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Julia Kersten

Cooperativity and its Use in Robust Control and State Estimation for Uncertain Dynamic Systems with Engineering Applications

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Preface

This Dissertation Thesis was done as part of my scientific work as a Research Associate with the Chair of Mechatronics at the Faculty of Mechanical Engineering and Marine Technology at the University of Rostock, Germany.

Firstly, I want to thank Prof. Dr.-Ing. Harald Aschemann, Head of the Chair of Mechatronics, for giving me this opportunity as well as for his supervision, scientific comments and the overall experience I gained while with his Chair. I further want to give my special thanks to Prof. Tarek Raïssi (CNAM, Paris, France) for serving as another reviewer of this thesis and his insightful comments on the subject. Additionally, I like to thank all commission members for their contribution and especially for their willingness to conduct the procedure with such promptness. This holds especially for both reviewers. I thank Prof. Dr.-Ing. Harald Aschemann for his straightforward organization despite the challenging pandemic-related inconveniences.

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Rostock, August 2020 Julia Kersten

Cooperativity and its Use in Robust Control and State Estimation for Uncertain Dynamic Systems with Engineering Applications
— Abstract —

In control engineering, model-based designs are applied to a broad variety of applications. Here, one aims to find a balance in the modeling approach depicting the reality as detailed as necessary while keeping the complexity as low as possible in terms of realizability. For this, simplifications are used, e.g. in the form of approximation of nonlinearities, parameter couplings or order reduction. Additionally, errors may occur in parameter identification due to physically motivated phenomena, measurement effects, or possible numerical discretization errors. As a result, basically all real-life systems are subject to uncertainties.

In the presented work, those uncertainties are regarded as intervals, where worst-case bounds are represented by the upper and lower limit of an uncertain parameter. Novel control designs are introduced, which are based on a linear matrix inequality approach suitable for uncertain systems. Two extensions to state-of-the-art designs were given; the first with a constant controller gain approach over the complete time horizon and a second using a gain scheduling design over temporal subslices. Here, both rely on iterative solutions in the terms that controller gains are adapted based on the reachability analysis of former simulations. This means, that an efficient application of such methods is only realized with a reliable computation of possible interval enclosures. State-of-the-art enclosure techniques are often subject to overestimation, a possible solution comes in form of so-called cooperative systems. The structure of these systems allows for a separately, point-valued evaluation of the worst-case bounds, while guaranteeing the real value to be insight said bounds. This property can be found in numerous systems, however, exceptions occur especially concerning models from the fields of electrical as well as mechanical applications. To widen the applicability of cooperativity into these fields, this work presents transformation methods to adapt the structure of the treated system in such a way that it becomes cooperative while keeping its original stability properties. Due to the nature of said transformations this is done for systems with purely real eigenvalues and systems including conjugate-complex ones. As a final theoretical contribution, a state estimation is added to the controlled system as a form of fault diagnosis. Here, two possible approaches are presented. The first aims at keeping the structure of the controlled (and transformed into a cooperative form) system and, hence, is called cooperative-preserving observer. A second design is oriented on the control design making use of the duality principle, meaning that the controlled system is transformed and a parallel model, including the observer is also transformed into a cooperative system. Both results are then compared for the fault diagnosis to detect actuator or/and sensor faults.

Overall, this work gives a generally applicable method combining robust control designs with the computation of verified interval enclosures, and estimators as fault diagnosis tools. Based on the theoretical findings, suitable application scenarios are given in the second part of this work. Here, a constant gain controller design is applied to an electrical circuit, which is then subject to a transformation approach with purely real eigenvalues and a cooperativity-preserving observer design. Next, two mechanical, oscillatory systems are used to show a transformation based on complex-conjugate eigenvalues. Fault diagnosis models are further implemented in parallel. As an extension, the theory is applied to a fractional-order system to show that it works equally well for such models and highlight necessary adaptions. Finally, limits of the presented methods are acknowledged and an alternative solution is demonstrated on the example of an inverted pendulum.

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