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# PROPOSITION DE SUJET DE THESE

**Intitulé : Combined nonlinear and robust autopilot designs for hypersonic vehicles / Conception combinée de pilotage robuste et non linéaire pour véhicules hypersoniques**

Référence : **TIS-DTIS-2024-34**
*(à rappeler dans toute correspondance)*

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| **Début de la thèse :** Septembre 2024 | **Date limite de candidature :** Juin 2024 |

**Mots clés**

Control systems, flight dynamics, nonlinear control, robust control, autonomous vehicles, hypersonic/ Automatique, dynamique du vol, commande non linéaire, commande robuste, véhicules autonomes, hypersonique

**Profil et compétences recherchées**

Engineering school or Master with specialization in control systems, aerospace systems/Ecole d'ingénieur ou Master 2 Recherche avec spécialisation en automatique, systèmes aérospatiaux

Control theory, flight dynamics, Matlab,Simulink, /Automatique, dynamique du vol, Matlab, Simulink

Good level in scientific writing and english/ Bon niveau rédactionnel et bon niveau d'anglais

Hypersonic vehicles are in the centre of developments for future space (e.g. Moon-to-Earth, Orbit-to-Earth) and civil transportations (in the spirit of the Concorde). Although such vehicles have been studied in the past (e.g. Single-Stage-To-Orbit (SSTO), re-entry capsules), new vehicle designs and their corresponding subsystems are more complex and require functioning under stringent constraints and specifications. These are particularly oriented in enhancing passenger comfort and safety. In order to guarantee increased performances despite this plethora of constraints as well as model uncertainties (e.g. aerodynamic, aero-elasticity) and perturbations (e.g. wind-gusts), it is imperative to develop innovative control algorithms.

Throughout the last 30 years of active research on the control of hypersonic vehicles a number of different methodologies has been applied such as classical linear, robust, dynamic inversion, adaptive, sliding mode, backstepping, see [2-7] and [1] for a more exhaustive list. However, due to the complex nature of hypersonic vehicles (e.g. high angle-of-attack flight conditions, aero-elastic-propulsive couplings) current designs are not satisfactory, providing conservative performance and safety guarantees that further result in under-exploiting the advanced capabilities of such vehicles. The most popular control design approach for aerospace applications in general is robust control [8]. It proposes a systematic design and a number of adapted toolboxes for gain selection and simulation. Furthermore, the design specifications (temporal performances, robustness) as defined in the aerospace industry are easily integrated in the robust control context. These advantages render robust control (H-infinity in particular) a strong candidate for a successful design for the control of a hypersonic vehicle. Drawbacks of robust control are that it cannot easily accommodate for parameter variations and that it can lead to conservative designs as it relies on the linearization of the system about an operation point (which usually is not even perfectly known).

On the other hand, nonlinear and adaptive control designs provide mathematical tools capable of accounting for nonlinearities and uncertainties during the whole envelope. Such designs can allow exploiting to the maximum the dynamic capabilities of the vehicle. The major drawback of such designs is that they cannot be rendered systematic as they are model-dependent and that there is a lack of available toolboxes. In addition, design specifications can be difficulty integrated a priori in the synthesis phase.

The complementarity of robust and nonlinear techniques suggests that their possible combination could lead to significantly elevated closed-loop performances. This Phd thesis aims at exploring this research avenue.

To this end, a first natural idea will be to apply the widely used Nonlinear Dynamic Inversion (NDI) [9,10], that will allow to put the system dynamics in an almost linear form and without neglecting the nonlinear terms. Then, a robust (Hinfinity) synthesis step will lead to an effective control law valid in the complete flight envelope. Furthermore, a more application-realistic version of NDI that directly accounts the available sensors, termed Incremental NDI (INDI) [11-14], will be used. A major advantage of this alternative design is that it provides increased robustness with respect to uncertainties in the aerodynamic model. To further enhance the performances of the INDI/Hinf control law with respect to safety (state, inputs) constraints, we will explore the use of Barrier-Lyapunov functions (BLF) [15,16]. Such function are types of Lyapunov function that can be used to ensure that the system converges to a desired trajectory/equilibrium while making sure that system trajectories does not enter a particular unsafe region.

The objective of this Phd is to explore the systematic combination of robust (H infinity) and nonlinear (INDI and BLF-enhanced) control techniques with the goal of enhancing closed-loop performances for hypersonic vehicles. The closed-loop performances will be evaluated on the 6-DoF model of NASA's X30 hypersonic aircraft, called the General Hypersonic Aerodynamic Example (GHAME) [17].

The Phd thesis will be organised as follows: Modelling and simulation of the GHAME vehicle, bibliographical overview of control design techniques with a focus on H-infinity/NDI/INDI, H-infinity/NDI/INDI control design applied to the GHAME vehicle, bibliographical overview on barrier/barrier-Lyapunov functions for safety specifications, BLF-enhanced (I)NDI control design for GHAME.

This Phd thesis will be co-advised by Dr. Ioannis SARRAS (ONERA) and Profs Spilios THEODOULIS, Erik-Jan van KAMPEN and Coen DE VISSER (TU Delft). The candidate is expected to spend equal time at ONERA (Palaiseau, FRANCE) and TU Delft (Delft, The Netherlands).

## REFERENCES


[1] Xu, B., Shi, Z. (2015) An overview on flight dynamics and control approaches for hypersonic vehicles. Science China Information Sciences.

[2] Buschek H, Calise A. (1997) Uncertainty modeling and fixed-order controller design for a hypersonic vehicle model. Journal of Guidance, Control and Dynamics.

[3] Xu, H. and Ioannou, P.A. (2004). Adaptive sliding mode control design for a hypersonic flight vehicle. AIAA Journal of Guidance, Control and Dynamics.

[4] Wang, Q., and Stengel, R. (2000) Robust Nonlinear Control of a Hypersonic Aircraft. Journal of Guidance, Control, and Dynamics

[5] Dydek Z, Annaswamy A, Lavretsky E. (2010) Adaptive control and the NASA x-15-3 flight revisited. IEEE Control System Magazine.

[6] Parker J, Serrani A, Yurkovich S, et al. (2007) Control-oriented modelling of an air-breathing hypersonic vehicle. Journal of Guidance, Control and Dynamics.

[7] Fiorentini, L., Serrani, A., Bolender, M., Doman, D. (2009) Nonlinear robust adaptive control of flexible airbreathing hypersonic vehicles. Journal of Guidance, Control and Dynamics.

[8] Skogestad, S., and Postlethwaite, I. (2005) Multivariable Feedback Control: analysis and design, 2nd ed., John Wiley & Sons Ltd.

[9] Stevens, B., Lewis, F., and Johnson, E. (2015). Aircraft Control and Simulation: Dynamics, Controls Design, and Autonomous Systems. Wiley.

[10] Khalil, H. (2002). Nonlinear Systems, Third edition, Pearson Education, Prentice Hall.

[11] Sieberling, S., Chu,Q.P., & Mulder, J.A. (2010). Robust flight control using incremental nonlinear dynamic inversion and angular acceleration prediction. Journal of Guidance, Control, and Dynamics.

[12] Pollack, T. and van Kampen, E. (2023) Robust Stability and Performance Analysis of Incremental Dynamic-Inversion-Based Flight Control Laws. Journal of Guidance, Control, and Dynamics.

[13] Grondman, F., Looye, G., Kuchar, R., Chu, Q. P., and van Kampen, E. (2018). Design and Flight Testing of Incremental Nonlinear Dynamic Inversion-based Control Laws for a Passenger Aircraft. 2018 AIAA Guidance, Navigation, and Control Conference, Kissimmee, FL, USA.

[14] Matamoros, I., and de Visser, C. C. (2018). Incremental Nonlinear Control Allocation for a Tailless Aircraft with Innovative Control Effectors. 2018 AIAA Guidance, Navigation, and Control Conference, Kissimmee, FL, USA.

[15] K. P. Tee, S. S. Ge, and E. H. Tay, "Barrier Lyapunov functions for the control of outputconstrained nonlinear systems," Automatica, 2009.

[16] E. Restrepo-Ochoa, "Coordination control of autonomous robotic multi-agent systems under constraints," Ph.D. dissertation, University Paris-Saclay, Gif sur Yvette, France, 2021, https://tel.archivesouvertes.fr/tel-03537341.

[17] Zipfel, P. H. (2017). Modeling and Simulation of Aerospace Vehicle Dynamics, Third Edition, AIAA Education Series.


**Collaborations envisagées**

TU Delft

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