1990, the Outstanding Papers Award at the Joint Hungarian-Japanese Symposium on Fuzzy Systems and Applications in Budapest, Hungary, in 1991, the Best Young Researchers Award from the Japan Society for Mechanical Engineers, in 1994, the Outstanding Book Awards from the Japan Society for Fuzzy Theory and Systems, in 1995, the 1999 IFAC World Congress Best Poster Paper Prize, in 1999, the 2000 IEEE TRANSACTIONS ON FUZZY SYSTEMS Outstanding Paper Award in 2000, the Best Paper Selection at 2005 American Control Conference in Portland, OR, USA, in 2005, the Best Paper Award at 2013 IEEE International Conference on Control System, Computing and Engineering in Penang, Malaysia, in 2013, the Best Paper Finalist at 2013 International Conference on Fuzzy Theory and Its Applications, Taipei, Taiwan, in 2013, and the Best Poster Award, The First International Symposium on Swarm Behavior and Bio-Inspired Robotics, Kyoto, Japan, in 2015. He was also the recipient of the 2021 IEEE Computational Intelligence Society Fuzzy Systems Pioneer Award.

Jerry M. Mendel (Life Fellow, IEEE) received the Ph.D. degree in electrical engineering from the Polytechnic Institute of Brooklyn, Brooklyn, NY, USA.

He is currently an Emeritus Professor of Electrical Engineering with the University of Southern California, Los Angeles, CA, USA. He has authored/coauthored more than 580 technical papers and is author and/or coauthor of 13 books. He has more than 54 000 citations to his publications on Google Scholar. His current research interests include type-2 fuzzy logic systems and computing with words.

Prof. Mendel is a Distinguished Member of the IEEE Control Systems Society and a Fellow of the International Fuzzy Systems Association. He was a member of the Administrative Committee of the IEEE Computational Intelligence Society for nine years, and Chairman of its Fuzzy Systems Technical Committee and the Computing With Words Task Force of that TC. Among his awards are four IEEE Transactions Best/Outstanding paper awards, a 1984 IEEE Centennial Medal, an IEEE Third Millennium Medal, and a Fuzzy Systems Pioneer Award in 2008 from the IEEE Computational Intelligence Society.