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Design and Validation of Aerospace Control Systems: an Overview of Methods & Tools

Since their early development in the 1970's with the introduction of fly-by-wire technology, control systems have considerably evolved. Thanks to powerful on-board computers whose capacities have undergone an exponential growth over the past thirty years, together with the development of enhanced sensors and actuators, the complexity of aerospace control systems is almost no longer bounded today. This is true at least from a technological viewpoint. Control engineers should, however, keep in mind that there are many risks in developing unnecessarily complex systems whose validation will become a real issue. In this world, where technological constraints have been considerably relaxed and where autonomous systems have become a universal Holy Grail, a good balance must be found between the design and validation phases in the development of control systems. Some complexity is inevitable during the design phase to cope with that of the plant itself, as well as with the required level of autonomy. However, complexity must be controlled, so that the validation phase remains as quick and cheap as possible.

In this general context of rapidly growing complexity, the development of efficient control design and analysis tools has become a critical issue. Here again, the exponential growth in computing capacity has played a key role and contributed to a rapid development of many fields in control theory. As a result, if one focuses at least on the linear control framework and its numerous extensions (such as robust control theory, parameter-varying control and adaptive control, to cite a few), a high level of maturity is now reached.

However, the gap between theory and practice remains to be filled. This is the main focus of this thirteenth issue of Aerospace Lab, which is dedicated to the most recent techniques for the design and validation of Aerospace Control Systems, with a particular emphasis on Matlab-oriented tools and toolboxes together with realistic applications. This issue is also strongly connected to the SMAC (Systems Modeling Analysis & Control) toolbox developed by ONERA.

Advanced design and analysis tools

The constantly growing "complexification" of aerospace control systems reinforces the need for advanced but user- friendly design and analysis tools. Within the control community, both in academic and industrial worlds, Mathworks™ with its MATLAB/SIMULINK™ product is the undisputed world-leader in this field. It provides a flexible and powerful object-oriented environment for control system design and analysis, using both Mathworks-provided1[1] and external toolboxes. Among those, this special issue of the Aerospace Lab journal, through various aerospace applications, will focus on the following:

- **SMAC toolbox**: http://w3.onera.fr/smac

  This toolbox developed by ONERA includes several modeling, analysis and control libraries, which are illustrated in various contributions of the present issue [2, 5, 7, 10]. The core of

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[1] Such as the Control and Robust Control toolboxes.

this toolbox is the Linear Fractional Representation (LFR) object, which enables a wide class of uncertain systems to be captured in a unified framework perfectly well suited to many design and robustness analysis techniques. Among the nine libraries that are currently available with the SMAC toolbox, four are of particular interest in this issue:

- **SMAC/GSS**: this library interfaced with Simulink, based on the gss object (generalized state-space), is dedicated to LFT modeling, reduction and interconnections.
- **SMAC/SMART**: this library, devoted to linear time-invariant (LTI) robustness analysis, implements a collection of efficient tools to compute accurate robustness margins for complex systems involving numerous states and uncertainties.
- **SMAC/IQCFD**: this library, based on the Integral Quadratic Constraints (IQC) theory can be viewed as an extension of SMART to systems including sector nonlinearities. The computational burden is then higher, but a specific implementation makes this tool quite attractive for large order systems.
- **SMAC/SAW**: this library implements two complementary techniques for design and analysis of anti- windup systems, in order to better understand and then alleviate the effects of saturations in control systems. Thanks to its Simulink interface, this tool is quite user-friendly.

- **LPVtools**: http://www.aem.umn.edu/SeilerControl/software.shtml

  This toolbox, developed by the University of Minneapolis, is dedicated to the class of Linear Parameter Varying (LPV) systems that frequently appear in aerospace applications. Note that LPV systems can always be represented in the aforementioned LFR format. Thus, strong connections and complementarity exist between LPVtools, which is illustrated in [6] and the SMAC toolbox.

- **R-ROMULOC**: http://projects.laas.fr/OLOCEP/romuloc/

  This toolbox, mainly developed by LAAS-CNRS in collaboration with the IEIIT-CNR (Politecnico di Torino, Italy) and at the Institute for Control Science (Moscow, Russia) is intended to gather multiple theoretical results obtained recently in Robust Control and Randomized Methods. The aim is to have some simple functions for manipulating uncertain systems and building LMI optimization problems related to robust multi-objective control problems. Both deterministic and probabilistic methods are considered, as illustrated in [4].

- **SATAW-Tool**: http://homepages.laas.fr/queinnec/sataw-tool.html

  This toolbox (SATuration AWare Tool), developed by I. Queinnec and S. Tarbouriech at the LAAS-CNRS, implements various theoretical results regarding the presence of saturation elements in the control loop, for both analysis and control design operations. Note that strong connections exist between these tools and the SAW Library from the SMAC toolbox, as shown in [7].

A brief summary

This thirteenth issue of the Aerospace Lab journal is composed of ten original papers, with a good balance between design and analysis oriented contributions.

The first paper [1] presents an overview of structured H_∞ control theory and a non-smooth optimization-based approach to solve this difficult non-convex problem. The proposed algorithm has been implemented in the hinfstruct and systune routines provided with the MathWorks Robust Control Toolbox. Various possible extensions are discussed in the paper, such as multi-model design. This is further illustrated in the following two papers [2, 3] dedicated to nonlinear and gain-scheduled control applications, respectively. Challenging applications of structured H_∞ control to future European launchers are also described in [8]. An alternative design approach is then proposed in this special issue, with a contribution describing the application of mixed randomized and robust control tools [4]. The main interest of such a strategy is to relax part of the conservatism induced by fully deterministic methods. In short, the main idea is to avoid low-performance controllers that are unnecessarily robust against unlikely situations. The last design-oriented contribution focuses on the impact of saturations in control systems with an application to anti-PIO (pilot-induced-oscillation) systems [7]. Various anti-windup design algorithms available with SATAW-Tool and SMAC/SAW are proposed and evaluated.

As mentioned above, a significant part of this issue is also dedicated to recent analysis tools taking into account various aspects of the closed-loop systems to be analyzed, such as:

- **Nonlinear elements**: this can be treated by IQC analysis [5, 10]. The main drawback of this approach is the computational load, which has thus deserved specific attention in the proposed algorithms, which are described and illustrated with realistic examples.

- **Parameter-varying elements**: based on the LPV framework, an original approach is detailed in [6] to compute robustness margins for linear parameter-varying systems. One of the potential applications of the proposed algorithm is the stability analysis of systems with fast time-varying dynamics, such as launchers, for example.

The above tools are very useful to “pre-validate” control systems and usually provide constructive information for further improving control laws. Their application is usually restricted to simplified versions of the closed-loop plant. Optimization and oriented simulation-based approaches are therefore required for further validation of complex systems. This aspect is discussed in the last paper [9], in the context of a flexible launcher ■

References

[1] P. APKARIAN, D. NOLL - *The H_∞ Control Problem is Solved*. Aerospace Lab Issue No. 13.

[2] J.-M. BIANNIC, C. ROOS, J. LESPRIER - *Nonlinear Structured H_∞ Controllers for Parameter Dependent Uncertain Systems with Application to Aircraft Landing.* Aerospace Lab Issue No. 13.

[3] F. SEVE, S. THEODOULIS, P. WERNERT, M. ZASADZINKI, M. BOUTAYEB - *Gain-Scheduled H_∞ Loop-Shaping Autopilot Design for Spin-Stabilized Canard-Guided Projectiles*. Aerospace Lab Issue No. 13.

[4] M. CHAMANBAZ, F. DABBENE, D. PEAUCELLE, C. PITTET, R. TEMPO - *Randomized and Robust Methods for Uncertain Systems Using R-ROMULOC, with Applications to DEMETER Satellite Benchmark.* Aerospace Lab Issue No. 13.

[5] F. DEMOURANT - *Stability Analysis by a New Algorithmic Approach Based on Integral Quadratic Constraints: Application to an Aircraft Benchmark*. Aerospace Lab Issue No. 13.

[6] A.-K. SCHUG, P. SEILER, H. PFIFER - *Robustness Margins for Linear Parameter Varying Systems*. Aerospace Lab Issue No. 13.

[7] I. QUEINNEC, S. TARBOURIECH, J.-M. BIANNIC, C. PRIEUR - *Anti-Windup Algorithms for Pilot-Induced-Oscillations Alleviation*. Aerospace Lab Issue #13.

[8] M. GANET-SCHOELLER, J. DESMARIAUX, C. COMBIER - *Structured Control for Future European Launchers*. Aerospace Lab Issue No. 13.

[9] A. KAMATH, P. P. MENON, M. GANET, G. MAURICE, S. BENNANI - *Surrogate Assisted Computation of Parametric Safety Margin of a Flexible Launcher.* Aerospace Lab Issue No. 13.

[10] P. VUILLEMIN, F. DEMOURANT, C. POUSSOT-VASSAL - *Stability Analysis of a Set of Uncertain Large Scale Dynamic Models with Saturations*. Aerospace Lab Issue No. 13.