ERCIM "ALAIN BENSOUSSAN" FELLOWSHIP PROGRAMME

ERCIM
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Scientific Report

First name / Family name	Damiano Rotondo
Nationality	Italian
Name of the *Host Organisation*	NTNU
First Name / family name of the *Scientific Coordinator*	Tor Arne Johansen
Period of the fellowship	01/05/2016 to 30/04/2017

I – SCIENTIFIC ACTIVITY DURING YOUR FELLOWSHIP

Research project: Fault diagnosis and fault tolerant control for uncertain nonlinear systems.

The main goal of this research project has been developing techniques for fault diagnosis and fault tolerant control in uncertain nonlinear systems. In particular, the research project has pursued an integration of three different paradigms: linear parameter varying (LPV), interval arithmetic and unknown input observers. The developed techniques have been applied to several examples, the most relevant one being icing diagnosis in unmanned aerial vehicles (UAVs).

Main achievements:

1. Development of an LPV model reference control framework for UAVs;
2. Icing diagnosis in UAVs using LPV multiple model estimators;
3. Robust fault diagnosis using LPV interval unknown input observers and application to icing diagnosis;
4. Robust fault tolerant control of uncertain systems using interval virtual actuators;
5. Development of a quadratic parameter varying (QPV) framework for control of nonlinear systems.

II – PUBLICATION(S) DURING YOUR FELLOWSHIP

1) D. Rotondo, A. Cristofaro, K. Gryte, T. A. Johansen, LPV model reference control for fixed-wing UAVs, **accepted** in 20th IFAC World Congress, July 2017.

ABSTRACT: This paper proposes a linear parameter varying (LPV) model reference-based control for fixed-wing unmanned aerial vehicles (UAVs), which achieves agile and high performance tracking objectives in extended flight envelopes, e.g. when near stall or deep stall flight conditions are considered. Each of the considered control loops (yaw, pitch and airspeed) delivers an error model that can be reshaped into a quasi-LPV form through an appropriate choice of the scheduling variables. The quasi-LPV error models are suitable for designing error feedback controllers using linear matrix inequalities (LMIs), which are derived within the quadratic Lyapunov framework. Simulation results are used to show the effectiveness of the proposed approach.

2) D. Rotondo, A. Cristofaro, V. Hassani, T. A. Johansen, Icing diagnosis in unmanned aerial vehicles using an LPV multiple model estimator, **accepted** in 20th IFAC World Congress, July 2017.

ABSTRACT: The phenomenon of icing, i.e. ice accretion on aircraft surfaces, affects the flight performance of unmanned aerial vehicles (UAVs). Autonomous icing detection schemes are needed in order to assure high efficiency and limit energy consumption of de-icing and anti-icing schemes. The novel contribution of this paper is to apply a linear parameter varying multiple model adaptive estimator to the model of the longitudinal nonlinear dynamics of a UAV, in order to achieve an icing diagnosis that provides information about the icing location. An advantage of applying a linear parameter varying approach is that the icing diagnosis scheme is consistent with the UAV dynamics for a wide range of operating conditions, and it uses only existing standard sensors. Simulation results are used to illustrate the application of the proposed method.

3) D. Rotondo, A. Cristofaro, T. A. Johansen, F. Nejjari, V. Puig, State estimation and decoupling of unknown inputs in uncertain LPV systems using interval observers, **submitted** to International Journal of Control.

ABSTRACT: This paper proposes a linear parameter varying (LPV) interval observer for state estimation and unknown inputs decoupling in uncertain continuous-time LPV systems. Two different problems are considered and solved: i) the evaluation of the set of admissible values for the state at each instant of time; and ii) the unknown input observation, i.e. the design of the observer in such a way that some information about the nature of the unknown inputs affecting the system can be obtained. In both cases, analysis and design conditions, which rely on solving linear matrix inequalities (LMIs), are provided. The effectiveness and appeal of the proposed method is demonstrated using an illustrative application to a two-joint planar robotic manipulator.

4) D. Rotondo, A. Cristofaro, T. A. Johansen, Fault tolerant control of uncertain dynamical systems using interval virtual actuators, **submitted** to International Journal of Robust and Nonlinear Control.

ABSTRACT: In this paper, a model reference fault tolerant control (FTC) strategy based on a reconfiguration of the reference model, with the addition of a virtual actuator block, is presented for uncertain systems affected by disturbances and sensor noise. In particular, this paper: (i) extends the reference model approach to the use of interval state observers, by considering an error feedback controller which uses the estimated bounds for the error between the real state and the reference one; (ii) extends the virtual actuator approach to the use of interval observers, which means that the virtual actuator is added to the control loop in order to preserve the nonnegativity of the interval estimation errors and the boundedness of the involved signals, in spite of the fault occurrence. In both cases, the conditions to assure the desired operation of the control loop are provided in terms of linear matrix inequalities (LMIs). An illustrative example is used to show the main characteristics of the proposed approach.

5) D. Rotondo, A. Cristofaro, T. A. Johansen, F. Nejjari, V. Puig, Robust fault and icing diagnosis in unmanned aerial vehicles using LPV interval observers, **submitted** to International Journal of Robust and Nonlinear Control.

ABSTRACT: This paper proposes a linear parameter varying (LPV) interval unknown input observer (UIO) for the robust fault diagnosis of actuator faults and ice accretion in unmanned aerial vehicles (UAVs) described by an uncertain model. The proposed interval observer evaluates the set of values for the state which are compatible with the nominal fault-free and icing-free operation, and can be designed in such a way that some information about the nature of the unknown inputs affecting the system can be obtained, thus allowing the diagnosis to be performed. The proposed strategy has several advantages. First, the LPV paradigm allows taking into account operating point variations. Second, the noise rejection properties are enhanced by the presence of the integral term. Third, the interval estimation property guarantees the absence of false alarms. Linear matrix inequality (LMI)-based conditions for the analysis/design of these observers are provided in order to guarantee the interval estimation of the state and the boundedness of the estimation. The developed theory is supported by simulation results, obtained with the uncertain model of a Zagi Flying Wing UAV, which illustrate the strong appeal of the methodology for identifying correctly unexpected changes in the system dynamics due to actuator faults or icing.

6) D. Rotondo, A. Cristofaro, T. A. Johansen, F. Nejjari, V. Puig, Diagnosis of icing and actuator faults in UAVs using LPV unknown input observers, **submitted** to Journal of Intelligent and Robotic Systems.

ABSTRACT: This paper proposes a discrete-time linear parameter varying (LPV) unknown input observer (UIO) for the diagnosis of actuator faults and ice accretion in unmanned aerial vehicles (UAVs). The proposed approach, which is suited to an implementation on-board, exploits a complete 6-degrees of freedom (DOF) UAV model, which includes the coupled longitudinal/lateral dynamics and the impact of icing. The LPV formulation has the advantage of allowing the icing diagnosis scheme to be consistent with a wide range of operating conditions. The developed theory is supported by simulations illustrating the diagnosis of actuator faults and icing in a small UAV. The obtained results validate the effectiveness of the proposed approach.

7) D. Rotondo, T. A. Johansen, Analysis and design of quadratic parameter varying (QPV) control systems with polytopic attractive region, **submitted** to Journal of the Franklin Institute.

ABSTRACT: This paper proposes a gain-scheduling approach for systems with a quadratic structure. Both the stability analysis and the state-feedback controller design problems are considered for quadratic parameter varying (QPV) systems. The developed approach assesses/enforces the belonging of a polytopic region of the state space to the region of attraction of the origin, and relies on a linear matrix inequality (LMI) feasibility problem. The main characteristics of the proposed approach are illustrated by means of a simple example, which confirms the validity of the theoretical results.

8) D. Rotondo, T. A. Johansen, Robust fault and icing diagnosis in small unmanned aircrafts, ERCIM News, 109, April 2017.

ABSTRACT: Small unmanned aircraft working in harsh weather conditions such as those encountered in the Arctic will suffer from the consequences of icing. In order to assure high efficiency and autonomous operation, a robust diagnosis scheme that detects both faults and icing is required. Research at NTNU is focusing on developing these schemes and integrating them with fault tolerant control techniques.

III – ATTENDED SEMINARS, WORKHOPS, CONFERENCES

1) September 7th and 9th 2016, SYSTOL16: 3rd International Conference on Control and Fault-Tolerant Systems, Barcelona, Spain.

2) September 8th 2016, invited talk at XXXVII Jornadas de Automática, Madrid, Spain.

3) February 9th-10th 2017, invited talk at XV Simposio CEA de Ingenieria de Control, Salamanca, Spain.

IV – RESEARCH EXCHANGE PROGRAMME (REP)

1. October 17-21 2016, INRIA Lille-Nord Europe, France.
   Contact person: Dr. Denis Efimov, denis.efimov@inria.fr
   Main topic: Fault detection for LPV systems using interval observers
   Invited talks: Design of parameter-scheduled state-feedback controllers using shifting specifications; Icing detection in unmanned aerial vehicles using unknown input observers

   In addition to the REP, the following short stay has been financed by NTNU and Università di Camerino:

2. January 9-13 2017, Università di Camerino, Italy.
   Contact person: Dr. Andrea Cristofaro, andrea.cristofaro@unicam.it
   Main topic: LPV techniques for optimal steady-state tracking in underactuated systems
   Invited talk: Advances in gain-scheduling and fault tolerant control techniques