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Editorial

Higher Order Sliding Modes

By the early 1980s the control community had perceived that the main advantages of sliding mode control, i.e. robustness to matched disturbances and a finite time convergence, were offset by a side effect, named chattering [1], caused mainly by unmodelled cascade dynamics. The latter increases the system's relative degree and perturbs the ideal sliding mode, which exists in the system with the original (ideal) input–output dynamics [1–3].

In order to overcome the chattering problem in the sliding mode higher order sliding mode (HOSM) control was introduced in the PhD dissertation of Arie Levant (Levantovsky) [4] (see also [5–7]). Levant [8] systematized the second-order sliding mode algorithms and obtained estimates of their accuracy.

HOSM attracted the full attention of the international control community after the presentation [9] at the Third IEEE Workshop Variable Structure and Lyapunov Theory and the publication of the first tutorial paper on HOSM [10]. Since 1996 the number of publications on second order sliding modes theory and applications has grown exponentially generally by the efforts of Professor Bartolini and his group [11] (see [12] and reference therein too).

The second-order sliding mode differentiator, based on the super-twisting algorithm, was proposed in 1998 [13] and gave further impetus to the development of the mathematical theory and applications of HOSM algorithms.

Two other major contributions by Levant: arbitrary-order HOSM control in 2001 [14] and arbitrary-order asymptotically optimal robust exact differentiators in 2003 [15] allowed the design and the implementation of universal arbitrary-order HOSM output-feedback controllers [15].

However, design of new types of HOSM controllers still remained complicated. Recently, generalized algorithms for designing universal arbitrary-order HOSM controllers have been developed based on the homogeneous [16] and quasi-homogeneous [17] properties of HOSM dynamics.

The aim of this Special Issue is to report the current state of art of modern HOSM control. The issue has two main topics:

- modern HOSM controller and applications;
- second-order sliding mode controllers: their properties and applications.

The volume begins with the paper 'Generalized homogeneous quasi-continuous controllers' by A. Levant and Y. Pavlov. It presents a *new class* of arbitrary-order homogeneous quasi-continuous sliding mode controllers, containing numerous functional parameters. All the studied controllers are presented in an output-feedback format. A numerical algorithm is developed for setting the parameters of the designed controllers.

The paper 'Higher order sliding mode observer for state estimation and input reconstruction in nonlinear systems' by L. Fridman, Y. Shtessel, C. Edwards and X. G. Yan is devoted to the most successful application of HOSM algorithms: observation and identification of uncertain systems. This paper proposed a *new class* of higher order sliding mode observers for nonlinear locally *observable* and *detectable* systems estimating exactly the observable states and asymptotically the unobservable ones for multiple-input multiple-output nonlinear systems with unknown inputs and stable internal dynamics. It is shown that the unknown inputs can be identified asymptotically.

In the paper 'Actuator fault diagnosis for linear systems with arbitrary relative degree and unmatched unknown inputs using a high order sliding mode robust differentiator' by W. Chen and M. Saif, for actuator fault diagnostic problems for a general class of linear systems in the presence of unmatched unknown inputs are studied and the relative degree assumption is removed. The problems are studied by using both the outputs and their higher order derivatives. The higher order output derivatives are estimated using the recently developed HOSM robust differentiators.

In the paper 'High order sliding mode observer for a quadrotor unmanned aerial vehicle' by A. Benallegue, A. Mokhtari and L. Fridman, a feedback linearization-based controller with a high order sliding mode parallel observer is applied to a quadrotor unmanned aerial vehicle. The model of the system has a vector relative degree (4, 4, 4, 2) with respect to the measurable outputs. The HOSM observer estimates the effects of the external disturbances such as a wind for example.

F. Plestan, A. Glumineou and S. Laghrouche in the paper 'A new algorithm of high order sliding mode control' propose a novel input/output controller for uncertain linear minimum phase systems. The system's trajectory is steered to the sliding manifold by the designed higher order sliding mode controller in finite time.

In the paper 'Nonminimum-phase output tracking in causal systems using higher order sliding modes' by S. Baev, Y. Shtessel and I. Shkolnikov, asymptotic output tracking in a class of causal nonminimum-phase uncertain nonlinear systems is addressed *via* higher order sliding modes. Local asymptotic stability of the output tracking error dynamics is provided. An output reference profile and external disturbance forcing the internal dynamics are defined by an unknown linear exosystem. Its characteristic polynomial (which is used in the output tracking control algorithm) is identified online by using a higher order sliding mode parameter observer. A numerical example illustrates efficiency of the developed HOSM control algorithm.

In the paper 'Stabilization of single-input nonlinear systems using higher order term compensating sliding mode control', D. Voytsekhovsky and R. Hirschorn develop a new approach to the sliding mode control design. For a given approximately feedback linearizable system, a local coordinate transformation is introduced; and a sliding mode controller steers the new states to the origin in the sliding mode.

The paper 'High order sliding mode for an electropneumatic system: a robust differentiator-controllers design' by M. Smaoui, X. Brun and D. Thomasset deals with the robust control problem of a pneumatic actuator subject to parameter uncertainties and load disturbances. The control strategies are based on second- and third-order sliding mode approaches. Levant's differentiator is used in order to estimate the acceleration.

The paper 'Analysis of response of second-order sliding mode controllers to external inputs in frequency domain' by I. Boiko, I. Castellanos and L. Fridman, analyses the input–output properties of second-order sliding mode control algorithms. The analysis is carried out using the concept of the equivalent gain as a model for propagating the averaged values of the signals through the nonlinearities of the system. Analytical expressions for the equivalent gains are derived. Analysis of the response of the systems controlled by the twisting and super-twisting algorithms to the external harmonic inputs of variable frequency is presented.

Control of nonholonomic systems with uncertainties *via* second-order sliding modes is considered in the paper by A. Ferrara, L. Giacomini and C. Vecchio. A suitable transformation of the system coordinates is performed in order to transform the system to a form with only matched uncertainties. A particular sliding manifold is designed and enforced by a second-order sliding mode controller. Apart from the robustness features typical for the sliding mode approach, the proposed control law has the advantage of being continuous, thus more acceptable in some applications such as those of a mechanical nature.

The two-part paper 'Second order sliding mode control of underactuated mechanical systems', co-authored by S. Riachy, R. Santiesteban, Y. Orlov, T. Floquet and J.-P. Richard is of both theoretical and technological value. In this paper, a second-order sliding mode control methods is developed using quasi-homogeneous synthesis [17] and applied to controlling some mechanical systems with friction. In the first part of the paper, quasi-homogeneous local stabilization is performed for underactuated mechanical systems with friction. In order to stabilize such a system locally around an unstable equilibrium, its output is specified in such a way that the corresponding zero dynamics is locally asymptotically stable. Once such an output has been chosen, the desired stability property of the closed-loop system, and robustness against friction forces are provided by applying a quasi-homogeneous controller, driving the system to the zero dynamics manifold in finite time. A second-order sliding mode appears on the zero dynamics manifold, which is of co-dimension greater than the control space dimension. The proposed controller is studied experimentally on an underactuated cart–pendulum system with both Coulomb and viscous friction forces. The orbital stabilization of a cart–pendulum system is studied in the second part of the paper. The quasi-homogeneous synthesis is applied to follow a periodic orbit that is the harmonic limit of a modified van der Pol oscillator in the phase space. The proposed modification still possesses a stable limit cycle, governed by a standard linear oscillator equation, and therefore it constitutes an asymptotic harmonic generator as opposed to a standard van der Pol oscillator, exhibiting a non-sinusoidal response in its limit cycle. The parameters of the van der Pol modification are shown to specify damping, amplitude and frequency of oscillation so that the resulting closed-loop system proves to be capable of moving from one orbit to another by simply changing these parameters dynamically. The proposed orbital stabilizing synthesis is supported by an experimental study of the swing-up/balancing control moving the pendulum, located on the actuated cart, from its stable downward position to the unstable inverted position and stabilizing it about the vertical line.

P. Kaveh and Y. Shtessel in the paper 'Blood glucose regulation using higher order sliding mode control' discuss diabetes as a serious condition in which the body's production and use of HOSM techniques, in specific prescribed convergence law, quasi-continuous and super-twisting control algorithms are used to robustly stabilize the glucose concentration level of a diabetic patient in the presence of parameter variations and meal disturbance. The structure of the proposed higher order sliding mode controllers is appropriate for making the insulin delivery pumps in the closed-loop control of diabetes. A computer simulation is performed to manifest the theoretical analysis. The super-twisting algorithm is employed to attenuate the effect of chattering and obtain continuous control in the simulations. The efficiency of the proposed controller, i.e. robustness and high accuracy, in the presence of physical disturbances like food intake and parametric uncertainties, is verified *via* simulations.

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In the paper 'A combined first/second order sliding mode technique in the control of a jet propelled vehicle' by G. Bartolini, N. Orani, A. Pisano, E. Punta and E. Usai, the design and practical implementation of a position/attitude sliding mode controller for a surface vessel prototype is studied. The prototype is equipped with a special propulsion system based on hydro jets with an adjustable output section. The sliding mode controller comprises a second order sliding mode velocity observer and a simplex-based sliding mode controller. Some major implementation issues are discussed and experimental results are shown.

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YURI B. SHTESSEL
The University of Alabama in Huntsville, Huntsville AL, U.S.A.

LEONID FRIDMAN
National Autonomous University of Mexico, Mexico

ALAN ZINOBER
The University of Sheffield, U.K.

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