PHD THESIS EVALUATION REPORT

Thesis title: **Measures and LMIs for V&V of Adaptive Control**

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PhD thesis deals with the problem of Verification and Validation (V&V) of adaptive control laws of aircraft models considering various nonlinearities, uncertainties and unmodeled dynamics. This challenging problem, so far unsolved, is achieved via applying advanced computational methods based on occupation measures and LMI relaxations. The thesis, which is written on 89 pages, is composed of seven chapters. The core of the thesis is given in chapters 3 to 6, where various V&V problems are solved and validated on case study problems.

In the first, introductory chapter, the problem at hand is motivated by claiming general need for reliable and efficient methods for validating the advanced aircraft control systems. The traditional V&V approaches, mainly based on linear analysis and Monte-Carlo methods, are efficiently applicable for linear control feedback only. Thus, as soon as adaptive control methods are to be applied, these methods are inefficient. With no doubt, this naturally opens space for further research. However, the presented general state of the art section within the chapter one is relatively brief, written on two pages only. In this part, only 27 references are mentioned with two multiple references [9-16], [17-20]. Even though the state of the art is extended within the core chapters 3-6 afterwards (thesis includes 65 references), it should have rather been condensed and included here in order to identify the knowledge gap and motivate the performed research. At the end of this chapter, thesis contributions are presented, summarising the content and contributions of the core chapters.

In the second chapter, theoretical preliminaries are presented in neat and compact form. It includes formulation of polynomial dynamical optimization problem, extended further on to piecewise polynomial form. This nonconvex optimization problem is then approximated as generic convex infinite dimensional LP problem of measures using parsimony. Subsequently, the standard Model Reference Adaptive Control (MRAC) is defined, which is then considered in the tested control schemes and problems within the chapters 3-6.

The chapter 3 presents V&V problem of the longitudinal control of F-16 fighter aircraft. For the second order nonlinear short period model, the MRAC control scheme is designed combining the LQR state feedback with the adaptive part to obtain a predefined closed loop dynamics. The problem at hand is then presented as a polynomial dynamical optimization problem. Consequently, it is turned to primal problem on measures and solved as a moment LMI relaxations problem. For numerical validation, three cases with piecewise disturbances are considered. For each of them, LQR with and without MRAC are validated. The upper bounds obtained by Gloptipoly 3 and the SDP solver MOSEK are compared with results by Monte Carlo method. Concerning the chapter evaluation, one needs to acknowledge clarity of the problem formulation. On the other hand, interpretation of the presented result should deserve much more space. The results presented in the figures and tables are only very briefly described. The benefits of the proposed methodology should be distinctly stressed and clearly outlined in the conclusion part of the chapter.

In the subsequent chapter 4, the proposed LMI based V&V framework is applied to standard LQR + MRAC augmentation control of lateral F-16 dutch-roll polynomial model with reduced control effectiveness at large roll angles. In addition to what has been done in chapter 3, the complexity of solving the LMI relaxations is reduced by exploiting sparsity of ODEs. The trimmed nonlinear dutch-roll dynamics of an F-16 aircraft at a selected operational point is described by a fourth order model with nominal dynamics determined by a matrix A and a nonlinear term at the input including unknown higher order dynamics. The given problem of assessing the bound of state trajectories from any initial conditions lying in a predefined range is turned to measure-LP problem and solved by GloptiPoly and MOSEK as hierarchy of moment LMI relaxations. The obtained results are again compared with numerical results by Monte Carlo method. As demonstrated, Monte Carlo method may not detect all the unsafe trajectories, if the sampling is not properly selected. On the other hand, the proposed LMI based V&V framework is identified as exact in this aspect – it can directly detect the unsafe trajectories. Even though the interpretation of the presented results is better than in chapter 3, still, more attention should have been paid to this aspect. For example, the figure and table captions should be more detailed, the results in the graphs should be interpreted more distinctly in the body text (what we see, what is important...), the pros and cons of used methods should be clearly stated in the concluding subsection (it only provides summary what has been done).

In chapter 5, V&V problem of model reference adaptive control in the presence of unmodeled flexible dynamics is addressed. Based on the up-to-date state of the art, it is the first time such an analysis is done for an aircraft with flexible dynamics and MRAC. The proposed methodology is first illustrated on a simple five order linear system with uncertain parameters. This is followed by application to short-period dynamics of a linear and polynomial F-16 aircraft models coupled with uncertain flexible dynamics. The proposed approach is based on approximating and partitioning the state dynamics by exploiting parsimony for ODEs. Analogously to Chapters 3 and 4, polynomial dynamical optimization of MRAC+LQR V&V problem is approximated using infinite dimensional measures and solved as moment LMI relaxations problem by Gloptipoly 3 + MOSEK. The results presented in this chapter clearly show the benefits of the proposed V&V methodology over Monte-Carlo simulations, also presented for comparison and identified as unreliable for the given problem. In the last core chapter 6, the V&V problem of chapter 5 is extended to aircraft model with uncertain actuator dynamics. In particular, F-16 longitudinal model with MRAC and uncertain third order elevator dynamics with deflection saturation and bounded uncertainties is addressed. Otherwise, the chapter follows the analogous scheme as Chapters 3-5, with analogous numerical results showing clearly the benefits of proposed V&V methodology compared to traditional methods. To sum up, the chapters 5 and 6 provide the most interesting results of the thesis and clearly highlight high potential of measures and LMI based V&V of aircraft adaptive control. Though, also here the presentation of the results should deserve more detailed description and comments. The main contributions of the thesis and future research directions are given in the last chapter 7, again in a rather brief way.

Based on the above thesis chapter overview, it is clear that the thesis presents original methodology for V&V of aircraft adaptive MRAC+LQR control by employing moment sum-of-squares hierarchies efficiently solvable by available off-the-shelf-software. For the nonlinear adaptation control laws, considering also the uncertainties and unmodeled dynamics, the traditional approaches, such as Monte Carlo methods, are inefficient due to high demands on state space sampling and computational time. On the other hand, the presented V&V approach built up on the measures and LMIs has ability to provide granted numerical certificate taking into account the worst case scenario. As such, the methodology has high practical potential, taking into account that V&V of aircraft control systems is among the most important and most demanding control system development stages. A substantial contribution of the thesis also lies in systematic effort to decrease the computational complexity, e.g. by exploiting sparsity of ODEs. This enables

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addressing large scale problems that are numerically intractable otherwise. The quality of presented research is also confirmed by related publications, which count one journal paper published, another one in the review, and three papers in top conferences of the field. The only criticism I have is related to rather brief state of the art overview in the introductory chapter, to the generally brief presentation of numerical results and to the rather vague highlights of the main contributions within the thesis chapters.

To sum up, the results presented in the thesis clearly show that the author is an independent researcher with wide and complex research abilities that cover: i) adaptive control design of aircraft, ii) reformulation of the optimization problem to solvable forms by applying measures and LMI hierarchies, iii) parameter reduction of large scale problems, and iv) Verification and Validation of aircraft adaptive control strategies. I fully recommend the thesis for defence.

Questions for the defence

1. How the correctness of the upper bounds obtained by the solvers and presented throughout the thesis in the Tables is guaranteed and verified?

2. Can the presented methodology be modified to test the control system performance under abrupt changes of the model parameters, or even model structure? For example within the change of subsonic to ultrasonic flight.

3. Could the presented methodology be applied to analyse the effects of small delays (communication, computational delays) within the closed loops?

4. Is there a chance to automate the problem formulation and turn it to a 'user friendly' software that could be used by engineers in V&V of aircraft control systems? Or is it too case depended and experience with using the LMI solvers is needed?

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