Development of Observer Design Algorithms for Nonlinear Systems

Ali Zemouche, Cédric Delattre

1. Background of the thesis

State estimation of dynamical systems is a crucial and important research area for control, diagnostics, and system monitoring. Furthermore, the need for nonlinear estimation and observer design has been recognized and pursued in many modern and essential applications, including self-synchronization in multi-agent systems, achieving consensus in system networks, and detecting cyberattacks and/or denial of service attacks. In the case of nonlinear systems, the problem of state observer design becomes complex and challenging when certain performance criteria must be met, especially in the presence of external disturbances and parametric uncertainties. The difficulty may also arise from the complexity of the system's nonlinearities. Well-known approaches have been proposed in the literature, such as high-gain observers, the extended Kalman filter, observers based on Linear Matrix Inequalities (LMI), methods relying on nonlinear transformations using normal observability forms, and estimation methods based on modulating functions. Despite the many powerful observer design techniques proposed in recent literature [1] [2] [3] [4], the problem remains far from being fully resolved for general nonlinear systems. Many research avenues remain to be explored to improve current methods. The proposed thesis fits into this context.

2. Objectives of the thesis

In this thesis, we aim to work on new methods based on LMIs. The primary objective is to introduce new stability tools to reduce the conservatism of current approaches. Among these tools, we will exploit the concept of "incremental-Exponential Input/Output-to-State Stability (i-EIOSS)," which will lead to more general and less restrictive LMI conditions. Indeed, since the recent work of Andrew Teel and his co-authors, the i-EIOSS property has become essential for synthesizing robust estimators for nonlinear systems. It has been particularly used to develop new stability conditions for certain estimators, such as the Moving Horizon Estimator (MHE). We would like to exploit this interesting property to build nonlinear observers, particularly those based on LMI techniques. Indeed, the i-EIOSS property could overcome some feasibility difficulties encountered by standard LMI approaches.

For example, in the case of systems with non-monotonic nonlinearities, we demonstrated that all LMI approaches fail to provide solutions [5], and we plan to use the i-EIOSS condition, which will lead to conditions under a new structure, thus overcoming the non-feasibility of classical LMIs. Solving this problem will allow significant progress in this field since many real-world applications are affected by this issue, including vehicle kinematic models, magnetic sensor models, battery state-of-charge models, LED optical communication models, and many others. However, to exploit such a property for observation, it is necessary to introduce new definitions or stability criteria based on certain parameters of the i-EIOSS

Contact:
Cédric Delattre : cedric.delattre@univ-lorraine.fr
Ali Zemouche : ali.zemouche@univ-lorraine.fr
Required Profile: Master's degree in Control Engineering or Applied Mathematics
Funding: Doctoral contract, Université de Lorraine
Start Date: October 1, 2025
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condition. Indeed, some parameters may imply system contraction, leading to the convergence of its trajectories toward each other. To apply this concept to our problem, it is essential to establish a direct and explicit relationship between the system's observability and the monotonicity of nonlinear functions.
Therefore, it is critical to revisit the LMI approaches used in the design of nonlinear observers and improve them by changing the LMI structure to overcome the non-feasibility. In this context, we will reconsider the case of the observer based on a switched gain developed in [5], possibly even moving towards a time-varying observer gain. In some formulations, the theoretical results will not always be easy to implement in practice, and we will need to use Deep Learning techniques for calculating certain transformations and inverse functions [6]. A direct application to the synthesis of parameters for the Moving Horizon Estimator will be addressed [7], and validations on real models will be carried out, particularly on vehicle dynamics models [4], [8].

Keywords : Estimation, observer design, nonlinear systems, deep learning approaches, vehicle dynamics.

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