



Chair:
Prof. Pierangelo Masarati

DOCTORAL PROGRAM IN AEROSPACE ENGINEERING

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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MONOCULAR VISION FOR UNCOOPERATIVE TARGETS THROUGH AI-BASED METHODS AND SENSORS FUSION

Michele Bechini – Supervisor: Prof. Michèle Roberta Lavagna

Autonomy in spacecraft relative navigation is an enabling technology for incoming space missions that gained an increasing interest in the last years. The work presented in the Thesis focuses on the enhancement of vision-based algorithms within the context of autonomous spacecraft relative navigation in target-chaser systems. Namely, the analyses are restricted to the case of uncooperative-known targets being the most attractive and challenging scenario, like on-orbit servicing and active debris removal, i.e., hot-topics in both academic and industrial research. This research scenario entails a relative state estimation process solved autonomously onboard to ensure the reactivity, effectiveness, and reliability in nominal and off-nominal operations. Most of the vision-based relative pose estimation architectures rely on VIS monocular cameras to acquire images processed onboard to feed the relative state to the GNC chains. Several architectures have been proposed through the years, achieving astonishing performances in terms of accuracy of the estimated relative pose enabled by the introduction of AI-based algorithms and the publication

of a few synthetic spaceborne image datasets. Despite that, most of the best-performing architectures aim at increasing the accuracy, disregarding the constraints imposed by the reduced computational resources available onboard and facing deployability issues due to the huge CNNs employed. Further, VIS cameras offer undoubted advantages like reliability and well-established heritage but suffer the drawback of being highly sensitive to the illumination conditions of the scene, being unable to capture reliable images in low illumination conditions, jeopardizing the vision-based navigation algorithms. The research performed focuses on enhancing the vision-based algorithms for autonomous spacecraft relative navigation leveraging lightweight CNNs that are more likely to be deployed onboard and exploiting sensor fusion techniques to increase the reliability and robustness of critical navigation tasks. The Thesis starts by facing the problem of generating photorealistic synthetic spaceborne images, i.e., the starting point for developing vision-based algorithms. Namely, two rendering tools to generate images in the visible spectrum are proposed, detailing the needed

approximations and strategies to increase photorealism. Further, a novel sensor model is introduced, relying on high-fidelity noise models that increase the accuracy and representativeness of the images generated, as demonstrated by the comparison with the frames acquired with an actual sensor. Concerning the autonomous relative pose estimation problem, a first algorithm that leverages lightweight CNNs was developed to assess the performances of smaller models compared to the top-performing architectures. Namely, the algorithm relies on lightweight CNNs for target and line segment detection developed for inference on mobile devices. The outcomes of the tests on a benchmark dataset shown in Fig. 1 demonstrate that the performances are

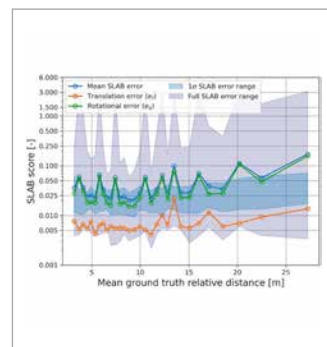


Fig. 1 - M-LSD-based pose initialization outcomes on SPEED images.

comparable with top-performing architectures, proving that light CNNs can provide accurate and robust estimates.

The main drawback of the proposed algorithm is the high processing time needed to retrieve a pose estimate relying on the output of the CNNs. Namely, the computational time is compatible with the pose initialization task, but it is prohibitive for the pose tracking phase. Consequently, a second pose estimation algorithm has been developed by relying on a computationally efficient CNN multi-tasking model that performs both target detection and keypoint regression in a single inference. The architecture developed achieved better performances (see Fig. 2) than the former algorithm for all the metrics evaluated, including the computational time due to faster postprocessing of the CNN outputs to retrieve the relative pose estimate. The CNN was tested on several datasets, proving the robustness and reliability of the estimates provided for a wide range of scenarios and increasing image

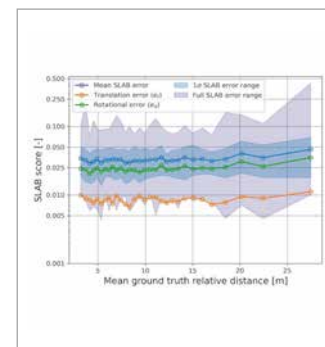


Fig. 2 - YOLOv8-based pose initialization outcomes on SPEED images.

noise levels, also within an AI-GNC simulation environment with rendering-in-the-loop developed within this work, despite being not well suited for highly symmetric targets.

The possibility of relying on VIS and TIR sensor fusion to prevent the drawbacks of VIS cameras has been investigated by developing two LOS estimation algorithms for two far-range scenarios leveraging long-exposure images. The sensor fusion step compares and validates the LOS estimates retrieved independently from the VIS and TIR image streams. The outcomes demonstrate that relying on measures extracted from frames acquired at different spectral bands and then performing the sensor data fusion increases the robustness of the proposed approaches with respect to processing VIS-only images, resulting in pipelines more precise and accurate in detecting the target also in far-range scenarios with stars in the background.

Lastly, a preliminary feasibility study is detailed to prove the effectiveness of sensor fusion even in the relative pose

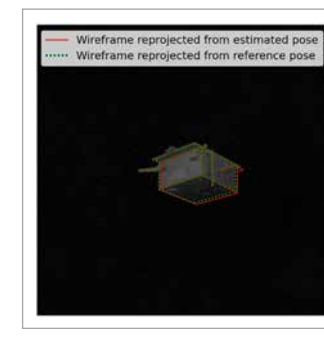


Fig. 3 - Reprojected wireframe on a VIS-TIR Fused image using estimated and reference pose.

estimation task, leveraging the promising outcomes of the analyses for the LOS estimation. Namely, the possibility of retrieving a relative pose estimate from a single frame generated by fusing VIS and TIR images at pixel level has been assessed, demonstrating that the fusion process enhances the retrievable information for low illumination scenarios without affecting the outcomes for nominal illumination conditions. The feasibility of the proposed approach has been demonstrated by processing a dataset of fused images also with the single-CNN algorithm introduced in the Thesis, pointing out that VIS-TIR fused images allow retrieving a relative pose estimate for those cases in which the pose initialization algorithm fails due to the low illumination condition, as in Fig. 3, resulting in a promising solution, possibly solving the most severe drawback of vision-based navigation.

STRATEGIES FOR SAFE OPERATIONS OF REMOVAL AND SERVICING MISSIONS IN LOW EARTH ORBIT

Giacomo Borelli – Supervisors: Prof. Camilla Colombo, Dr. Gabriella Gaias

The space sector, as in many technology fields, is rapidly evolving lately. Similarly, the sustainability challenge is presenting itself also in the space domain. A paradigm shift from the one-use satellite platforms towards reusability and servicing is set to improve the advantages of space exploitation. Moreover, the sustainability of space activities is challenged by the growth of in-orbit debris, which is essentially creating risks for current and future missions to operate safely in orbit. Answers to these all-around challenges have been proposed within the space community at every level, starting from the technological advancements in rocket reusability, to mitigation guidelines and rules for end-of-life responsible disposal operations for debris mitigation. Within the realm of solutions to sustainability problems in space, the implementation of In-Orbit Servicing (IOS) and Active Debris Removal (ADR) mission architectures have been studied by the space community and received great attention in the last few years. The former guarantees the reusability of the in-orbit platform after failure or extension of these services provided through repair, refuelling etc. and will

benefit the feasibility of future missions in terms of cost per service and design reliability. The active debris removal mission is instead explored to remove high-risk objects and avoid the uncontrolled proliferation of debris in space. Despite the strong interest in this innovative solution, only a few notable examples of successful applications are present in literature for servicing satellites, while no mission has been performed yet to remove a debris object from space. Several challenges have slowed down the development of this mission and are closely related to the complex operations that the servicer satellites must perform in proximity to the objects to be serviced. One of the main challenges arises from the requirements of safety and autonomy of the proximity phases, which will require in general a complex scenario. This Ph.D. project addresses these specific challenges of IOS and ADR missions, which are identified as crucial for the advancement in this sector and judged as an enabler for future systematic applications of the operations within the new in-orbit space ecosystem. The study focuses on low Earth orbit applications, the main interest for

removal mission architectures. These challenges are addressed firstly considering the problem at the mission planning level, where for example for removal missions an index-based target selection and mission design is developed to account for the interest of its removal and the feasibility and safety of capture. To this aim a novel ADR index to rank the debris population is formulated and included in a multi-objective optimisation mission planning tool. An example of the environmental and economical values of the ADR index for the LEO debris is shown in Figure 1. Subsequently, the design of guidance and control strategies for the proximity operations phases envisioned within a servicing and removal

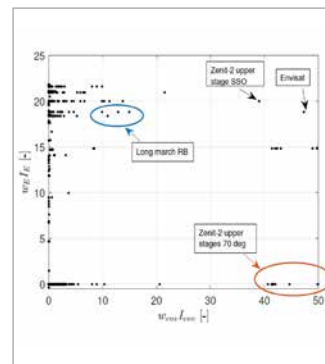


Fig. 1 - Scatter distribution of the debris objects in LEO in function of their environmental index and economical index, with some notable objects highlighted.

mission is studied, addressing novel developments which prioritize the safety of operations and improve their robustness. Among these phases, far-range and close-range rendezvous trajectory planning and guidance navigation and control are dealt with, tackling the challenges of angles-only observability in the former and improved flight safety in the latter. For both scenarios, the passive abort safety concept is extensively used and applied to guarantee trajectory robustness and collision avoidance concerning any major failure of the servicer

satellite. Convex formulations of the trajectory planning problems are developed and selected to enable autonomous operations. An example of a safe trajectory for close range rendezvous is depicted in Figure 2. Moreover, a motion planning algorithm for the inspection phase is devised, which can guarantee passive abort safety while optimising for the information cost, a metric that quantifies the quality of inspection observations performed with an onboard camera. Once the target is characterised, it may happen that its rotational state does not

allow for safe capture operations. This complication is considered and mitigated in this research by designing a contactless plume impingement strategy which slows down the rotation of the uncontrolled debris while operating in a safe manner. An example of the application of the plume impingement contactless control to a failed spacecraft is shown in Figure 3. Lastly, this Ph.D. project presents the application of these concepts to the phase A design of the SpEye mission, funded by the Agenzia Spaziale Italiana (ASI). As a result, this research introduces improvements in the operational safety of strategies involved in IOS and ADR missions. Particularly, the significance of including advanced safety concepts at the early design level in the proximity operations of servicing and removal missions is highlighted and studied. The research developed in this Ph.D. project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme as part of project COMPASS (Grant agreement No 679086).

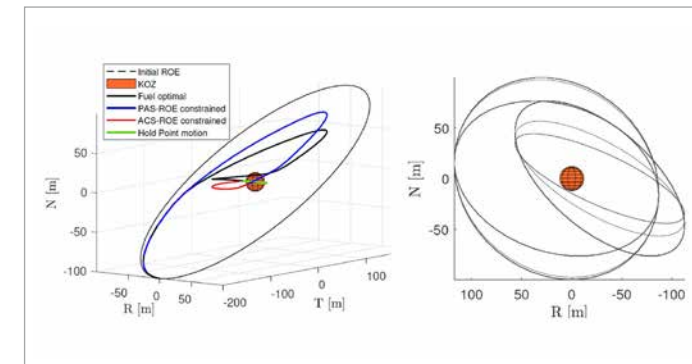


Fig. 2 - Left: Trajectories for the close-range rendezvous synchronisation, displaying fuel optimal solution (black) and safe solution (colours). Right: Passive safety evolution of the safe trajectory ensuring robust collision avoidance during the approach.

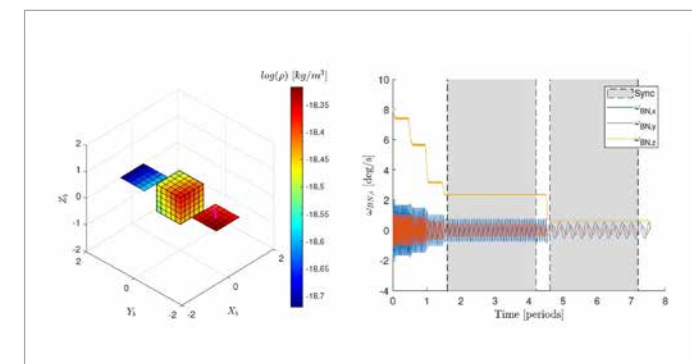


Fig. 3 - Left: plume density field on the debris target. Right: Detumbling control during impingement operation showing the decrease of the target's angular rates.

AI-BASED GUIDANCE FOR SPACECRAFT PROXIMITY OPERATIONS AROUND UNCOOPERATIVE TARGETS

Andrea Brandonisio – Supervisors: Prof. Michèle Roberta Lavagna

In recent years, space research has heavily shifted its focus towards enhanced on-board autonomy for spacecrafts' on-orbit servicing (OOS), which, together with the automatization of proximity operations, may include a great variety of activities aimed to increase the reliability, flexibility, and cost-effectiveness of a space mission, lowering down all the possible associated risks. Concurrently, the rapid development of Artificial Intelligence (AI) is strongly influencing aerospace research, particularly in the framework of autonomous guidance, navigation, and control (GNC) systems. Therefore, among all, these two research branches may converge towards the autonomy and adaptability of GNC, which may represent one of the most effective ways of reducing human intervention during spacecraft missions. Within this context, adaptive guidance depends on the ability of the system to build a map of the uncertain environment, figuring out its location inside of it and accordingly determining the control law. Thus, this autonomous navigation problem is usually framed as an active Simultaneous Localization and Mapping (SLAM) problem and modeled as a Partially

Observable Markov Decision Process (POMDP). Nowadays, the state-of-the-art methodology to approach POMDP optimization is Deep Reinforcement Learning (DRL), which relies on the Proximal Policy Optimization (PPO) algorithm for continuous state-action space models. The optimization algorithm schematization is summarized in Figure 1.

In this context, this PhD thesis wants to investigate the design and development of an autonomous agent capable of cleverly planning trajectory around unknown and uncooperative target objects to optimize the shape reconstruction of the target itself. The first part of the work covers all the background analysis and mathematical

model selection in order to evaluate the best options for the environment and agent design. These choices are afterwards explained and tested to assess the feasibility of the approach and the baseline performance results. The guidance algorithm is evaluated in terms of target map reconstruction, by rendering the space object with a triangular mesh and then considering the number of quality images for each face to reconstruct its map through image processing. A major differentiation in the algorithm implementation is provided by the employment of either a discrete or a continuous action space, a perfect or noisy state space, and, moreover, different neural network architectures. In particular, two architectures have been analysed

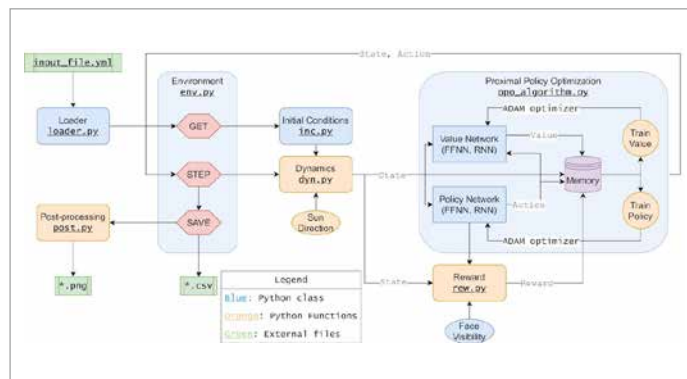


Fig. 1 - Schematic of the Python-based tool for training simulation.

to assess their potential and issues: feed-forward (FFNN) and recurrent (RNN) neural networks. All the models of the AI agent investigated throughout the thesis are evaluated making use of some pre-defined metric parameters, i.e. reward score, map level, and time, as shown in Figure 2.

The proposed model is trained with increasing difficulty reward definition and then extensively tested, always starting from random initial conditions, to verify the generalizing capabilities of the DRL agent. Once the foundation of the agent is set and the robustness of the approach is guaranteed, this guidance block

is inserted into a more general AI-based GNC system, based on image generation and processing, and navigation tools. Extensive tests, in different scenarios characterized by fixed camera pointing or attitude control requirements, are performed to verify the capability of the agent and the overall pipeline. The trajectories resulting from these different trained models can be very different considering the simulation agent and environment, an example is depicted in Figure 3.

In the end, the applicability of DRL methods and neural networks to support autonomous guidance is further corroborated with other kinds of guidance and control environments (always characterized by the same level of complexity as in the main scenario), aiming to assess the training and testing methodology. A four-step process is proposed based on increased complexity level in the agent (network definition and reward function) and environment (initial conditions) models. Overall, the proposed approach for autonomous guidance design is demonstrated to be an effective possibility towards increased autonomy of the spacecraft's GNC system.

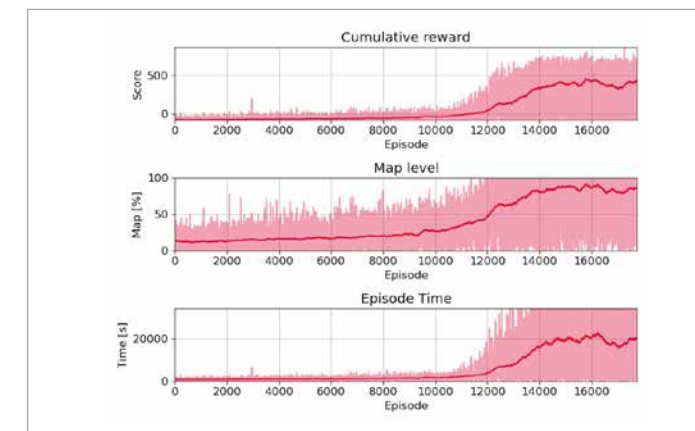


Fig. 2 - Evolution of the metrics (reward score, map level, time) along the training simulation of the TANGO-based case study.

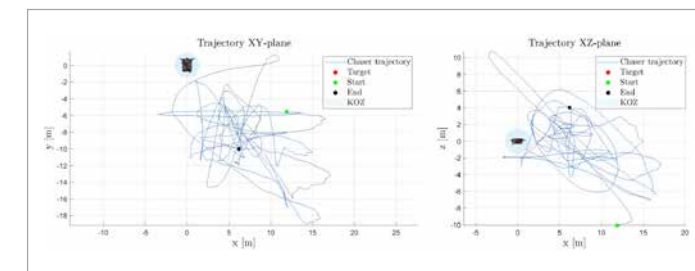


Fig. 3 - Example of the chaser-target relative trajectory in the controlled target pointing case for a simulated episode of the agent around the TANGO object.

MODELING, VALIDATION D ROBUST DESIGN OF ELECTRO-THERMAL ICE PROTECTION SYSTEMS UNDER OPERATIONAL UNCERTAINTIES

Mariachiara Gallia - Supervisor: Prof. Alberto Guardone

In-flight icing occurs when aircraft, rotorcraft, or UAVs fly through a cloud of supercooled water droplets. Their temperature is below freezing point, but they are still in the liquid phase. The equilibrium is broken upon impact with a moving surface, leading to ice formation on surfaces like wings, rotor blades, and engine intakes. This ice can degrade performance and lead to accidents.

Ice Protection Systems (IPS) are employed to prevent or remove ice accretion, functioning in anti-icing to prevent ice formation and de-icing modes to eliminate existing ice layers. Electro-Thermal Ice Protection Systems (ETIPS) are widely used for their lightweight and adaptability, suiting applications like rotorcraft and UAVs. Nonetheless, their high energy consumption poses challenges, especially for electric aircraft and large surfaces like wings and blades.

Conducting certification tests for aircraft and rotorcraft in known icing conditions is imperative for safe operation. However, executing planned certification tests under natural icing conditions is difficult due to unpredictability and high

costs. Alternative methods such as icing spray systems, icing wind tunnels, and numerical codes have been explored. All these methods are affected by uncertainties in replicating icing conditions. Icing wind tunnel tests, for instance, exhibit up to 20% uncertainty in critical cloud parameters even in well established facilities. Achieving aero-thermal equilibrium with supercooled large droplets is also problematic. These uncertainties significantly impact test conditions and the ice accretion process, undermining the validation of numerical codes reliant on experimental data.

It is crucial to characterize and account for these uncertainties during testing and when using numerical codes for more reliable ice accretion modeling and validation. Designing ice protection systems requires evaluating thermal power requirements for effective water evaporation and, for modular systems, distributing thermal power across protected components to ensure adequate protection under different icing conditions. However, uncertain cloud conditions during flights often lead to overly cautious designs. Robust design and optimization approaches can

mitigate this challenge by quantifying deviations from target performance due to inherent uncertainties, enabling consistent and predictable performance without unnecessary conservatism.

This thesis aims to model, validate, and robustly design electro-thermal ice protection systems (ETIPS) under operational uncertainties. The research starts by developing and validating a numerical model to predict ETIPS performance, encompassing both disabled and enabled IPS in anti-icing and de-icing modes. Various validation test cases are considered to assess the model's ability to replicate icing wind tunnel test results accurately. In modeling in-flight ice accretion with and without IPS, roughness emerges as a significant factor, enhancing convective heat transfer and ice growth rates while potentially triggering boundary layer transition. A preliminary investigation into roughness characterization in in-flight ice accretion conditions is conducted utilizing two methods: analyzing ice roughness from ice shapes generated in icing wind tunnels and predicted through

numerical simulations using the morphogenetic approach. The Self-organizing maps (SOM) algorithm is employed to extract average roughness distribution from data point clouds, demonstrating effectiveness through validation against synthetic test cases. Numerical simulations using the morphogenetic model suggest that existing tools can replicate ice roughness observed in experimental data, expanding our understanding of roughness evolution during ice accretion.

Following model validation, a comprehensive optimization study is undertaken for given cloud and flight conditions, focusing on an airfoil equipped with an ETIPS comprising seven independent heating elements. The heat flux distribution across these heaters is optimized to minimize IPS thermal power consumption while ensuring safe operation. Optimization is conducted through the Mesh Adaptive Direct Search (MADS) algorithm, treating the objective function as a black-box. Various objective functions, constraints, and problem formulations are explored, demonstrating that the optimized heat flux layout can evaporate impinging water more efficiently.

In the second part of the research, operational uncertainties are reintroduced. Uncertainty Quantification (UQ) methods are employed to assess IPS optimal design performances under uncertain cloud conditions, particularly

focusing on runback ice formation. A Monte Carlo-based forward uncertainty propagation analysis is conducted, revealing that deterministic optima may become suboptimal under off-design conditions. Additionally, the impact of uncertainties in icing wind tunnel tests and aerothermal slip of supercooled large droplets (SLD) produced in an Icing Wind Tunnel (IWT) on ice accretion characteristics and IPS performances is investigated. These findings underscore the importance of incorporating uncertainties in ice protection system design to avoid unnecessary conservatism and the necessity of considering aerothermal slips in SLD model calibration to eliminate biases.

Finally, in the last part of the thesis the optimization and uncertainty quantification techniques are combined to perform a robust optimization under uncertain cloud conditions. First, a robust optimization framework is constructed and validated through analytical test functions, demonstrating effective convergence to optimal designs. Then, it is applied to a reference Ice Protection System test case. The optimization problem formulation accounted for operational uncertainties, specifically those associated with cloud properties and air temperature. Two different cost functions are used: one minimizes the 95 quantile of ice accretion rate to reduce the risk of severe ice formation, and the other

seeks consistency in the fully evaporative IPS performance outside nominal conditions. Robust designs are compared to baseline and benchmark configurations with a fixed power budget, revealing potential improvements in heat flux distribution that enhances flight safety even under nonnominal environmental conditions. Furthermore, the presented framework's flexibility allows adaptation to different uncertain input parameters, objective functions, geometry, and environmental conditions.

To conclude, this research contributes to the understanding of electro-thermal ice protection systems design, highlighting the importance of a systematic treatment of uncertainties in the modeling, validation, and design processes of Ice Protection System for in-flight icing.

DEVELOPMENT OF A NON-INVASIVE PILOT INCEPTOR FORCE SENSOR FOR FLIGHT SIMULATION APPLICATIONS

Pierre Garbo – Supervisor: Prof. Giuseppe Quaranta

In the intricate field of human-machine interaction (HMI) within helicopter flight operations, the stakes couldn't be higher. Each flight presents a delicate balance of factors, from environmental conditions to the mental and physical state of the pilots themselves. Yet, despite the advancements in aviation technology, the human element remains the linchpin of safety and success in the skies. Pilots must navigate a complex array of controls and systems while contending with factors such as fatigue, stress, and the ever-present specter of excessive workload. In this high-stakes environment, the ability to accurately assess and manage pilot workload in real-time is not just desirable, it's imperative. Traditionally, workload assessment in aviation has relied on subjective measures or post-flight debriefings, lacking the immediacy and granularity necessary for effective intervention. This gap in capability has spurred the development of innovative solutions aimed at providing pilots with timely, actionable insights into their cognitive and physical workload levels. Enter the OPT-IN sensor system, a groundbreaking technology designed to seamlessly integrate

into helicopter control sticks and monitor pilots' hand activity in real-time. Developed through rigorous research and development efforts, the OPT-IN system represents a paradigm shift in HMI monitoring, offering unprecedented insights into pilot workload dynamics. At its core, the OPT-IN system harnesses a fusion of cutting-edge technologies, including optical principles and advanced force estimation algorithms. By directly contacting the pilot's hand, the sensors embedded within the control stick capture a wealth of data, ranging from muscle activity to grip pressure. This fine-grained information provides a window into the pilots' cognitive and physical states, enabling real-time analysis and intervention to optimize performance and safety. The validation of the OPT-IN system's efficacy and reliability is a cornerstone of the doctoral research presented here. Through a meticulously designed series of laboratory and flight simulation tests, researchers seek to demonstrate the system's ability to accurately assess pilot workload in real-world operating conditions. In the controlled environment of the laboratory, the sensors undergo comprehensive characterization,

with researchers probing their responses to various stimuli and environmental factors. These tests not only validate the accuracy and reliability of the OPT-IN system but also lay the groundwork for its deployment in actual flight operations. Transitioning to flight simulation tests, the OPT-IN system is put through its paces in a variety of operational scenarios, from routine maneuvers to emergency situations. Test pilots, equipped with the OPT-IN sensors, navigate simulated flights while researchers monitor their hand activity in real-time. The data collected during these tests provide valuable insights into the relationship between pilot workload and performance, shedding light on potential areas for improvement and optimization. The significance of workload assessment in helicopter flight operations cannot be overstated.

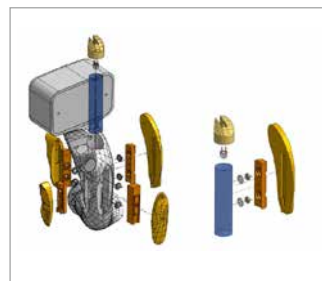


Fig. 1 - Exploded view of the OPT-IN system

Adverse interactions between pilots and aircraft, such as Pilot Induced Oscillations (PIOs) or Pilot Assisted Oscillations (PAOs), can have catastrophic consequences if left unchecked. By providing pilots with real-time feedback on their cognitive and physical workload levels, the OPT-IN system serves as a crucial tool for enhancing situational awareness and mitigating the risks associated with excessive workload. The dissertation structure reflects a comprehensive exploration of the OPT-IN system and its implications for helicopter flight operations. Detailed discussions cover a wide range of topics, including the underlying principles of helicopter control, workload analysis methodologies, OPT-IN system components,



Fig. 2 - The OPT-IN system

calibration processes, simulation studies, and the extension of OPT-IN's application to fixed-wing aircraft. Each aspect of the research contributes to a deeper understanding of the OPT-IN system's capabilities and its potential to revolutionize HMI monitoring in aviation. In conclusion, the doctoral research on the OPT-IN sensor system represents a significant advancement in the field of HMI monitoring. By providing pilots with real-time insights into their workload levels, the OPT-IN system offers a powerful tool for enhancing safety and performance in helicopter flight operations. As aviation continues to evolve, the insights



Fig. 3 - OPT-IN system integrated in a motion platform during a test

gleaned from this research will undoubtedly shape the future of HMI monitoring and pave the way for safer, more efficient flight operations

HYBRID CONTROL TECHNIQUES FOR UAVS

Giovanni Gozzini – Supervisors: Prof. Marco Lovera

Hybrid systems are dynamical systems that incorporate both continuous and discrete dynamics, so that the states of the system can “flow” when governed by the continuous dynamics and “jump” when governed by the discrete dynamics.

The recent development of a comprehensive theory for hybrid dynamic systems that allows to integrate continuous-time dynamical systems and discrete-time dynamical systems in a unified manner, provides a unifying modelling language for different applications to complex control systems. In particular, control of aerospace systems is one of the areas among the several engineering and technological fields for which hybrid systems theory has provided innovative solutions.

The dissertation leverages the aforementioned comprehensive theory and demonstrates its application to Unmanned Aerial Vehicles (UAVs).

In the first part of the dissertation the complex problem of the Air-to-Air Automatic Landing (AAAL) of a small drone on the top of a larger one during flight is investigated (Figure 1). The mission endurance of smaller drones, denoted as followers, is extended allowing them to take-off and land on top of a flying larger and heavier carrier

drone, that could additionally be equipped and used as a recharging platform.

The non-cooperative problem in which the follower drone has to estimate the state of the carrier using only onboard sensors is solved dividing it in a navigation sub-problem and a control sub-problem (Figure 2). The navigation function is based on a Kalman filter able to reconstruct position and velocity of the carrier using images coming from a vision-based system onboard the follower.

The information about the state of the carrier is then used for the control sub-problem, solved with a three-layer architecture composed by a Quasi Time-Optimal (QTO) position control law with a hybrid logic, an observer-based adaptive velocity control law and a geometric attitude stabilizer.

Simulation and experimental results demonstrate the advantages of the hybrid systems control framework in solving such a complex scenario.

The AAAL presents a significant contribution primarily through its practical application. By employing the hybrid systems formalism, a crucial breakthrough in simplifying a complex task is achieved. This approach breaks down the problem into smaller

subproblems, ensuring safety and stability throughout the process.

In the second part of the dissertation, a hybrid strategy is proposed to solve the problem of trajectory tracking for an underactuated UAV in the presence of constant or slowly varying disturbances. The hybrid switching strategy (Figure 3) combines a local Proportional-Integral-Derivative (PID) controller with feed-forward compensation of the reference velocity for tracking in the presence of small errors (local mode) and a QTO stabilizing controller with a term compensating for the disturbance which handles large errors and saturation limits (global mode). The hybrid logic is applied also to the reference: during global mode the reference is slowed down to ease the stabilization



Fig. 1 - ANT-X and CARRIER-1 drones employed for testing vision-based Air-to-Air Automatic Landing. The small drone is equipped with a monocular camera, while the larger drone is equipped with a fiducial marker.

task, while, once the local mode is reactivated, the reference is speeded up to restore the nominal behaviour.

An adaptive bias observer is used to retrieve the estimate of the disturbance needed by the hybrid blend mechanism and by the compensating term of the global controller.

Stability, simulation and experimental results show the effectiveness and advantages of the proposed hybrid strategy. In addition to its application to the complex non-linear dynamical model of a quadrotor UAV, the significant contribution is the proposed hybrid strategy. Specifically, the strategy is adapted to effectively handle

the presence of constant disturbances. This enhances the robustness and practical applicability of the hybrid approach, making it more suitable for real-world scenarios where disturbances are common.

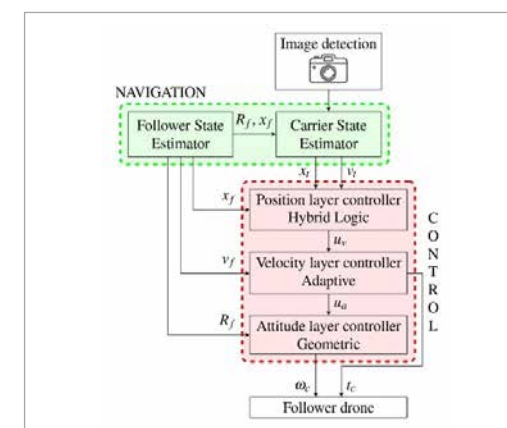


Fig. 2 - Block diagram of the autonomous system for the landing problem. The navigation block in green is kept separated from the control one in red. The navigation function compute estimates of the state of the follower and of the carrier, the control function has a three-layer architecture.

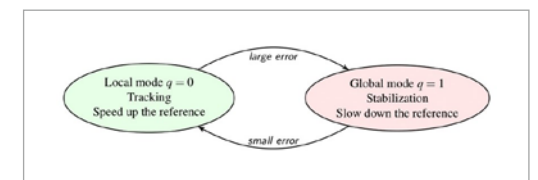


Fig. 3 - Hybrid automata for the tracking problem. During the local mode, the reference trajectory is speeded up to the nominal flow and a control law that ensures local tracking is adopted. Conversely, when the global controller is active, the reference trajectory is slowed down and the controller guarantees stabilization considering saturation constraints.

COMPUTATIONAL GUIDANCE FOR LOW-THRUST SPACECRAFT IN DEEP SPACE BASED ON CONVEX OPTIMIZATION

Christian Hofmann – Supervisor: Prof. Francesco Topputo

The current landscape of space exploration is evolving rapidly, with increasing interest in new technologies and applications, particularly in the exploration of minor and major bodies in deep space. CubeSats, a class of nanosatellites, have emerged as a low-cost alternative to conventional spacecraft. Despite their limitations, recent successes such as NASA's MarCO mission have demonstrated the feasibility of interplanetary CubeSats, leading to expectations of a significant increase in small deep-space probes in the near future. This trend is expected to make interplanetary missions more economically viable, paving the way for new discoveries in our solar system. However, the current standard practice of operating spacecraft from ground encounters challenges such as the saturation of ground facilities, high costs, and manpower requirements. Consequently, there is an urgent need for autonomous guidance, navigation, and control (GNC), especially for long-duration transfers in unknown environments where onboard decision-making is crucial due to communication delays and limited bandwidth. This paradigm shift, known as computational guidance and control, involves

performing these flight-related tasks onboard without human intervention, utilizing iterative numerical algorithms for real-time optimization. However, the transition towards autonomous GNC represents just the beginning of a new era in space exploration where self-driving spacecraft become a reality. This dissertation focuses on the guidance design, emphasizing the need for real-time trajectory computation in uncertain environments. In this investigation, convex optimization techniques are used to enhance the optimization of interplanetary low-thrust trajectories in terms of reliability, accuracy, robustness, and computational efficiency, with particular focus on onboard applications. A guidance approach is developed where trajectory optimization and guidance are combined to recompute the trajectory onboard when needed. Instead of directly solving the nonlinear optimal control problem, it is approximated as a convex problem to reduce computational effort and enhance convergence. Sequential convex programming (SCP) is employed to attain a solution satisfying all nonlinear constraints. Two key aspects of

SCP, discretization and trust-region methods, significantly impact results, especially convergence properties. Convex formulations of the adaptive Radau pseudospectral method are developed, in both differential and integral forms, and compared with other collocation methods. Various hard and soft trust-region methods are presented and evaluated, with the first-order method and an adaptive hard trust-region strategy often offering the best compromise in terms of convergence, accuracy, and optimality for the considered problems. Additionally, the choice of the coordinate set significantly impacts the performance of numerical methods for problems in astrodynamics. This work introduces modified orbital elements (MOE) and non-minimal Kustaanheimo-Stiefel coordinates for low-thrust trajectory optimization, leveraging the linearization of the Keplerian system. Time regularizations are applied to formulate a convexified optimal control problem. A thorough assessment of these coordinates' convergence and performance properties is conducted, with MOE emerging as an excellent choice for preliminary studies due to their rapid speed and

robustness. In order to reliably solve problems with high-fidelity models, a homotopic approach is developed in this dissertation. This method incrementally increases the problem complexity, incorporating n-body dynamics, solar radiation pressure, and variable specific impulse and maximum thrust into the SCP algorithm. Unlike standard homotopic approaches, the homotopic parameter's step size is dynamically adjusted based on the maximum constraint violation. This ensures a gradual increase of the perturbing accelerations and introduces a mapping from lower to higher thrust levels, improving convergence for complex problems. Simulations demonstrate that incrementally increasing the dynamical model's complexity significantly enhances convergence. Additionally, an adaptive trust-region technique expands the algorithm's accessible region, while a bang-bang mesh refinement procedure accurately determines fuel-optimal control profiles, further enhancing convergence and accuracy. A typical transfer trajectory and thrust profile for a

transfer to asteroid Dionysus are shown in Figure 1.

In the autonomous guidance scenario, spacecraft autonomously determine their reference trajectories in real time. A deep-space closed-loop guidance approach is proposed that combines trajectory optimization and guidance, with control actions repeatedly reoptimized onboard instead of tracking a given reference trajectory. Operational constraints like duty cycle constraints are included, and time-varying endpoint constraints using planetary ephemeris are considered. A processor-in-the-loop experiment assesses the performance of the SCP algorithm on hardware akin to spaceflight processors, demonstrating reliable trajectory computation within an acceptable CPU time of approximately one minute per optimization, even in the face of large, unexpected disturbances, making it a promising candidate for real space missions. Achieving an optimal solution remains challenging in case of highly nonlinear dynamics and complex constraints. While

many constraints can be relaxed and convexified, effectively handling nonlinear dynamics is difficult. Typically, dynamics are approximated using a first-order Taylor series, limited to local approximations. To address this, research into Koopman operator theory was conducted at the Massachusetts Institute of Technology. This theory transforms nonlinear systems into linear ones by elevating them into a higher-dimensional space. In this context, external controls are included in the formalism, and methods for bilinearization and linearization of nonlinear dynamical systems are explored.

In conclusion, the methods developed in this dissertation enhance the reliability, accuracy, robustness, and computational efficiency of low-thrust trajectory optimization. The findings of this research can serve as a valuable contribution to the field of computational guidance for spacecraft equipped with low-thrust propulsion systems.

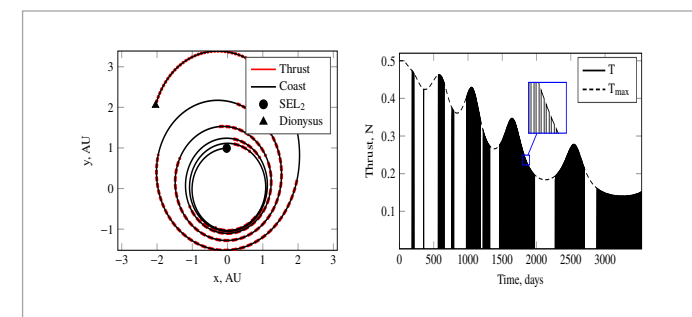


Fig.1 - Transfer trajectory (left) and thrust profile (right) for a transfer to asteroid Dionysus.

DATA-DRIVEN IMAGE PROCESSING FOR ENHANCED VISION-BASED APPLICATIONS AROUND SMALL BODIES WITH MACHINE LEARNING

Mattia Pugliatti – Supervisor: Prof. Francesco Topputo

The space sector is undergoing rapid growth, especially in near-Earth orbits, promising unprecedented benefits through integrated space-based services. At the same time, CubeSats are reshaping deep space by diversifying scientific objectives and complementing traditional missions. Profiting from this favorable environment, a surge in deep-space missions dedicated to the exploration and exploitation of the Solar System is on the horizon. Within this context, small celestial bodies, such as asteroids and comets, emerge as intriguing targets due to their abundance, proximity to Earth's orbit, ancient origins, importance for planetary defense, potential for resource utilization, and the quest for extraterrestrial life. However, the operation of a large fleet of spacecraft exploring these deep space bodies poses critical challenges when approached with the current ground-based paradigm. Driven by the need for real-time decision-making and cost-effective solutions, technological advancements are gearing towards autonomous spacecraft operations. Within this context, artificial intelligence enhancements on computer vision tasks are posed to enrich perception

and spatial comprehension of the surrounding environment, enabling intelligent spacecraft to operate effortlessly and autonomously. In this regard, in this research convolutional architectures such as the one schematized in Figure 1, are investigated for different applications around small bodies. Amongst the most interesting ones, image segmentation and visual-based navigation represent

the most challenging and promising and are thus extensively investigated using neural networks and machine learning approaches. Image segmentation is proven to be easily implemented for onboard applications to distinguish several morphological layers of a small body surface, as illustrated in Figure 2. Deep-learning centroiding networks can successfully be employed for navigation purposes both around

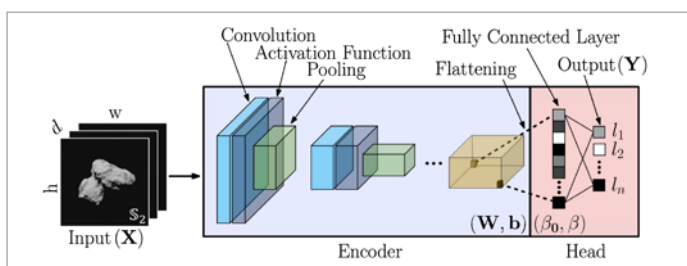


Fig.1- Example of a Convolutional Neural Network architecture.

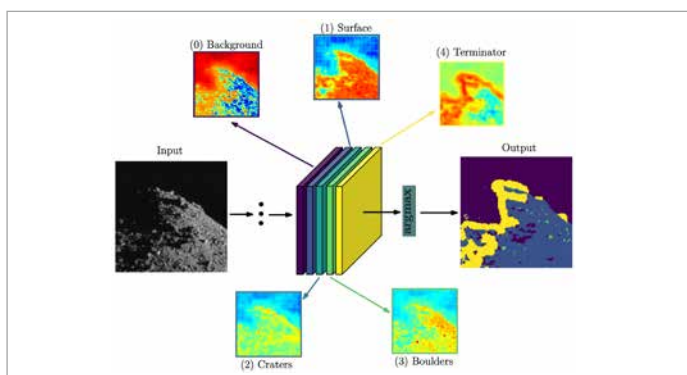


Fig. 2 - Example of small-body segmentation masks.

irregular and regular shapes. Data-driven image processing options are also assessed for the future CubeSat mission Milani, which will visit the Didymos binary system. Milani's semi-autonomous vision-based capabilities pave the way for adopting data-driven algorithms in deep space. As illustrated in Figure 3, the data-driven image processing pipeline of Milani performs better than traditional approaches and at the same level of performance as feed-forward neural networks. At the same time, convolutional architectures outperform both approaches with unprecedented performance for centroiding estimation. Assessing the performance of these techniques is as important as highlighting their drawbacks and the challenges associated with their development, primarily related to the availability of

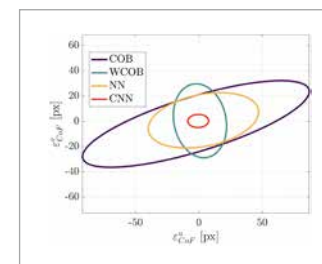


Fig. 3 - Centroid performance comparison between traditional (COB and WCOB) and deep-learning methods (NN and CNN).

high-quality training data. The integration of artificial intelligence and autonomous capabilities holds the potential to revolutionize our engagement with minor bodies, shaping the future of space exploration.

A MID-FIDELITY AEROELASTIC ENVIRONMENT FOR TILTROTOR ANALYSIS AND DESIGN

Alberto Savino – Supervisor: Prof. Vincenzo Muscarello

Rotary-wing vehicles like tiltrotors pose a significant challenge for engineers and scientists. To develop new aircraft designs, it is crucial to conduct complete aeroelastic simulations that account for the interaction between the aerodynamics of the rotating wings and the structural dynamics of the vehicle. Additionally, in order to gain deeper insights into the vehicle's performance and guide the design process effectively, it is important to have a thorough understanding of the airflow around the aircraft. The purpose of the research work presented in the thesis is to build and obtain a numerical environment for aeroelastic simulations suitable for complex vehicles such as tiltrotors. The tool aims to position itself among various branches already widely established and explored by the research and aviation sector in general, such as the aerodynamic, aeroelastic, aeromechanical, and design fields. The underlying idea is to provide an environment in which different analyses can be carried out at the same time, thus allowing a complete understanding of the machine's behavior already in the preliminary design phase. To achieve this, a mid-fidelity aerodynamic solver based on the vortex particle method for

wake modeling, DUST, is coupled through the partitioned multi-physics coupling library preCICE to a multibody dynamics code, MBDyn. By utilizing a multibody structural model in combination with mid-fidelity numerical software, the method allowed for accurate assessment of aerodynamic interaction effects inherent in rotary-wing aircraft while maintaining a cost-effective approach when compared to traditional and more sophisticated CSD/CFD tools. All of this was done with an open-source approach in order to provide the research community with an accessible and usable tool that can be developed in the future to enhance its capabilities for upcoming studies. The new developed numeric tool has been implemented and validated by comparing their results considering a classic aeroelastic benchmark of wing. Validation tests revealed that providing a more precise explanation of aerodynamics is crucial for replicating the dynamic performance of a

wedged wing during flutter state with detail. Particular attention has been dedicated to the solution of the aerodynamic part in order to demonstrate its abilities and limitations in typical configurations of the interactional aerodynamics present in tiltrotors and in VTOL vehicles, through comparisons with numerical and experimental literature data. In general, the results of DUST simulations showed the capability to obtain a degree of accuracy, respecting the limits of the theory on which the code is based, similar to the high-fidelity CFD approach, but at a much lower computational cost. Furthermore, the strength of the DUST approach based on the description of the free wake, has been demonstrated to be the ability to capture the physics of the flow field around the aircraft, a fundamental factor for understanding and investigating different designs in the preliminary phase. This result further highlighted the potential of the implemented approach for the design and investigation

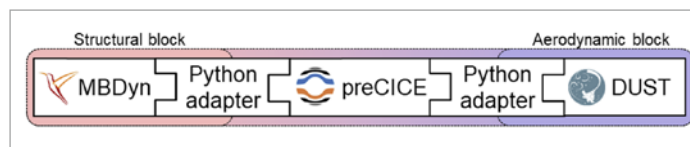


Fig. 1 - scheme of the communication between MBDyn and DUST.

of rotorcraft configurations. To demonstrate the modeling flexibility and the type of results that can be achieved, a complete aeroservoelastic tiltrotor model has been implemented. Thanks to the large amount of public data, the XV-15 tiltrotor aircraft equipped with Advanced Technology Blade (ATB) is chosen. In order to highlight the advantages of a more complete and realistic modeling, different hybrid models with different levels of complexity were used. Globally, a good correlation was reached in the analysis for the entire system with literature data. The transient roll maneuver of a complete tiltrotor aircraft is performed, to show the capability of the coupled solver to analyze the aeroelasticity of complex rotorcraft configurations. Simulation results show the importance of the accurate representation of rotary wing aerodynamics provided by

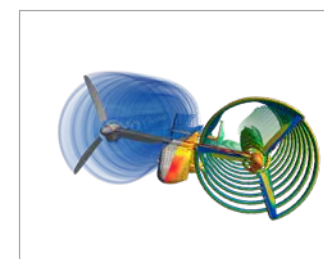


Fig. 2 - aeroservoelastic model of the XV-15 tiltrotor.

the vortex particle method for loads evaluation, aeroelastic stability assessment and analysis of transient maneuvers of aircraft configurations. This work represents a significant advancement in the scientific and industrial community by introducing a novel perspective on coupled simulations utilizing a mid-fidelity aerodynamic solver. The results of this study demonstrate that this approach can yield highly accurate results while utilizing substantially less computational effort than conventional, higher-fidelity CSD tools. The numerical environment that was developed has broad applications across various branches of aeronautical projects and beyond, such as in wind energy and turbomachinery applications.

MULTIPLE SATELLITES FORMATION FLYING FOR EARTH OBSERVATION APPLICATIONS IN LOW EARTH ORBIT

Francesca Scala – Supervisors: Dr. Camilla Colombo, Dr. Gabriella Gaias

Earth observation has gained importance in the last decades to support daily life and better understand natural processes, driven by the need to study global climate changes. Most space agencies around the globe have developed sophisticated systems to collect data about planet Earth based on microwave, optical or magnetometer sensors. Currently, several missions carry synthetic aperture radars (SAR) or interferometers to measure key parameters in the microwave range. However, most of these missions, such as Cloudsat, MetOp, SMOS, SMAP and many others, are based on a monolithic satellite architecture. This approach limits the potentiality to improve data quality and spatial resolution to monitor natural events: with a monolithic approach, this can only be obtained by employing rather large antennas. The introduction of constellations and distributed systems promises a significant improvement in data quality and coverage. In the context of active SAR, few mission concepts have been developed based on distributed systems improving scientific data quality by observing the same terrain area from different platforms. One example is the TanDEM-X - TerraSAR-X mission launched in

2010 by the German Aerospace Center. On the other hand, no distributed missions carrying passive radiometers have been designed and launched, and few studies are currently available to design such missions. There are several research and technological challenges connected to these mission concepts. First, vehicles should be separated by a few tens of meters to perform passive interferometry with a swarm/formation, which indeed triggers many difficulties in operating such space systems. Second, precise navigation and control techniques are required, even for the real-time relative guidance, navigation, and control subsystem. In this thesis, we start from these challenges and assess to what extent distributed missions can be realistically implemented to improve the spatial resolution of passive interferometers. Consequently,

the research questions regard how we can design guidance, navigations and control techniques to support distributed systems compliant with the need for on-board autonomy and robust control techniques to fill the current gap in the literature. This work proposes a preliminary mission design technique to enable future distributed multi-satellite systems for high-resolution interferometry and to understand how operational and payload constraints can be included in the design from the early phases of the process (see figure 1). To this end, first, the needs for future mission concepts for microwave observations are identified, and different cluster geometries are analysed in terms of performances achievable by the combined scientific instrument. Then, the generation of guidance profiles for the maintenance and reconfiguration

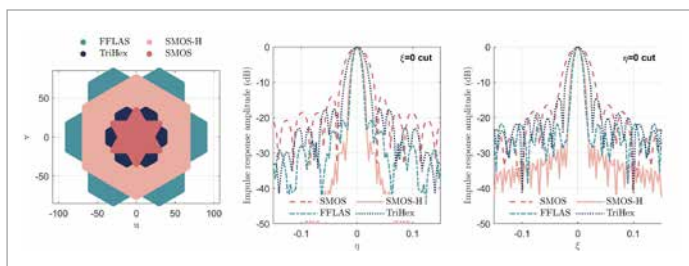


Fig. 1 - Comparison of visibility and impulse response for single and multiple satellites

of a formation is addressed. The latter is designed based on a convex description of the fuel optimal problem employing a continuous control law. Such a computation of the relative trajectory is then embedded into a relative guidance, navigation and control framework to simulate in a reliable, robust, and fast way the overall achievable performances of the distributed system, including operational requirements (see one example of formation reconfiguration in figure 2). Finally, the methodology is applied to test case studies involving active and passive microwave-distributed systems. As a result, this research provides a possible baseline for mission analysis design and preliminary outcomes of passive microwave applications, including typical control and navigation errors. This dissertation shows that indeed distributed systems can be designed to support future

missions carrying microwave antennas and future cluster studies. In addition to the results associated with the specifically investigated microwave architectures, the significance of this study relies on the flexibility of the developed methodology, which can be applied to several multiple-spacecraft formation concepts, not only in the Earth observation field. Furthermore, the proposed approach can be extended to other orbital regions and space applications, opening the path for new passive microwave remote sensing applications.

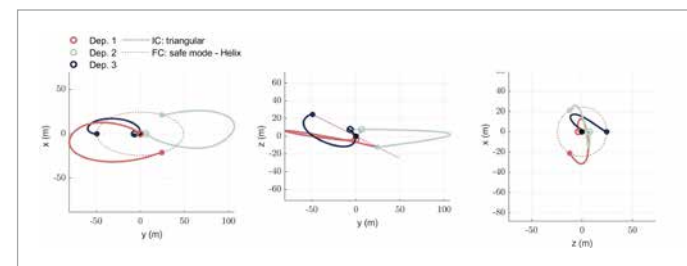


Fig. 2 - Example of reconfiguration manoeuvre between a triangular and helix relative geometry.

CONCEPTUAL DESIGN OF WINDPLANES

Filippo Trevisi – Supervisors: Prof. Alessandro Croce



Fig. 1

Windplanes can be understood as an evolution of conventional wind turbines. In this thesis, the conceptual design of windplanes is investigated by addressing two main research questions. The first research question is “Given a wingspan, which design maximizes power?”. The windplane is idealized as a point mass flying circular trajectories. If gravity is removed from the model, the dynamic problem is axial symmetric and the solution is steady. The generated power can be expressed in non-dimensional form by normalizing it with the wind power passing through a disk with radius the wingspan. Since the reference area is taken to be a function of just the wingspan, looking for the design which maximizes this power coefficient addresses the

first main research question. The optimal designs have a finite aspect ratio and operate at the maximum lift-to-drag ratio of the airfoil. Airfoils maximizing the lift-to-drag ratio are then optimal for windplanes. If gravity is included in the model, the gravitational potential energy is being exchanged with the kinetic energy, the aerodynamic energy and the electric energy over one revolution. Since this exchange comes with an associated efficiency, the plane mass and the related trajectory are designed to reduce the potential energy fluctuating over the loop. Reducing the potential energy means reducing the turning radius and the mass. However, for decreasing turning radii, the available wind power decreases because the windplane sweeps

a lower area. For these two conflicting reasons, the optimal mass is finite. Depending on the independent variables, extremely light designs might then not be required. High power coefficients can be obtained even at low wind speeds.

The second research question is “Can windplanes fly stable orbits?”. The windplane is modeled as a rigid-body with an aerodynamic model analytically linearized about non-linear operating points and subject to gravity. The nonlinear equations of motion are solved with a harmonic balance method to look for periodic solutions. If the gravity is removed from the model, the problem has a steady solution. The windplane is trimmed in the circular crosswind trajectory which maximizes the swept area. The vertical stabilizer pushes outwards, to compensate for the yaw moment induced by the centrifugal force. If the gravity is included in the model, the simplest control strategy is to trim the horizontal stabilizer, the vertical stabilizer and the turbine thrust coefficient to constant values, to actuate the ailerons cyclically and to control the vertical stabilizer in closed loop. The cyclic control of the ailerons rolls the plane and redirects the lift to compensate gravity and

to stay airborne. The vertical stabilizer is controlled in closed loop to increase directional stability and damp the precession mode. A moderate reduction in power coefficient between the steady case and the dynamic case with this simple control is found at low wind speed. A complete stability analysis is carried out, showing that the pendulum mode is lightly damped and the precession mode needs feed-back control.

The development of a reference economic model for airborne wind energy has been initiated and will be concluded in the near future.

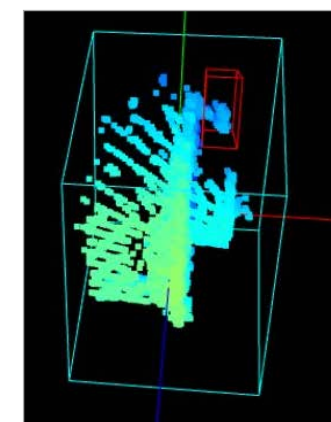


Fig. 3 – LIDAR-based relative pose estimation during capture of uncooperative spacecraft, tested on experimental data.

PLANETARY RESOURCES HANDLING FOR OXYGEN EXTRACTION: NUMERICAL MODELING AND EXPERIMENTS TOWARDS A PILOT PLANT DESIGN

Ivan Troisi – Supervisor: Prof. Michèle Roberta Lavagna

According to the recent plans of the space community, lunar missions are continuously getting more attention. Indeed, a concurrence of motivations like scientific needs, technology demonstrations and political reasons, make the Moon an ideal candidate. Furthermore, in the optic of human space exploration, the imminent retirement of the International Space Station and the Mars Race require a close but significant environment to settle new bases and test the key technologies. In Situ Resource Utilisation (ISRU) is one of these: it allows to locally produce what is needed to sustain the mission: life-support elements, construction materials, propellants... The largest available resource on the Moon is regolith, a layer of fragmental and unconsolidated rock material with a mean grain size of 60-80 μm and different compositional features according to the area. Everywhere, its major constituent is oxygen, that can reach about 45wt% of concentration. As on the Moon there is not an atmosphere that can sustain life or accessible water reserves, the focus of this research is on the extraction of the high quantity of oxygen embedded in the minerals and oxides of the lunar regolith. There are several

oxygen extraction processes currently under study from different research groups, such as the Fray-Farthing-Chen Cambridge (FFC) process, Solar Vacuum Pyrolysis (SVP) and the carbothermal reduction of molten regolith, as well as studies on the direct volatiles extraction. The research presented in the thesis is mainly focused on the carbothermal reduction of the lunar regolith through a methane/hydrogen gas mixture. Differently from the previously explored molten solution, it is carried out at low temperatures, < 1200°C. This avoids the melting of the batch, reducing some complexities deriving from a high temperature molten phase handling. Attention is also dedicated to some of the other extraction techniques,

not only to widen the horizons on the topic, but also to have a close view on their criticalities and advantages. In this way, it is possible to critically reason on the methods and transfer best practices and ideas among them. The thesis work aims at making a step forward in the demonstration, modeling and implementation of the available technologies, trying to answer the following research objectives. *Investigation of the most promising methods for oxygen/water extraction. Which are their advantages, criticality and which technological solution can be transferred to other methods to enhance the whole utilization procedure?* The community can benefit from a multiplicity of solutions

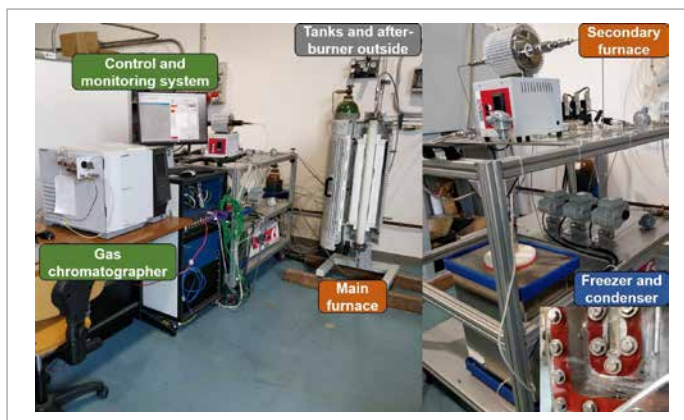


Fig. 1 - Optimal slew maneuver with keep-out cones

under investigation. A deeper understanding of their advantages and disadvantages is performed through the study of the most critical or interesting aspect with different methods: bibliographic review, modeling and experiments. Three processes are selected for this aim: Fray-Farthing-Chen Cambridge (FFC) process, Solar Vacuum Pyrolysis (SVP) and the Carbothermal Reduction of Regolith. The study on the SVP method is carried out during a visiting period at the European Astronaut Center (ESA) in Cologne, Germany.

The investigation then focuses on the last one, the carbothermal reduction, studied at Politecnico di Milano since the beginning of the previous decade. At the beginning of the Ph.D. period, a demonstrator plant was in the final part of its construction. This led to the second research objective. *After the demonstrator plant construction finalization, verification and performance characterization, which are the low-temperature carbothermal reduction governing parameters? How does the reaction behave when they are varied, identifying a way to maximize the yield? Can the process be modeled?*

Attention is dedicated to the demonstrator plant construction and to the verification of the expected performances. Once the plant, in Fig. 1, is operative, experiments are conducted on the plant varying what are identified as the process governing parameters. An experimental campaign aimed at inspecting in particular some of them, with the focus on the consolidation of a first baseline set of parameters. On the basis of these experiments, different modeling strategies are adopted to have a first model to use for the other objectives. After the understanding of the process, one of the main concerns of an ISRU process is to make it self-sustainable, with a limited supply of consumables from Earth. So, the third objective is here reported. *Can the process be considered self-sustainable, with a limited intervention from Earth? How the gases H_2/CH_4 can be reused in the process? Can the deposited, not-reacted, coke be recovered or used for other purposes?* To this aim, an investigation of the gas cycle closure strategies, from the separation techniques to a simulation of the control laws is done. Then, an analysis of the deposited coke and its recovery/utilization strategies

is performed, exploiting also the knowledge gained during the other processes investigation. The final and fourth objective is to understand if the process is scalable, in both directions, for a real plant design or for a scaled initial demonstration. *Is the process scalable in both directions, according to process yield and technological implications? In view of a downscaling of the process for a demonstration test, necessary before thinking to a full-size plant, which are the main constraints and criticality?* Starting from the results of the experiments and of the models developed, the most critical aspects in the design of a scaled payload are faced. The design and trade-off constraints are fixed by a possible demonstration on a commercial lunar lander.

All these challenges and the future steps to be performed in this context are of inspiration for the research, and not a blocking point. And if they are faced as a community, each of us giving its contribution, the result can only be great and unheard-of.