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Luise Senkel

Sliding Mode Techniques for Robust Control, State Estimation and Parameter Identification of Uncertain Dynamic Systems

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Preface

This dissertation originates from my scientific work as a research associate at the Chair of Mechatronics at the Faculty of Mechanical Engineering and Marine Technology at the University of Rostock.

After the completion of my masters degree, Prof. Dr.-Ing. Harald Aschemann gave me the opportunity to research in the presented topic for which I am very grateful. I would like to thank my supervisors Prof. Dr.-Ing. Harald Aschemann and Prof. Dr.-Ing. habil. Bernd Tibken for serving as reviewers of this thesis. Additionally, I would like to thank Prof. Dr.-Ing. Hermann Seitz and Prof. Dr.-Ing. habil. Christoph Woernle for participating in the examination board.

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Karben, January 2018 Luise Senkel

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Uncertainty is a problem that affects all real-life systems. Insufficient knowledge of system parameters or internal processes, sensor inaccuracies, random disturbances or environmental influences are only a few types that cannot be considered in the mathematical modeling without further ado.

Often, uncertain effects can be represented in terms of intervals by defining a minimum and a maximum value. These form a range of, for example, tolerances of measured data or varying parameters where the true values must be located within this range under all circumstances for all times. If such a case occurs, then calculations with intervals instead of faulty or inaccurate point-values are the better choice. All classical arithmetic operators for floating-point values can be transferred to interval computations with the help of already existing libraries to deal with the first class, called bounded uncertainty.

In real systems, it is not always possible to assign uncertain effects to a special parameter because of random characteristics, as for example process or measurement noise. These are examples for the second class – stochastic uncertainty. This type of uncertainty is not only characterized by random occurrences but also by the fact that fixed range bounds can hardly be defined.

Interval methods have already been used for different purposes in the literature. The calculation of verified state enclosures, parameter identification methods and verified global optimization procedures are known application areas. However, all of them are performed offline and typically not real-time capable. Hence, the online usage of intervals within robust control and estimation approaches is a novel area of research.

Another problem in real-life systems is to find a suitable mathematical model that reflects the most important dynamics and is not too complex for implementation in real-time. The next step, robust control of a system at hand with the self-defined mathematical model in a reliable way is often complicated additionally by the limited number of measurable system states. Therefore, all non-measurable states need to be estimated. The application of state estimation approaches for systems which are influenced by stochastic effects is a well-known problem that is commonly solved by filtering approaches. Especially for linear systems with additive normally distributed disturbances, Kalman filters are established. The possibility to combine such methods with uncertain bounded effects to consider both types of uncertainty within one approach is not state-of-the-art.

Robust control approaches have to ensure sufficiently good trajectory tracking despite bounded and stochastic disturbances. For that reason, it is shown in this thesis that sliding mode approaches can be generalized such that, on the one hand, interval methods are used to represent bounded uncertainty and, on the other hand, stochastic effects are considered. Due to the usage of the Itô differential operator for stochastic processes with a suitable Lyapunov function, it is possible to modify state-of-the-art sliding mode approaches such that an online approach results. In contrast, state-of-the-art sliding mode methods for control and estimation are commonly parameterized offline which may lead to more conservative solutions. The presented extension taking into account bounded and stochastic uncertainty aims at an improvement of the state-of-the-art procedures from the literature such that not only the system's stability is guaranteed for all times but also the actuator effort is decreased.

The general procedure of sliding mode techniques is based on the definition of a stable operation mode (called sliding surface). Once the system has reached this mode, the system will always stay in its near surrounding area and never diverge. Moreover, a variable-structure gain that has a switching characteristic commonly needs to be defined in an intelligent way. To overcome this, it is shown, how the variable-structure gain can be calculated systematically in an online manner in each time step, where intervals defining range bounds for parameters as well as control, estimation, and measurement errors are included. The combination of sliding mode techniques with intervals and the Itô differential operator enables the possibility to include not only stochastic effects such as process and measurement noise, but also an insufficient knowledge of parameters, disturbances, rounding errors and other influences. Because the variable-structure gain is calculated in each time step, the most serious problem when calculating with intervals, namely overestimation due to the wrapping effect as well as the dependency problem, can be reduced significantly.

The advanced sliding mode techniques are used in this thesis for both, control and estimation purposes to overcome the problem of insufficient or even missing measurements. In such a way, a closed-loop control becomes possible not only in simulation but also in real-time environments.

Two application scenarios are presented in this thesis: a drive-train test-rig and the thermal part of a high-temperature fuel cell system. For the first one, not only states are estimated but also system parameters are identified in real-time. A closed-loop control using the advanced sliding mode approaches is performed in simulation and experiment. Moreover, the importance of the used intervals is further analyzed. For the second test-rig, firstly, a complex mathematical model describing the processes in the preheating system and the centerpiece of the system, the fuel cell stack, is explained. To decrease implementation effort, a simplified model is shown additionally. It is demonstrated that a controller based on the simple model is able to track the desired temperature trajectory of the system described by the complex model with good accuracy. An observer-based closed-loop control is realized on the considered test-rig.

The presented extended sliding mode strategies are compared with different known methods from the literature: state-of-the-art sliding mode control and estimation, Luenberger observer design, state-feedback control design with static or dynamic feedforward control, proportional-integral extensions of the control law, as well as the least-squares method for parameter identification. These approaches are used to verify the novel interval-based sliding mode methods also in a real-time framework.

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