MECHANICAL ENGINEERING | PHYSICS | PRESERVATION OF THE ARCHITECTURAL HERITAGE | STRUCTURAL, SEISMIC AND GEOTECHNICAL ENGINEERING | URBAN PLANNING, DESIGN AND POLICY | **AEROSPACE ENGINEERING** | ARCHITECTURE, BUILT ENVIRONMENT AND CONSTRUCTION ENGINEERING | ARCHITECTURAL, URBAN AND INTERIOR DESIGN | BIOENGINEERING | DATA ANALYTICS AND DECISION SCIENCES | DESIGN | ELECTRICAL ENGINEERING | ENERGY AND NUCLEAR SCIENCE AND TECHNOLOGY | ENVIRONMENTAL AND INFRASTRUCTURE ENGINEERING | INDUSTRIAL CHEMISTRY AND CHEMICAL ENGINEERING | INFORMATION TECHNOLOGY | MANAGEMENT ENGINEERING | MATERIALS ENGINEERING | MATHEMATICAL MODELS AND METHODS IN ENGINEERING

PhD Yearbook | 2025

DOCTORAL PROGRAM IN AEROSPACE ENGINEERING

Chair:
Prof. Camilla Colombo

The aim of the course is the acquisition of the high level competences that are required to carry out innovative research and/or state of the art advanced applications in industries, public or private research centers, Universities or public and service companies in the area of aerospace engineering, including all the associated fields, with specific attention to its interaction with the human operators, the users, the environment and the society at large.
The level of the course provides the graduates with the ability to compete in a European and international environment.
The course duration is three years, requiring 180 credit points (ECTS), including possible study-abroad periods and internships in private or public institutions.
The program and credits are divided in two main educational areas:

1) Courses for at least 20 credits, on transferable competencies (at least 10 credits), on themes specific to aerospace engineering disciplines (at least 5 credits), and the remainder on topics of choice, to be acquired during the first year.
2) Development of the Doctoral Thesis (160 credits): the thesis is developed within the Department or, in some cases, in other institutions, in close contact with the Department.

The research activity starts immediately (40 credits in the first year) and is developed in the second and third year (60 credits each) of the doctoral program.
If the candidate's background curriculum lacks some introductory knowledge required for the Doctorate, the Faculty Board will ask to recover such knowledge, with the assistance of the tutor.
Afterwards, the Faculty Board will verify the overcoming of whatever was lacking during the annual meeting of admission to the second year of the course.
The course program related to point 1 does not follow a rigid scheme. So, besides widening the basic scientific culture of the candidate, it takes into consideration also the objectives and the core topics of the candidate's thesis. The program will also consider general cultural requirements as well as what is deemed to be specifically related to the thesis subject, as agreed between the candidate and the Faculty Board.
To complete the research activity, a study period in a foreign country or in an external institution is allowed and strongly recommended. Its duration may range from a few weeks up to one and a half years, with an average duration of 6 months. The related activities are usually carried out in well-known and qualified scientific institutions (universities, research centers, etc.), and contribute to the cultural and scientific achievements of the research.
Due to the amplitude and interdisciplinarity of the aerospace sector, the professional skills achievable will span a broad area and not cover just a specific topic.
The educational goals will create high level specialists in the domains of helicopters and rotary wing aircraft, fixed wing aircraft, space vehicles and missions, and related technologies.
In this context, specific competence can be gained either in a single subject or in the integration of special subjects such as: Aerodynamics and Fluid Mechanics, Structures and Materials, Flight Mechanics and Control, and emerging disciplines requiring an enhanced multidisciplinary approach such as rotary wing aircraft, electric airplanes, drones, innovative materials and structures, space mission design, space trajectory design, space situation awareness, innovative propulsion technologies, advanced fluid dynamics, etc.
In this respect, some examples of professional skills achieved during the past 35+ years of the doctoral program are here reported:

- expert in computational and/or experimental fluid mechanics, with capabilities to develop methods and models for both aerospace applications and generic vehicles.
- expert in active and passive control of the dynamics of aerospace structures, integrating global and subsystem design.
- expert in active and passive structural safety of vehicles, both aerospace and non-aerospace.
- expert in vibration and noise control, including modeling analysis, system design and implementation of specific subsystems.
- expert in the dynamics and control of aerospace vehicles and related operational missions.
- expert in integrated design of complex aerospace systems, including their missions and overall life cycle.

Since its foundation, more than 35 years ago, the doctoral course in Aerospace Engineering has awarded more than 180 PhDs.

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MULTIFIDELITY AERODYNAMIC AND AEROACOUSTICS OF PROPELLERS AND ADJOINT BASED OPTIMIZATION FOR NOISE REDUCTION

Luca Abergo – Supervisor: Alberto Guardone
Co-Supervisor: Beckett Zhou

Urban Air Mobility (UAM) vehicles powered by electric propulsion systems face strict noise constraints, making propeller noise a major design challenge. This research focuses on minimizing noise emissions from low-Reynolds-number isolated propellers by optimizing blade geometry using a discrete adjoint approach, reducing computational costs compared to fully unsteady simulations.
Three hybrid CFD-CAA solvers of varying fidelity and computational demand were developed to predict the tonal noise emission of small-scale propellers. These solvers integrate aerodynamic simulations with the Ffowcs Williams-Hawkings (FWH) integral formulation to assess noise. Primarily focusing on forward flight conditions, the study validates its approaches against experimental data from anechoic wind tunnels. Among the tested methods, the Reynolds-Averaged Navier-Stokes (RANS) approach in a rotating reference frame (RRF) emerged as a favorable trade-off, effectively predicting tonal noise with reduced computational requirements. Additionally, this method was enhanced to estimate broadband self-noise by integrating an analytical model that automatically determines boundary layer thickness at blade trailing edges.
To further reduce noise emissions, an adjoint-based optimization framework was developed, separately targeting tonal and broadband noise.
By leveraging reverse-mode automatic differentiation, this framework efficiently computes noise sensitivity with respect to blade geometry, enabling noise reduction while preserving aerodynamic performance. The resulting sensitivity maps offer valuable insights into how design changes impact acoustic and aerodynamic characteristics.
The research is structured into two main parts: the first part evaluates and compares hybrid CFD-FWH solvers, while the second part presents the adjoint-based noise minimization framework. Key research questions addressed include:

1) Can low/mid-fidelity methods effectively capture the tonal noise emissions of small-scale propellers in forward flight?
2) How does neglecting unsteady pressure variations in steady RANS-RRF simulations impact tonal noise prediction accuracy?
3) Can steady RANS-RRF simulations be extended to automatically estimate broadband self-noise in forward flight?
4) To what extent can high-fidelity reduced-order models, such as harmonic balance, provide accurate tonal noise predictions compared to fully time-resolved simulations?
5) Is a discrete adjoint approach feasible for automatic propeller blade shape optimization to reduce noise emissions without requiring fully unsteady optimization simulations?

The study confirms that low-fidelity methods can capture trends in aerodynamic performance and noise emissions, particularly when modeling vortex interactions in multi-propeller configurations. The RANS-RRF solver proved highly effective for tonal noise prediction, offering computational efficiency while maintaining accuracy. To address broadband noise, the Amiet model was incorporated into the framework, demonstrating reasonable agreement with experimental data.
Reduced-order models like harmonic balance provide accurate tonal noise predictions, approximating fully time-resolved simulations at a lower computational cost. However, for certain observer locations, simpler steady-RRF simulations still deliver comparable results with significantly reduced computational effort.
The research also demonstrates that a discrete adjoint approach is a feasible and efficient method for automatic propeller blade shape optimization to minimize noise emissions. The developed framework separately optimizes tonal and broadband noise, effectively reducing noise while maintaining aerodynamic efficiency. Using algorithmic differentiation, the optimizer can generate noise-sensitive shape modifications, such as changes in blade twist, thickness, camber, and dihedral angle, achieving substantial noise reductions.
Overall, this study advances numerical methodologies for propeller noise estimation and reduction in UAM applications. It provides a foundation for efficient optimization frameworks compatible with industry design requirements, supporting future regulatory compliance and improved urban noise management. The findings highlight the potential of using steady-state adjoint-based optimization techniques to achieve meaningful noise reductions without the computational burden of fully unsteady simulations. Future work could explore integrating global optimization strategies, such as Bayesian methods or machine learning, to enhance design space exploration further.

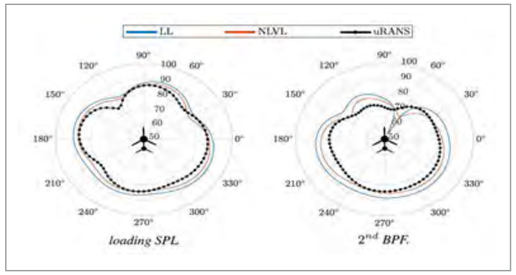

Fig. 1

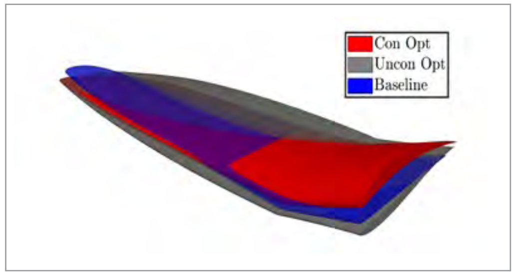

Fig. 2

DEVELOPMENTS IN AEROELASTIC WIND TUNNEL TESTING FOR HIGH ASPECT RATIO WING CONFIGURATIONS

Luca Marchetti - Supervisor: Sergio Ricci

The current trend of pursuing a significant reduction of aviation's impact on global emissions is leading to the exploration of new aircraft configurations that would help achieve this goal. Higher aspect ratio configurations are among these and, to overcome the weight penalty that has always prevented their use different solutions are evaluated: classical cantilever wing, strut-braced wing, folding wing tip, the main concern as the wings become more slender is their aeroelastic behaviour. The need for experimental data makes aeroelastic wind tunnel tests a crucial part of the assessment of these new configurations and, possibly, a tool in the design phase. This work shares the experience gained through the latest aeroelastic tests performed at Politecnico di Milano in its large wind tunnel facility, addressing the main challenges related to these activities. A practical example regarding the flutter tests of a strut-braced wing is presented to illustrate the general process and the findings for that specific configuration. An in-depth look at the design of the spar and the use of 3D printing for the aerodynamic sector follows, with the evolution from one model to another. Then, the problem of measuring large displacements is addressed. A study on a 3D camera tracking system is presented, with the improvements made throughout the most recent tests performed at GVPM using that technology, that led to a real-time 3D visualisation of a virtual wind tunnel model deforming as the physical one. Last, the steps made through the years towards achieving the correct flight dynamics inside the wind tunnel are illustrated, with the mechanical solutions on the model to get to a free body motion, the experimental data collected for future identification of the aerodynamic coefficients of the model, the writing of a simulator to perform the identification, and the results and lesson learned from the gust response tests of a folding wing tip configuration.

Fig. 1 - Rendering of the three configurations considered inside the U-HARWARD project: the folding wing tip configuration in the foreground, the strut-braced wing configuration on the top right corner, and the traditional configuration with a higher aspect ratio on the left.

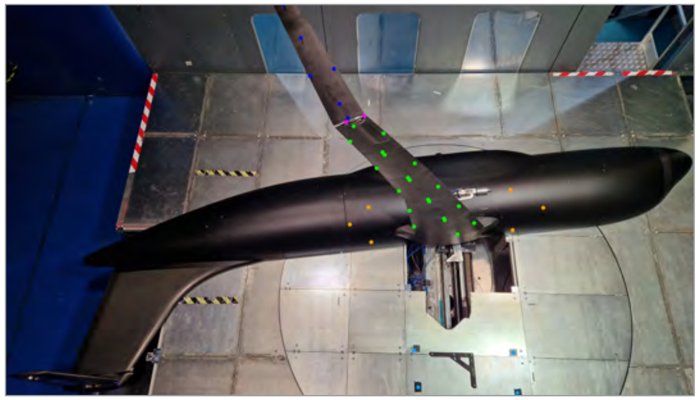

Fig. 2 - Aeroelastic wind tunnel model of the folding wing tip configuration for gust response testing. The position of markers for the 3D camera tracking system is highlighted with different colors.

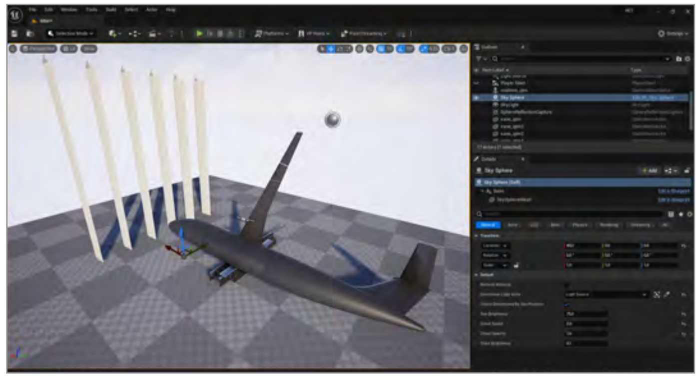

Fig. 3 - Virtual reconstruction of the wind tunnel testing in Unreal Engine 5. Deformations of the model inside the wind tunnel are measured by the 3D camera tracking system and are streamed in real time to the virtual environment to drive the deformation of the virtual copy of the model.

OPTIMIZATION BASED UNMANNED AERIAL VEHICLES TRAJECTORY GENERATION

Roberto Rubinacci - Supervisor: Marco Lovera

Over the past few decades, Unmanned Aerial Vehicles (UAVs) have received significant attention due to their increasing utility across a wide range of civilian and military applications. These include, but are not limited to, surveillance, search and rescue operations, precision agriculture, aerial photography, and goods delivery. As these applications grow more sophisticated, the coordination of multiple UAVs, commonly referred to as UAV swarms, has emerged as a powerful paradigm. Swarm coordination offers several advantages, including improved mission efficiency, reduced operation times, and enhanced robustness through redundancy and adaptability.

A fundamental challenge in UAV deployment lies in trajectory generation, the process of computing a sequence of control inputs that drive the UAV from an initial state to a target destination while optimizing a given performance metric (such as time, energy, or safety). This problem is often approached using optimization techniques. Particularly in the case of multicopters, planning trajectories based on the derivatives of position has proven highly effective. When formulated as a convex optimization problem, trajectory generation can be solved efficiently with strong theoretical guarantees. However, many interesting scenarios lead to non-convex formulations, especially when considering dynamic constraints or obstacle avoidance. In such cases, it is common practice to approximate the non-convex problem with a convex surrogate that can be solved more reliably and efficiently. This thesis explores two novel approaches to constructing these convex approximations in the context of quadrotor trajectory generation: Outer approximations, which aim to recover globally optimal solutions; Inner approximations, which efficiently provide feasible locally optimal solutions.

The thesis is organized into two parts, each tackling a distinct aspect of UAV trajectory planning through advanced optimization frameworks. The first part focuses on the computation of globally optimal trajectories in environments with static obstacles. Specifically, it targets the obstacle avoidance problem by developing tight convex outer approximations based on polynomial optimization theory. The proposed method reformulates the original non-convex problem as a hierarchy of Semidefinite Programming (SDP) problems. As this hierarchy progresses (i.e., as the relaxation order increases), the solutions converge to the global optimum. To enhance tractability, the proposed approach exploits the sparsity inherent in the problem, particularly its chain-like structure. A novel sparse hierarchy is introduced, reducing computational overhead while preserving convergence properties. This framework enables the certification of global optimality for minimum-time trajectories among obstacles, offering strong theoretical and practical results.

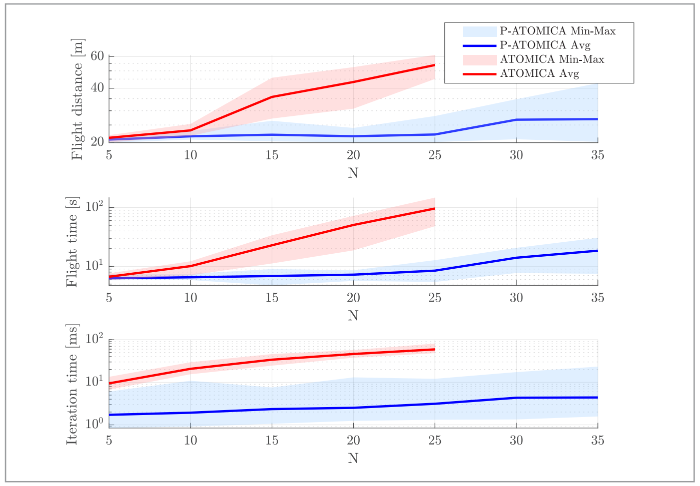

Fig. 1 - Comparison of ATOMICA and P-ATOMICA performance for an increasing number of UAVs and obstacles.

The second part addresses the problem of real-time trajectory planning for multiple UAVs. While centralized optimization approaches can solve this problem in theory, they suffer from poor scalability. As the number of UAVs increases, centralized approaches become computationally intractable for real-time operation. Additionally, centralized methods introduce a single point of failure, reducing the overall robustness of the system. To overcome these limitations, this thesis exploits a decentralized coordination framework. Each UAV computes its own trajectory in real time using local convex approximations of the non-convex constraints. Although this approach sacrifices global optimality, it enables fast computation and is well-suited for real-time applications.

A novel anytime optimization algorithm, named ATOMICA (Anytime Trajectory Optimization for Multi-drone systems with guaranteed Collision Avoidance), is proposed. Each UAV communicates with others and treats them as dynamic obstacles within the receding-horizon framework. Recursive feasibility is ensured by always maintaining a safe backup trajectory. Time-dependent collision avoidance constraints are efficiently handled using positivity certificates, eliminating the need for potentially unsafe time discretization while enabling fast collision checking. The non-convex optimization problem is solved using the convex-concave procedure, which gives ATOMICA its anytime capability, allowing users to predefine the duration of each replanning step. The algorithm was validated through extensive simulations and real-world experiments, demonstrating remarkable real-time performance, resulting in reduced flight times and shorter flight distances compared to existing methods in the literature. Figure 1 illustrates the performance of the developed algorithms, ATOMICA and P-ATOMICA (an enhanced version), as the number of UAVs and obstacles increases.