ECOLE DOCTORALE SYSTEMES - ED309
Maison de la Recherche et de la Valorisation
118 route de Narbonne
Tel : (33) (0) 5 6 25 00 66
Email : edsys@laas.fr
Web : https://www.adum.fr/as/ed/edsys

PhD position in Control Systems

ISAE-SUPAERO / ONERA
Toulouse (France)

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- **Title :** Nonlinear control of high aspect ratio aircraft using nonlinear deformation formulations.

- **Thesis description** :

The aeronautic engineering community has long confronted reducing aerodynamic drag during aircraft design to achieve lower fuel consumption. A known theoretical solution is to increase the wing aspect ratio (i.e., wingspan to chord lengths ratio). In practice, the resulting increased structural flexibility in high-aspect-ratio wing designs progressively couples aeroelastics with flight dynamics and generally gives rise to instability or poor handling qualities. Stable and safe piloting calls for stability augmentation systems that simultaneously account for elastic and traditional flight dynamics degrees of freedom.

Although not the focus of this thesis, high-altitude pseudo-satellite (HAPS) platforms provide notable motivating examples. They fly above the troposphere, thus avoiding atmospheric disturbances during cruise flight. This feature is desirable since current solar energy technologies provide limited power, which significantly motivates lightweight, flexible structures, which are, unfortunately, very susceptible to turbulence. However, HAPS aircraft still suffers from disturbances during climb and descend phases in the troposphere, significantly pushing the platform from its traditional linear envelope into nonlinear regimes. Such phenomena have been observed in recent mishaps in different platforms during tropospheric flight and reported in [1,2]. These mishaps expose the vulnerability to disturbances that quickly cause excessive deviation from the nominal flight set-points. Therefore, safer tropospheric flight calls for nonlinear robust stability augmentation and wing shape estimation systems.

Usual dynamic modes of interest in a conventional aircraft represent overall vehicle motion (i.e., rigid body modes, e.g., phugoid mode, short-period mode, dutch roll mode) and structural deformation (i.e., flexible modes, e.g., first bending mode, second torsional mode). Traditionally these concepts can be divided into two separate classes due to their significant difference in response time magnitudes. This separation additionally allows for independent analysis and control design. However, as novel aircraft designs push toward high-aspect and very flexible wings, the structural modes response time becomes slower and intertwine with the rigid body modes, consequently precluding subsystems separation and traditional design approaches. State-of-the-art techniques to tackle this rely mostly on departing from the modal decoupling approach. Indeed, recent work favors analyzing and designing controllers for all modes collectively. This strategy often entails modelization using high-fidelity finite element methods in high-dimensional state spaces. Traditional model reduction techniques yield linearized low-dimensional models for local controller design for given operating conditions.

This thesis project sets out to challenge the soundness of the approach mentioned above as the aircraft's aspect ratio increases and distributed propulsion takes place. The experimental outcomes mentioned above raise suspicion over the linearity assumption validity, given their significant trajectory deviation during troposphere climb and descending. Moreover, geometric nonlinearities are a known problem that traditional linear/local approaches do not directly tackle. Finally, distributed propulsion systems yield increased prop wash effects and call for higher-order terms not present in linear structures. To tackle these challenges, this thesis project pursues an alternative formulation of deformation parametrization. We offer a departure from the commonplace displacement-based formulation and study control design in special orthogonal group SO(3)-based deformation parametrization spaces instead. This strategy has already shown promising results in [9], in the context of wing shape estimation under large and nonlinear wing deflections. The SO(3)-based deformation parametrization maps a 1-dimensional, 2-dimensional or 3-dimensional space to the SO(3) rotation group. Intuitively, this formulation specifies local rotations to deformed shapes (lines, planes, or cubes) instead of the commonplace approach of assigning a displacement field to particles in the flexible body. Alternatively, this configures an infinite direct product of SO(3) groups.

Included in the opportunities that arrive by doing so, the Ph.D. candidate will benefit from the extensive literature on almost-global nonlinear control on the SO(3) group as a starting point for our study [3]. Note that no smooth vector field can have a global attractor unless the configuration manifold is homeomorphic to R^n, so almost-global asymptotic tracking is the best possible outcome. The candidate will generalize previous SO(3) finite-dimensional direct product almost-global stability results [4] to design novel infinite-dimensional higher-order [5] direct group control laws with theoretical guarantees of almost-global asymptotic stability, with locally exponential convergence. We are also interested in studying whether a separation principle exists for such controllers (as happens in [4]) and related conditions on the respective observers. The Ph.D. candidate should aim to express the feedback system in a coordinate-free fashion, avoid feedback linearization approaches [6], and focus on nonlinear feedback-linearization-like strategies [4].

A second, but equally relevant, research focus will be revisiting subsystem decomposition for very flexible aircraft. However, instead of decoupling the dynamic system modes into rigid and flexible ones, the Ph.D. candidate will pursue decoupling the dynamics into two submodules: a nonlinear large-angle SO(3)-based system and a bilinear and quadratic small-displacement-based module. The SO(3)-based module shall absorb the flight dynamics modes and slow structural modes that appear in large (and potentially nonlinear) amplitudes. All other faster modes (with smaller amplitudes) will fall in a superposed bilinear system to capture prop wash effects. The Ph.D. candidate will pursue an algorithm to identify an optimal couple of SO(3) and bilinear systems to a given aircraft, based on high-fidelity finite-element-method simulators provided from our collaborator in this project, namely, the University of Michigan, and model reduction techniques. This framework paints a novel picture of the problem, which is not yet published, and the Ph.D. candidate will kickstart this fundamental research opportunity. The infinite-dimensional direct product SO(3)-based control laws studied accordingly to the previous paragraph will then be applied to the SO(3)-portion of the system (with appropriately designed anti-alias filters). At the same time, the student will propose novel approaches to tackle the remaining bilinear part independently. This technique potentially allows for simultaneous high dimensional control of relevant modes and nonlinear control of large deflections while accounting for higher-order prop wash effects.

Thirdly, as described in the above paragraph, the proposed technique calls for bilinear systems modelling and control laws design. The nonlinear reduced-order modelling via bilinear (and quadratic) structures offers an interesting framework to deal with weak nonlinearities in a complex model and is a critical subject on this matter [7,8]. Finally, flexible aircraft wings undergo large deflections and call for appropriate large-angle aerodynamic models. This description is especially relevant to capture control reversal phenomena in high-aspect-ratio aircraft ailerons. The Ph.D. candidate will also benefit from previous large-angle aerodynamic models to fit the proposed framework [10].

To summarize, the Ph.D. candidate will propose a novel flexible aircraft modeling approach for nonlinear control purposes using the special orthogonal group SO(3) as the deformation parametrization paradigm. Using this idea, the candidate will uncouple fast modes from slow modes using adapted model reduction techniques and design their respective stabilizing control laws. The student will develop novel bilinear modelling and possibly control laws to stabilize fast modes and generalize previous nonlinear SO(3) control results to stabilize slower modes undergoing large disturbances. The candidate will seek separation principles and possibly integrate into the design the wing shape estimator already developed in the research group. This thesis's results might include generalized Lie groups stability results, novel bilinear controllers, and, consequently, a solution for large disturbance rejection in very flexible aircraft, yielding, hopefully, a powerful novel standpoint to analyze the problem.

- **Candidate profile** :

We are looking for self-motivated team-player candidates that match the following profile:

- A Master's degree in Aerospace Engineering, Control Systems, Robotics, or Dynamic Systems-related disciplines with excellent grades;
- Excellent knowledge in dynamic systems;
- Numerical simulation and programming skills (e.g., MATLAB, C/C++);
- Excellent oral and written communication skills;
- English language mastery (writing and presenting) is mandatory.

- **Conditions of employment :**

A full-time employment for three years, including:

- An intermediate evaluation after one year;
- To support you during your Ph.D. and to prepare you for the rest of your career, you will have access to personal development opportunities from the EDSYS doctoral school and mandatory coursework;
- A gross monthly salary and benefits in accordance to the ISAE-SUPAERO standard;
- Possibility of a visiting scholar period abroad with one of our international partners;
- A rich, diverse, and stimulating research group.

Candidates are expected to start around September 2021.

- **Application :**

All applications should be compressed (.zip, 5MB max.) and submitted by email to the addresses below, including:

- Cover letter including a statement of purpose and previous experiences;
- Detailed curriculum vitae;
- Course grades transcripts;
- A scientific writing sample (Master thesis, seminar paper, or equivalent);
- Contact information of two references.

Applications will be received until **May 1st, 2021**. Interviews will be held shortly thereafter.

For more information regarding this position, please contact:

Charles Poussot-Vassal
charles.poussot-vassal [at] onera.fr
+33(0)5 62 25 26 55

and

Leandro Lustosa
leandro.lustosa [at] isae-supaero.fr
+33 (0)5 61 33 81 60

- **References :**

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