Guest Editorial

VARIABLE-STRUCTURE systems (VSSs) with sliding modes (SMs) are currently among the most important research topics within the control engineering domain. This topic has always carried a special importance for the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, and many papers have been published on it over the years, reporting successful implementations of the theory in a very diverse field of applications, as well as survey papers from the leading authorities in the field. More recently, with the goal of reporting the latest developments in engineering applications of SM control (SMC), a call was launched for a Special Section. This call resulted in such a strong response that the selected papers had to be handled in two different parts. Out of a total of 415 manuscripts submitted, 29 accepted papers appeared in the November 2008 issue. This Special Section consists of the remaining 43 accepted papers.

Despite the extensive research activities carried out over the years, the key technical problems associated with SMC still remain as challenging research questions. To alleviate the problems, the use of soft computing (SC) methodologies has widely been advocated. The Special Section starts with a survey paper by Yu and Kaynak on the topic, providing the state of the art of recent developments in SMC systems with SC, examining key technical research issues and future perspectives. The next three papers in the Special Section are related to the survey paper in the sense that they utilize SC methodologies. The first one by Liang *et al.* studies the robust reliable control issues based on the Takagi–Sugeno fuzzy system modeling method and the SMC technique. The combined scheme is shown to have the merits of both approaches. In the second one, Wang *et al.* propose a neural-network-based terminal SMC scheme for the control of robotic manipulator including actuator dynamics. The proposed approach alleviates some of the drawbacks of the conventional linear SMC while maintaining its robustness to the uncertainties. In the last one, Su *et al.* propose first a hard variable-structure control for achieving uniform ultimate boundedness control and then a soft variable-structure control using fuzzy logic to help improve dynamic responses when the trajectories enter into the ultimate bound. A genetic-algorithm-based alpha–beta filter in front of the fuzzy controller is added to suppress noise and obtain smooth input signals. The performance of the control scheme is practically tested on a magnetic levitation system.

The Special Section continues with a group of six papers on high-order SMs. The first one by Beltran *et al.* deals with the power generation control in wind turbines that have two operation regions which depend on wind turbine tip speed ratio. A higher order SMC strategy is proposed to ensure stability in both operation regions and to impose the ideal feedback control solution in spite of model uncertainties. In the following paper by Reichhartinger and Horn, the control of an electronic throttle valve based on second-order SM concepts is presented. The third paper of the group by Zhang *et al.* uses the second-order SM technique to control DiffServ network, based on a nonlinear fluid flow model. The following paper is by Defoort *et al.*, and it deals with the robust control problem of a stepper motor subject to parameter uncertainties and load torque perturbation. The developed algorithm is based on a third-order SMC such that a desired angular motor position is accurately tracked. The next paper by Tanelli *et al.* deals with a traction control system for ride-by-wire sport motorcycles based on the second-order SM methodology. The controller design is based on a nonlinear dynamical model of the rear wheel slip, and the modeling phase is validated against experimental data measured on an instrumented vehicle. The last paper of the group by Defoort and Murakami is related to the previous one as it deals with the robust stabilization and trajectory tracking problems of a riderless bicycle. A dynamic model, which takes into account geometric stabilization mechanisms due to bicycle trail, is presented. A posture controller, which combines second-order SMC and disturbance observer, is derived.

The next group of nine papers is on the use of VSS theory in the design of observers. The first paper by Rao *et al.* presents two observers which provide motor speed, flux, and rotor resistance estimates simultaneously for a sensorless drive. The paper is related to the previous group in the sense that both observers, based on the rotor flux model in the stationary reference frame, are designed with inputs that enforce first-order (conventional) and second-order SMs, respectively, on appropriately chosen switching surfaces. Experimental results are presented. In the following paper by Alvarez *et al.*, an analog implementation of a control structure with disturbance identification for mechanical systems is presented. The control structure is based on a discontinuous observer that estimates the state and disturbances in the plant, improving the robustness of the closed-loop system. In the next paper by Veluvolu and Soh, an SM term is incorporated into the nonlinear high-gain observer to realize a robust high-gain observer. The following paper is by Lascu *et al.* In it, a new family of speed-sensorless SM observers for induction motor (IM) drives is developed. Three topologies are investigated in order to determine their feasibility, parameter sensitivity, and practical applicability. The next paper by Ghanes and Zheng is also on sensorless IM drives. In this paper, an SM observer that uses only the measured stator currents is used to estimate the speed, flux, and load torque, and a current-based field-oriented SMC is developed so as to steer the estimated speed and flux magnitude to the desired references. In the following paper, Comanescu presents a speed estimation method for IM drives, which is based on a special current control scheme called integral SM current control (ISM-CC). The paper describes both the ISM-CC method and the speed

Digital Object Identifier 10.1109/TIE.2009.2027372

estimator. Simulations and experimental results on a 1/4-hp three-phase IM confirm the validity of the method. The next paper by Feng *et al.* proposes a hybrid terminal SM (TSM) observer to estimate the rotor position and the speed in a permanent magnet synchronous motor control system. The paper by Bandyopadhyay *et al.* proposes a method for the design of switching surface in the presence of mismatched uncertainties. The states of the system are constructed by an SM observer based on high gain. The last paper of the group is again by Veluvolu and Soh. It addresses the problems of discrete-time state and unknown input/fault estimation for continuous-time nonlinear systems with multiple unknown inputs. The novelty of the paper lies in the formulation of multiple-SM estimator for the states that are directly influenced by unknown inputs, which cannot be decoupled by nonlinear transformation.

The next group of six papers is related to converters. The first one in the group is by Oettmeier *et al.* In this paper, a hybrid/switched/VSS state model is developed for a dc–dc (boost) converter for the purpose of applying hybrid optimal control theory. A switching function that minimizes a user-defined performance index is presented. In the next paper, Cortes *et al.* propose a dynamical SM controller for a boost inverter, based on the idea of indirectly controlling the output voltage through the inductor current. Unlike the usual approach of generating a sinusoidal voltage in both capacitors of the boost inverter, the strategy proposed in the paper focuses on generating a sinusoidal voltage on the load despite the voltage form of the capacitors. In the third paper of the group, Kukrer *et al.* propose a novel approach to the SMC of single-phase uninterruptible power system inverters. A three-level hysteresis sliding function is used to directly control the inverter switches, with the result that a transistor is switched during a half cycle while it remains either on or off during the other cycle. In the following paper, Castilla *et al.* present a comparative study of SMC schemes for quantum series resonant inverters. Simulation and experimental results are reported in order to validate the theoretical predictions. The fifth paper of the group is also on quantum resonant converters. The SM controller presented in this paper by de Vicuna *et al.* for a single-phase ac/ac quantum resonant converter improves regulation, sensitivity to disturbances, and transient response. Simulation and experimental results are presented. In the last paper of the group, a new variable structure controller design method based on Lyapunov–Metzler inequalities is suggested. Cardim *et al.* apply the method to the control of a dc–dc power converter.

The next paper of the Special Section is by Huang *et al.* For the control of piezoelectric actuators with nonlinear uncertainties, it proposes a controller with two parts: SM and adaptive components. Simulation and real-time experimental results are provided to verify the effectiveness of the proposed scheme. The following paper by Loukianov *et al.* considers an electrohydraulic actuator. For its control, integral block control, SMC, and H-infinity control are combined. In this way, the inherent nonlinearities of the actuator are compensated, matched external disturbances are rejected, and mismatched external disturbances are attenuated.

In the next paper of the Section, which is again by Huang *et al.*, the monitoring and control of linear drives subject to nonlinear uncertainties are considered. First, a residual generator based on SM is proposed to monitor the health of the linear drive. Second, an SMC system is designed, which can work in two modes: normal control and fault-tolerant control. Real-time experimental results are provided to verify the effectiveness of the proposed method.

The next two papers are by the same authors, Park and Chwa, on the control of pendulums. In the first one, an SMC law is designed to force a coupled sliding surface (which consists of sliding surfaces of both actuated and unactuated subsystems) to be reached in finite time, such that zero dynamics are generated in the form of a second-order damped and forced nonlinear differential equation. In the second paper, a coupled SMC method for the periodic orbit generation and the robust exponential orbital stabilization of inverted-pendulum systems is proposed.

The following four papers of the Special Section are application oriented. In the first paper by Akar and Kalkkuhl, an integrated chassis controller for vehicle emulation is designed, and its performance is evaluated. The proposed vertical controller consists of an active body controller and a force controller, which are both designed based on mathematical models derived from physical principles and also validated by experimental data. In the following paper, Alt *et al.* propose a multiple sliding surface controller for automotive engine control at idle condition, the control task being to hold engine speed and torque reserve at their reference values despite parameter uncertainties. In the next paper, Jin *et al.* propose a practical nonsingular TSM tracking control design for robot manipulators using time delay estimation. In the last paper of the group, Fu and Ozguner propose an extremum seeking approach for source tracing problems with vehicles subject to minimum turning radius and nonholonomic constraints. Extremum seeking control with SM is utilized for direction finding, and variable-structure control is designed to address the constraints on vehicle kinematics and the accessible area.

Discrete-time SMC is the subject matter of the next three papers. In the first one, Khan *et al.* propose a discrete-time SM controller based on Lyapunov theory for high-precision motion control of a piezostage. The system includes a robust disturbance observer. The paper by Abidi *et al.* argues that TSM control (TSMC) would be desirable in digital implementation where the limited sampling frequency may incur chattering if the controller gain that is overly high is known since it is known that TSM has high-gain property nearby the vicinity of the equilibrium while retaining reasonably low gain elsewhere. In their work, a linear switching surface with a terminal switching surface is integrated. The experimental results presented indicate the advantages of the TSMC design over the linear SMC. In the last paper of the group, a nonlinear sliding surface is proposed by Bandyopadhyay and Fulwani to improve the transient response for general discrete multiple-input–multiple-output linear systems with matched perturbations. The tracking case is analyzed, and it is shown that the proposed scheme is able to achieve low overshoot and low settling time simultaneously, with no chattering.

The next group of three papers is on time-delay systems. In the first one by Liu *et al.*, a fully linearizable single-input–single-output relative degree n system with an output time delay

is considered. To compensate for the difference between the actual delayed output and its approximate value obtained by the Padé approximation, a Smith predictor is used. A second-order supertwisting SM observer observes the disturbance in the plant. A nonlinear example is studied to show the effectiveness of the approach. In the following paper, Xia *et al.* use the delta operator approach, a delay-dependent sufficient condition is derived for the existence of linear sliding surfaces, and a reaching motion controller is developed. The last paper of the group is by Han *et al.* in which the development of SM-based output feedback controllers for uncertain systems which are subject to time-varying state delays is considered and a novel method is proposed for the design of the switching surface.

The Special Section concludes with three papers which are somewhat different from the rest in the sense that they are more on the theoretical side. The work of García-Rodríguez *et al.* deals with the output feedback control and the simultaneous online algebraic identification of an unknown perturbed 1-DOF suspension system. The estimated values of mass, stiffness, and damping are realized via an algebraic estimator, with great rapidity and robustness to noise process signals present in the input and output signals. A generalized proportional integral controller is designed for the trajectory tracking task and the rejection of a constant disturbance input. The efficiency of the complete procedure is demonstrated via digital computer simulations. In the following paper, Andrade-da Silva *et al.* propose a design framework for synthesizing SM output feedback controllers for plants with matched and mismatched uncertainties. The switching surface design problem is formulated in terms of linear matrix inequalities from a polytopic perspective, as a static output feedback problem with mismatched uncertainties. The last paper by Zhang *et al.* is included in this Special Section as an example of the topic of switched systems. In the paper, with the problems of stability and stabilization of a class of multimode systems, the switched linear discrete-time systems with polytopic uncertainties are investigated. Two types of switching, including fast and slow switchings among the modes of systems, are considered.

The main objective of this Special Section has been to present the readers with a broad range of recent industrial applications of SMC, as well as the recent theoretical advances. The Guest Editors believe that this ambitious objective has been successfully accomplished with the 29 papers of Part I and the 43 papers of Part II, in total of 72 high-quality papers, selected out of the 415 submitted ones. Some of the papers have gone through three review stages. The valuable comments and suggestions made by the reviewers during the process have no doubt helped the authors to improve their contributions so that the papers to be published are technically thorough, understandable, and of reference quality. The Guest Editors would therefore like to express their sincere gratitude to the authors who sent in their valuable contributions and to the reviewers for their time and effort. Thanks are also due to Prof. B. M. Wilamowski, who is the Editor-in-Chief of the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, for allowing the preparation of this Special Section to proceed and for his help, support, and encouragement. Last but not least, the Guest Editors would like to thank the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS Administrator, Sandra McLain, for her continuous kind and punctual support.

In conclusion, the Guest Editors hope that this Special Section will be of interest to the industrial electronics community and that the contributions presented here will enrich the current state of the art, and motivate and encourage new ideas and solutions in the SMC area.

OKYAY KAYNAK, *Guest Editor*
Bogazici University
34342 Istanbul, Turkey

ANDRZEJ BARTOSZEWICZ, *Guest Editor*
Institute of Automatic Control
Technical University of Łódź
90-924 Łódź, Poland

VADIM I. UTKIN, *Guest Editor*
The Ohio State University
Columbus, OH 43210 USA

Okyay Kaynak (M'80–SM'90–F'03) received the B.Sc. (with first class honors) and Ph.D. degrees in electronic and electrical engineering from the University of Birmingham, Birmingham, U.K., in 1969 and 1972, respectively.

From 1972 to 1979, he held various positions in the industry. In 1979, he joined the Department of Electrical and Electronics Engineering, Bogazici University, Istanbul, Turkey, where he is currently a Full Professor, holding the UNESCO Chair on Mechatronics. He has held long-term (near to or more than a year) Visiting Professor/Scholar positions at various institutions in Japan, Germany, the U.S., and Singapore. His current research interests are in the fields of intelligent control and mechatronics. He has authored three books and edited five and authored or coauthored more than 300 papers that have appeared in various journals and conference proceedings.

Dr. Kaynak is active in international organizations, has served on many committees of the IEEE, and was the President of the IEEE Industrial Electronics Society during 2002–2003.

Andrzej Bartoszewicz received the M.Sc. and Ph.D. degrees from the Technical University of Łódź, Łódź, Poland, in 1987 and 1993, respectively, and the Doktor Habilitowany degree in control engineering and robotics from the Academy of Mining and Metallurgy, Cracow, Poland.

He was a Visiting Scholar at Purdue University, West Lafayette, IN, and Strathclyde University, Glasgow, U.K. Then, for one year, he was with the University of Leicester, Leicester, U.K. He is currently a Professor at the Technical University of Łódź, where he is the Vice-Dean of the Department of Electrical, Electronic, Computer and Control Engineering, the Head of the Electric Drive and Industrial Automation Group, and the Vice-Director of the Institute of Automatic Control. He has published two monographs and over 150 papers, primarily in the fields of sliding-mode control and congestion control in data transmission networks

Vadim I. Utkin (F'04) received the Dipl. Eng. degree from the Moscow Power Engineering Institute, Moscow, Russia, and the Ph.D. degree from the Institute of Control Sciences, Moscow.

In 1960, he joined the Institute of Control Sciences, where he was the Head of the Discontinuous Control Systems Laboratory from 1973 to 1994. He has held visiting positions at universities in the U.S., Japan, Italy, and Germany. He is one of the originators of the concepts of variable-structure systems and sliding-mode control. He was the Principal Investigator of an international project between his Institute and "Energoinvest," Sarajevo, Bosnia and Herzegovina, and several projects with automotive companies in the U.S. He is an Honorary Doctor of the University of Sarajevo. He is currently with The Ohio State University, Columbus, where he was the Ford Chair of Electromechanical Systems from 1994 to 2002. He is the author of five books and more than 300 technical papers.

Prof. Utkin was the recipient of the Lenin Prize (the highest scientific award in the former U.S.S.R.) in 1972, the Oldenburger Medal in 2003, and the Humboldt Award in 2005. He was the International Program Committee Chairman of the 1990 International Federation of Automatic Control Congress in Tallinn, Estonia.