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 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 | 2023

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 competences (at least 10 credits), on themes specific of 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.
For the completion of 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 year, 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 in the course of the past 35+ years of 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 awarded more than 150 PhDs.

DOCTORAL PROGRAM BOARD		
Antonella ABBÀ	Pierluigi DI LIZIA	Marco MORANDINI
Franco AUTERI	Lorenzo DOZIO	Federico PISCAGLIA
Franco BERNELLI ZAZZERA	Antonio GRANDE	Maurizio QUADRIO
Paolo BETTINI	Alberto GUARDONE	Carlo RIBOLDI
Stefano CACCIOLA	Michèle LAVAGNA	Giuseppe SALA
Camilla COLOMBO	Marco LOVERA	Francesco TOPPUTO
Giovanni CONSOLATI	Filippo MAGGI	Riccardo VESCOVINI
Luca DI LANDRO	Mauro MASSARI	Alex ZANOTTI

ADVISORY BOARD
Valerio Cioffi, Leonardo Aeronautica
Gian Paolo Dallara, Dallara
Luca Medici, Leonardo Elicotteri
Marco Molina, SITAEL
Franco Ongaro, Estec
Matteo Ragazzi, Leonardo Elicotteri
Grazia Vittadini, Rolls-Royce

SCHOLARSHIP SPONSORS	
ANT-X	Italian Space Agency, ASI
BV-Tech	Istituto Nazionale di Astrofisica, INAF
Continental	Leonardo SpA
D-Orbit Spa	MBDA
Eumetsat	Thales Alenia Space-Italy
European Space Agency, ESA	Tyvak

EXPERIMENTAL AND NUMERICAL STUDIES ON PARTICLE AND FRICTION DAMPERS

Fabio Biondani - Supervisor: Prof. Marco Morandini

In these doctoral studies, two technologies for the passive damping of vibratory response were studied and analyzed in parallel. One is "particle damping", which is the dissipation of energy by means of collisions of particles enclosed in a box attached to a structure, the other is "friction damping", where damping is generated by exploiting dry friction generated between contacting surfaces in relative motion.
The control and attenuation of the vibratory response of structures are of great interest in many fields, including aerospace, mechanical, and earthquake engineering; the applications of this topic involve safety, reliability, durability, and also comfort. Control of vibrations is an essential tool to attenuate excessive oscillations, suppress undesirable resonances, and avoid fatigue failure.
Vibration damping techniques can be applied either actively or passively: although active damping has a broader operating range, it requires an external power supply and equipment.
Environmental conditions must also be considered: temperature constraints may hinder the application of sensors, actuators, and viscoelastic materials. This scenario is of particular interest in the aerospace and mechanical fields.
Particle and friction dampers address these concerns and share multiple advantages: they work in harsh environments, they are simple to fabricate, they can take up a small volume and be non-obstructive, they can be adapted to a wide range of frequencies, but they also have highly non-linear characteristics.
The research efforts for both technologies were focused on modeling and experimental characterization. The study of particle dampers and friction dampers presented different challenges due to the characteristics and phenomena involved in the dissipation mechanisms; therefore, the paths taken for the two technologies differ significantly.

Particle dampers can be built in countless ways; there is a huge number of design parameters. Furthermore, particle damping performance depends on the inner motion regime of the particles which cannot be described with analytical models, except for a few specific conditions.
For these reasons, the work on particle dampers has been focused on the efficient Discrete Element Method (DEM) modeling of particle dampers, and their validation through experiments and literature results. Particle dampers' DEM modeling was initially intended to be performed with Chrono; however, initial analyses showed that the version available at the time was time-consuming even in comparison to the commercial software Abaqus Explicit; therefore, a new DEM solver exploiting the GPU's computing capabilities was developed using CUDA.
The program, referred to as PMB, proved to be faster than the original choice of programs and also than the recent version of Chrono which includes GPU-computing capabilities.
In order to study the response of multibody systems with attached particle dampers, PMB was coupled to MBDyn with a loose co-simulation scheme. PMB's validation process involved different case studies compared with other DEM codes' results, experimental results, and the comparison of the simulated particles' motion regimes with literature.
Despite the adoption of GPU augmentation, the numerical study of particle damped structures remained costly enough to make parametric studies and optimizations difficult. Therefore, techniques to speed up the analyses without affecting significantly the analyses' damping estimations were analyzed:

- decrease of contact stiffness, considering the maximum overlap between particles and the natural frequency of the particles' contact;
- neglect the static friction in the simulated particle contacts by not memorizing contacts;
- compare the dissipation values for oscillations at given frequencies and amplitudes of standalone particle damper's simulations and coupled simulations, to explore the possibility to characterize a particle damped structure by simulating a structure and the accompanying particle damper separately.

Since particle damping is an extremely non-linear process and its response to a sinusoidal input may not be periodic, the performance of a particle damper was also analyzed statistically. Maps of dissipation dependent on amplitude and frequency for different particle dampers and for the identification of different "damping zones".
Finally, experimental investigations were performed both to help with numerical validation, and to explore the experimental domain where it was not yet explored in the literature; the effect of the mutual orientation of motion, gravity, and enclosure and of different inputs controlled to obtain imposed amplitudes is investigated. The experimental results were correlated using PMB coupled to MBDyn; to this end, a procedure to obtain efficiently the steady state response of a particle-damped structure subject to controlled oscillation amplitude was implemented.

The analyzed literature about friction dampers showed that great efforts have been taken to characterize and validate friction models. The activity of this research followed this trend; therefore, the initial intent was to experimentally characterize friction in metal-to-metal contacts and fit the experimental samples on existing friction models.
A fitting procedure to identify friction models' parameters was set up and tested with numerical produced samples; particular attention has been given to Dahl's and LuGre models.
Different experimental campaigns were undertaken with the goal of identifying the friction model's parameters. The experimental configurations were repeatedly improved after the analysis of the results highlighted problems and weak points in the setup.
The first campaign consisted of tests with four conformal contact surfaces; many issues were identified in this configuration; for instance, the application of the fitting procedure on the experimental samples did not result in conclusive values of the friction parameters.
Another notable issue was the uneven wear among the four contact surfaces; this issue led to the second experimental campaign that consisted in tests with only one conformal contact surface, a stiffer structure, and a great effort to make the contact surfaces as parallel as possible. This new configuration allowed the observation of different phenomena, such as an apparent evolution of the sliding friction coefficient with time; however, the contact surface still suffered uneven wear and the friction parameters could not be identified uniquely. The apparent evolution of the friction coefficient was validated also by a professional laboratory specialized in friction tests, contacted specifically.
Since the experiments showed that the identification of friction parameters with limited uncertainty could not be achieved, the research turned to the robust design of tuned mass dampers with friction.
An appropriate nondimensionalization and optimal response design curves of friction tuned mass dampers based on Dahl's model were obtained, the nondimensional parameters also consider the proximity to the sliding condition and the size of the presliding phase.
Considering that the maximum of the frequency response is most sensitive to the sliding friction coefficient and that the friction coefficient is greatly sensitive to wear, a robust optimization problem that considers the friction coefficient an epistemic variable has been set up. The optimization process consisted minimizing, for the variation of the stiction force, damper's tuning frequency, mass ratio, and sliding regime, the maximum of the frequency response of the friction tuned mass damper to a ground oscillation.
Finally, a case study was considered for the application of the developed theory and optimization techniques; the case study consists in a simply supported beam with a friction tuned mass damper to dampen the first bending mode of the beam. The friction tuned mass damper was optimized both deterministically and in a robust way.

COMPREHENSIVE MID-FIDELITY SIMULATION ENVIRONMENT FOR AEROELASTIC STABILITY ANALYSIS OF TILTROTOR WITH PILOT-IN-THE-LOOP

Alessandro Cocco - Supervisor: Prof. Pierangelo Masarati

Tiltrotor aircraft are challenging machines to design considering the various operating conditions and multipurpose missions that are expected to be performed by this complex type of aircraft. This machine combines the characteristic of a conventional turboprop aircraft with the vertical take-off and landing (VTOL) capability of a helicopter. In the past, some catastrophic accidents involved tiltrotors, which were caused by a combination of factors: complex three-dimensional unsteady aerodynamic flow field, structural loads, aeroelastic instabilities, and pilot control inputs. Therefore, the development of a comprehensive tool capable of capturing the combination of all these phenomena is of paramount importance for designing faster, lighter, and safer tiltrotors. The main objective of this work is to develop, validate, and evaluate the limits of aeroelastic and aeromechanical stability of a tiltrotor aircraft using a comprehensive approach in mid-fidelity.

Thanks to a large amount of freely available data, the Bell XV-15 tiltrotor equipped with Advanced Technology Blades (ATB) is chosen as a representative model; however, due to the modularity and parameterization of the model, other innovative rotary-wing configurations could be studied with the proposed approach. The model is built using a co-simulation approach based on the coupling between a mid-fidelity aerodynamic solver based on the vortex particle method for wake modeling, DUST, and the multibody dynamics code, MBDyn. This coupling is managed through the partitioned multiphysics coupling library preCICE.

In the first part of the work, the coupled tool is presented and validated by solving simple fixed-wing and rotary-wing problems from the open literature. In the second part, the multibody and aerodynamic modeling of each subcomponent, using the open-source software MBDyn and DUST, is illustrated and validated considering experimental and numerical results. Each subcomponent is extensively validated against the available results and, starting from these, they are extended to enable the validation with other analytical tools. Globally, a good correlation is reached in the dynamics analyses for the whole system. In particular, the coupled model shows great advantages in terms of computational time and accuracy concerning high-fidelity tools when used to estimate hover performance. A time-marching trim procedure is also proposed, and optimal longitudinal control of the tiltrotor is presented and validated to maintain altitude.

A detailed multibody biomechanical model of the upper body of a generic pilot is presented. It is made up of connecting a previously developed detailed model of the arms to a similarly detailed model of the spine. The entire model can be adapted to a specific subject identified by age, sex, weight, and height. The spine model and the scaling procedure are validated using experimental results for seat-to-head transmissibility. The coupled spine-arms model is used to evaluate the biodynamic response in terms of involuntary motion induced in the control inceptors, including related non-linearities.

Finally, the tiltrotor and pilot models are combined into a single comprehensive model in which the whirl flutter aeroelastic stability is investigated over the entire flight envelope, and the responses to discrete gusts were used to evaluate the effect of the pilot biomechanics and interactional aerodynamics. The results show that including an unsteady aerodynamic model is of paramount importance, especially when dealing with flight dynamics modes. This model enables a wide spectrum of different analyses: for example, this model will be used to study passenger comfort, and performance in transient maneuvers such as conversion and pull-up, aeroelastic stability, pilot-induced-oscillation, and pilot-augmented-oscillation phenomena. The coupled multibody-mid-fidelity tool can be used for performing the large number of aeroelastic analyses required in the preliminary design phase of innovative rotary-wing configurations, not only in the rotorcraft field but also in other domains, from wind energy to micro-aerial vehicles.

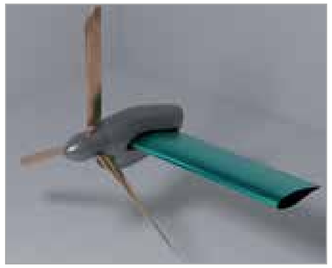

Fig. 1 - ATTILA multibody model

Fig. 2 - Upper body multibody model.

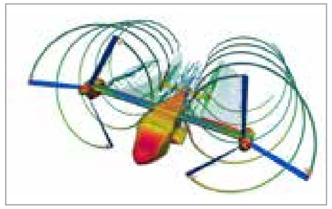

Fig. 3 - XV-15 MBDyn-DUST model during a rolling maneuver: wake visualization

UNDERSTANDING THE USE OF AUTOMATION IN HELICOPTERS

Daniel Friesen

Supervisors: Prof. Pierangelo Masarati, Dr. Marilena D. Pavel, Dr. Ir. Clark Borst

Helicopters possess the unique capability of hovering stationary in the air and landing with relative ease in a variety of terrain, which sets them apart from fixed-wing aircraft. However, due to operations close to terrain and obstacles, piloting a helicopter can be a challenging task that involves risk of incidents and accidents. One avenue to increase helicopter safety is providing improved cockpit automation functions which optimally support the pilots, such that they can react to every safety-critical situation to the best of their ability.
Throughout history, automation has brought tremendous improvements to human productivity. However, the effects of automation are not always beneficial. Automation can have a detrimental influence on manual control capabilities, the reaction time to safety-critical events, and workload, in particular in situations that have not been anticipated by the automation designer. It is therefore paramount that helicopter automation development takes the whole operational envelope into account, including off-nominal and unforeseen events.
Two distinct automation design philosophies are investigated in this dissertation: ecology-centred and task-centred automation. The ecology-centred or constraint-based design approach focuses on the ecology or work domain of the helicopter. It is based on ecological interface design, a methodology that, up until now, has not been widely applied in the helicopter domain. It aims to provide information about the underlying work domain structure and constraints, while leaving the final decision in the hands of the pilots. This design approach encourages robust control by providing a wide range of feasible solutions, with the pilots as the final decision-makers.
The task-centred or advisory design approach focuses on technology-centred automation capabilities. It aims to provide task-related information and optimal suggestions without disclosing the underlying reasoning. The given advice encourages optimal control by providing one specific suggested solution to the pilots.
How can these automation design philosophies improve helicopter safety at different timescales of operation? To answer this question, three subquestions are investigated: What are the peculiarities of helicopter automation; how do different automation design philosophies influence safety (and other parameters) in helicopters during short-, medium-, and long-term scenarios; and how can the experimental results be incorporated into guidelines for helicopter automation design? These questions are

Fig. 1 - Cockpit view of SIMONA Research Simulator.

Fig. 2 - Outside view of SIMONA Research Simulator.

first answered on separate timescales, utilising the results of four human-in-the-loop experiments performed in the SIMONA Research Simulator at Delft University of Technology (Figure 1, Figure 2). Afterwards, the results are discussed in the context of the whole operational envelope of helicopters.

To structure the work of this dissertation, two established automation classification methods are utilised: the level of automation and the stage of automation. These methods are extended with the level of control sophistication, which correlates with the timescale, complexity, and uncertainty of the task environments. Classifying automation systems in such a way enables the discovery of automation coverage clusters and gaps in the helicopter domain.
The experimental results show a significant negative impact of advisory automation on pilot decision-making during unexpected events (e.g., as shown in Figure 3). Constraint-based automation did not negatively impact the pilots' decision-making, but also failed to improve any of the other dependent metrics. This showcases the potential of constraint-based displays to avoid inadvertent automation effects, but also highlights their training and familiarisation issues.

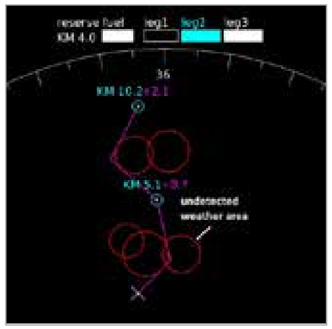

Fig. 3 - Advisory navigation display encountering an unexpected event.

NUMERICAL STUDY OF AERODYNAMIC AND AEROACOUSTIC METHODS BASED ON COMPUTATIONAL FLUID DYNAMICS FOR HELICOPTER ROTOR FLOWS: DEVELOPMENT, IMPLEMENTATION, AND VALIDATION ISSUES

Jinbin Fu - Supervisor: Prof. Luigi Vigevano

The simulation of helicopter rotor flows and the prediction of rotor impulsive noise are practically very challenging tasks from a computational perspective as the flight environment of a helicopter rotor contributes to extremely complex flow phenomenon and noise generation mechanisms, For instance, such rotor systems often experience the Blade-Vortex Interaction (BVI) phenomenon in low-speed descending flight, where the rotating blades interact with tip vortices shed from previous blades, resulting in obtrusive noise levels; and/or operate in high-speed flight conditions, where shock waves appear in the blade tip region, resulting in highly impulsive transonic noise. While analytical, semi-empirical, and low-fidelity numerical approaches can quickly provide results suitable for performance analysis, they are poorly predictive as these models are insufficient to fully resolve the complicated flow phenomenon described above. With this in mind, the present work combines Computational Fluid Dynamics (CFD) methods with the Ffowcs-Williams and Hawking (FW-H) acoustic analogy to accurately calculate the aerodynamics and aeroacoustics of helicopter rotors. The core of this dissertation is divided into three main parts; (i) construct and validate a simulation framework for helicopter rotor wake modeling and rotor noise prediction; (ii) implement the two vortex feature-based second vorticity confinement (VC2) models into the CFD solver ROSITA and assess the capabilities of these two models in three-dimensional dominated flows; (iii) develop a three-dimensional r-refinement method that effectively concentrates mesh points into regions of interest without mesh tangling for improving the vorticity preservation in helicopter rotor flows.

The first part of this thesis is dedicated to the construction and validation of the simulation framework for helicopter rotor aerodynamics and aeroacoustics. In this simulation framework, the CFD solver ROSITA is used for the simulation of helicopter rotor flows; a novel acoustic solver ROCAAP that employs the Retarded-Time based Permeable Surface FW-H (PS-FWH) equation for subsonic noise source and the Marching-Cube Emission-Surface (MCES) based PS-FWH equation for transonic/supersonic noise source is developed for noise prediction; a high-efficient rotor trim algorithm that combines the original delta trim algorithm with multiple levels of the grid and temporal resolutions is proposed for obtaining the trimmed rotor in forward flight. The validation work is then performed through a sequence of numerical test cases. Firstly, the acoustic solver is validated by comparing with analytical spherical monopole source solutions and the well-established WOPWOP solutions; three well-documented forward flight rotors are then employed to validate the rotor trim method; finally, the performance of the integrated simulation framework is demonstrated via the prediction of the transonic rotor noise and the BVI rotor noise.

In the second part, two locally normalized vortex feature detection techniques (non-dimensional Q and lambda_2 criteria) are combined with the original VC2 model, resulting in the FVC2-L2 and the FVC2-Q models, respectively. These two vortex feature-based VC2 models have been implemented into the CFD solver ROSITA and compared with the results of the standard CFD solver and those of the original VC2 model in two benchmark test cases (NACA0015 wing in steady state and Caradonna-Tung rotor in hover condition). The result shows that the performances of the feature-based VC2 models in terms of computational stability, aerodynamics prediction, vorticity preservation, and computational efficiency are significantly improved. In particular, the FVC2-L2 model allows using higher confinement parameter values to achieve better solutions than the FVC2-Q model. On this basis, the FVC2-L2 model is then adopted for the HART-II rotor descending flight case to enhance the prediction of the helicopter rotor BVI phenomenon. Afterward, the non-lifting UH-1H hovering rotor case and the AH-1/OLS forward flight case are employed to demonstrate the ability of the FVC2-L2 model to provide more reliable noise predictions than the non-VC models, even if there are no tip vortices shed from the blade tip.

The third part of this thesis describes an effective three-dimensional r-refinement method to improve the vorticity preservation in helicopter rotor flows. This approach relies on the Jacobian-weighted elliptic grid generation method, which derives from the combination of the variational principle and the least-square fitting of the inverse Jacobian matrix to the weight matrix. In this part, the original Jacobian-weighted elliptic method is extended from two dimensions to three, and the derivation of the weight matrix in three dimensions is presented for the first time. Several practical test examples are used to preliminary validate this three-dimensional method. The results show that this method is effective and reliable in generating grids without mesh tangling after the redistribution procedure. Furthermore, the potential of this method in the application of helicopter rotor flows is also demonstrated.

DEVELOPMENT OF NOVEL CFD METHODOLOGIES FOR THE OPTIMAL DESIGN OF MODERN GREEN PROPULSION SYSTEMS

Federico Ghioldi - Supervisor: Prof. Federico Piscaglia

The progressive increment of energy demand and CO2 emissions has produced severe environmental effects in the last five decades. For this reason, the signing of global agreements has indicated aggressive actions to promote decarbonization. Although energy transition cannot occur at the same pace in every sector, new solutions shall be provided to meet the demands of a more environmentally conscious society. Emission reduction can be accomplished by shifting to electrical systems, adopting carbon-neutral fuels, or letting these two options coexist. Both scenarios are addressed in this thesis.

Battery-powered electric propulsion systems are employed in various fields for numerous applications because they are characterized by a very precise control and response time. In Aerospace, they adjust the differential thrust control required to maneuver multirotor drones, fixed-wing unmanned aerial vehicles (UAVs), and Electric Vertical Takeoff and Landing (eVTOL) aircraft. Their design must include efficiency requirements and seek to minimize energy consumption. At the same time, the mitigation of the sensed thermal stress is fundamental to avoid an excessive reduction of the the electronics' lifetime. For that, systems should be optimized overall. Unconstrained optimization performed via Computational Fluid Dynamic (CFD) simulations is expensive. Thus, an analytical optimization methodology is developed to quickly and reliably predict the overall best configuration or severely limit the range of admissible layouts while reducing the computational cost and time. The electric configuration is subdivided into two zones: the solid heat spreader and the below cooling channel; each has its own characterization and optimization. First, the temperature distribution in the whole solid domain is predicted by the solution of the steady-state anisotropic Laplace's heat equation via closed-form expressions structured on Fourier expansion series. Next, the thermal resistance is computed via the Influence Coefficient Method for rectangular structures; for pyramidal compound systems an approximation is proposed. Finally, an automatic multi-variable optimization (MVO) of the solid top region is performed thanks to the bounded Limited-Memory BFGS algorithm (Fig. 1). In the below cooling channel, multiple arrangements of heat promoters are analytically compared. The characterization of the fluid domain is bonded by the accuracy of semi-empirical correlations available in the literature for pressure drop and heat transfer. Its optimization is performed by minimization of the entropy generated due to irreversibilities (EGM approach). Overall optimization of the configuration is obtained by coupling the two stand-alone minimization procedures.

On the other hand, in hard-to-abate sectors, biofuels or carbon-neutral propellants represent the key to enabling the transition to a low-carbon and resource-efficient combustion. However, the use of new reactive mixtures can induce a forced upgrade of the propulsion systems currently employed. This translates into the need to carry out new tests, experiments, or CFD simulations. The latter are affected by a severe increment of cost, caused (among other reasons) by the solution of Ns additional species conservation equations on top of the governing equations for the fluid flow. Plus, a complex stiff set of ordinary differential equations (ODEs) is present due to the finite-rate reaction mechanism developing in the domain. The large number of cells, the required stringent CFL criterion, and the need to preserve numerical stability for ODE integration severely limit the time step advancement. Hence, the computational time required by reacting flow simulations is the primary bottleneck in industrial and academic studies today and in the foreseeable future even on supercomputers unless CFD algorithm developments are made to produce significant time step accelerations. The research for methodologies to speed up the overall reactive-flow computation has increased the awareness in the combustion and software developer community to exploit the available fine-grain parallelism provided by Graphics Processing Units (GPUs). The novel heterogeneous paradigm proposed in this thesis allows rapidly and reliably performing reactive CFD simulation campaigns while taking advantage of the most advanced apparatus available in modern GPU-accelerated high-availability clusters (Fig. 2). Due to the hybrid architecture, a revision is required of the coupling strategy between the fluid transport and the chemistry problem in solvers based on the operator-splitting technique. Direct integration of the finite-rate chemistry problem on GPUs implies the use of an algebraically stabilized fast explicit approach. An explicit Runge-Kutta method with adaptive time-stepping is selected to fully exploit the capabilities of the device (GPU). The explicit nature of the code permits a parallelization of both chemical kinetics and fluid mechanics. More precisely, the parallelization of the chemistry problem is performed both on the size of the mesh and of the mechanism. Because of the object oriented nature of the framework, the new heterogeneous method for Direct Integration (DI) of finite-rate chemistry problems can be linked to any flow solver to simulate different types of flow regimes.

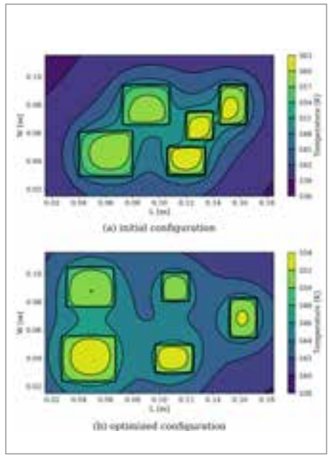

Fig. 1 - The MVO process minimizes thermal stress by relocating the electronics.

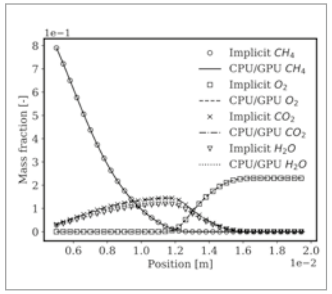

Fig. 2 - Evolution of the chemical species over an axial line in a counter flow flame simulation.

CLOUD TURBULENCE MICROPHYSICS AT INTERFACES: A DNS MODEL WITH PHASE CHANGE AND DROPLET INTERACTION

Mina Golshan - Supervisors: Prof. Antonella Abbà, Prof. Daniela Tordella

Clouds play a major role in meteorology and climate, due to their fundamental role in maintaining Earth's energy budget, by regulating the amount of solar energy that reaches the surface and the amount of the Earth's energy that is radiated back into space. Therefore, understanding how microphysical processes impact cloud generation and evolution is an important aspect of atmospheric physics and is still an open question. The complexity of the phenomenon is linked to the simultaneous action of many factors, including the evolution of atmospheric aerosols, interactions with water vapor, and associated unstable processes such as nucleation, condensation, evaporation, collision, and fragmentation of water droplets, all of which play a significant role in shaping the microphysical properties of clouds. The aforementioned main processes occur mainly in turbulent background airflow. Recently, the cloud boundary within cloud environments has attracted considerable interest. The specific study of these interfaces leads to essential results that can bring rapid progress in the assessment of cloud dynamics. These kinds of interfaces are significant examples of inhomogeneity and anisotropy within turbulent airflow. In the present work, I addressed a few problems in the area of small-scale cloud dynamics, using direct numerical simulations to study the temporal evolution of a perturbation located in the turbulent layer that generally separates a cloud from the surrounding clear air.

The second part of the research is related to in-field experimentation using the mini green radiosondes developed in H2020 COMPLETE Marie Curie Network (http:// www.complete-h2020network.eu).
In the first part, an initial value problem is considered, where the temporal evolution of an initial distribution of turbulent kinetic energy, temperature, humidity, and droplet distributions are observed. A sufficiently intense stratification was observed to change the mixing dynamics. The formation of a sub-layer inside the shear-less layer was observed.

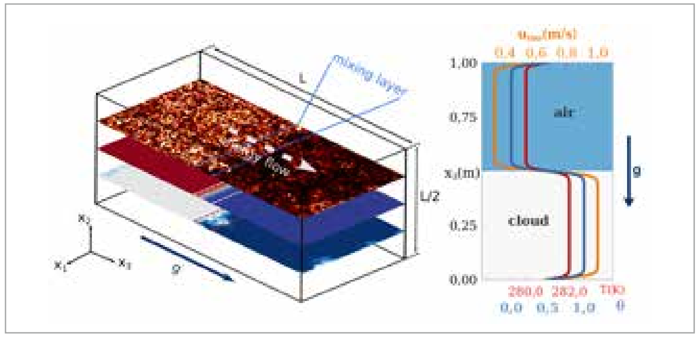

Fig. 1 - (a) Schematics of a flow inside the simulation domain. The energy flow is from left to right along the x3 direction. E1/E2 = 10

The sub-layer, under a stable thermal stratification condition, behaved like a pit of kinetic energy. However, it was observed that turbulent kinetic energy transient growth took place under unstable conditions, which led to the formation of an energy peak just below the center of the shearless layer. A monodisperse droplet population with a radius of 15 μm and a polydisperse distribution with radii within the 0.6 – 40 μm range. Polydispersity has shown a different behavior in droplet evaporation and condensation both within the homogeneous cloudy region and in the anisotropic interface mixing zone for both distributions. However, the two populations show a common aspect in the course of the transient, that is, an increased probability of collisions within the interface layer, which exhibits a marked anisotropic velocity fluctuation. These DNSs show that supersaturation fluctuations broaden the droplet size distribution and induce an increase in the collision rate. This result is in contrast to the classical growth of (non-turbulent) condensation, which leads to an increase in the average droplet size but also to a narrower droplet distribution. It was also found that although the turbulent kinetic energy of the airflow hosting the cloud decreased by 90 % over the course of the simulation, the collision activity decreased by 40% inside the cloud but increased by 25% in the mixing area of the interaction. The size distribution of the number density of the droplets for the initially monodisperse population in the mixing layer showed a standard deviation growth 15 times faster than that in the cloud region. In the polydisperse case, the concentration distributions were oppositely skewed, and the width of the distributions decreased more rapidly (about four times) over time within the interface region than in the cloud. Moreover, for the monodisperse population, a clustering of the values of the reaction, phase, and evaporation times, that is around 20-30 seconds, is observed in the central area of the mixing layer, just before the location where the maximum value of the turbulent supersaturation flux occurs. This clustering of values is similar for the polydisperse population but also includes the condensation time. The mismatch between the time derivative of the supersaturation and the condensation term in the interfacial mixing layer is correlated with the planar covariance of the horizontal longitudinal velocity derivatives of the carrier airflow and the supersaturation field, thus suggesting that a quasi-linear relationship may exist between these quantities. In the second part, which contains in-field experimentation with radioprobes, is a preliminary result of ongoing work. It is mainly a proof-of-concept, and in the future, more variables could be measured by equipping the probes with suitable sensors. This part of the research is aimed to study the water droplet dispersion due to turbulence in warm clouds. The analysis is afforded by means of both experimental and numerical approaches. The radiosonde data post-processing is based on distance-neighbor graphs, which was the original statistical analysis proposed by L.F. Richardson in 1926. While the first part of the work deals with DNSs and is limited to small-scale dynamics, the second part, which is experiments with radio probes, was aimed at analyzing a few aspects of large-scale dispersion, which cannot be dealt with DNSs, and measuring in a Lagrangian way the state changes that a parcel of moist air undergoes in the atmosphere, thus providing a reference for numerical simulations. Therefore, the two parts reflect the same point of view on the same research work, i.e., the interaction between droplets and turbulence is seen from a different timescale.

LEARNING-BASED CONTROL FOR AEROSPACE SYSTEMS: METHODS AND APPLICATIONS.

Salvatore Meraglia - Supervisor: Prof. Marco Lovera

Nowadays, researchers strive to design systems that can operate autonomously in safety-critical applications, such as, *e.g*, unmanned aerial vehicles and space systems. To ensure a predictable system response and safe operation, reliable control of these systems needs not only to meet performance specifications under nominal conditions, but also to accommodate graceful performance degradation when underlying assumptions are violated.

This dissertation focuses on the development, simulation and experimental validation of various control algorithms for aerospace systems, ranging from small UAVs to satellites with large rotating antennas. The main contribution is the development of systematic approaches that integrate the experience gathered during the operation (*data-driven* knowledge) into a classic (*model-based*) control framework. The thesis is structured so that the problem statements and proposed control solutions are addressed from a methodological and general point of view. Indeed, these solutions are specialized in the light of the particular case study only at the end.

The first Part of this work addresses two challenges for verifiable adaptive control systems, *i.e.*, the presence of actuator dynamics and systems with uncertain time-varying parameters. The resulting methods make it possible to check and satisfy different conditions such that the adaptive control system has performance and robustness guarantees. Finally, the proposed algorithms are specialized to a UAV position controller and an attitude controller for a spacecraft with time-varying inertial parameters (see Figure 1).

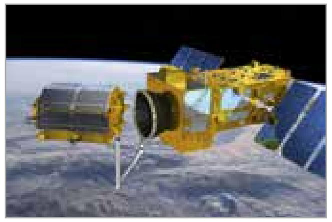

Fig. 1 - In-Orbit Servicing: Target Capture (Credits to ESA).

The second Part of this work is devoted to presenting and discussing two applications of HC algorithms. Specifically, an active balancing system for rotating orbital devices has been designed and a HC algorithm has been used to command the positions of the actuated masses. The main motivation behind this work is the Copernicus Imaging Microwave Radiometry (CIMR) mission which will feature a large rotating microwave radiometer (see Figure 2) to provide observations of sea-surface temperature, sea-ice concentration and sea-surface salinity. After extensive numerical simulations, a dedicated breadboard has been developed, and experimental validation of the control law has been carried out. Then, a second application of HC with a slightly different paradigm is presented. In particular, the HC framework is specialized in the helicopter rotor-induced vibration problem and the analysis of the interaction between the active control of structural response and a mast vibration absorber is done using a virtual helicopter model.

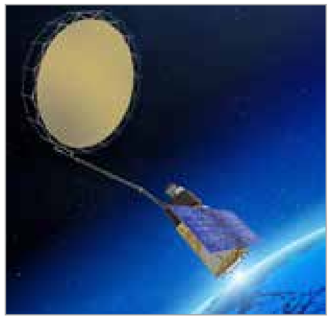

Fig. 2 - CIMR spacecraft (Credits to ESA).

The last Part of this work presents the novel Smoother-based ILC algorithm that takes advantage of the repetition of a specific task to improve performance from one trial to the next. The overall approach is schematized in Figure 3. This algorithm has been specialized to achieve high-performance trajectory tracking with UAVs, and an experimental campaign involving a small quadrotor has been carried out. However, the learning phase needed to apply such a technique is related to each specific system, thus making the application of ILC poorly scalable. To overcome this limitation, a novel H∞-optimization-based definition of a transfer map is proposed that allows transferring the knowledge acquired on a *source* system to a *target* system that needs to perform the same task. This transfer of data may be beneficial if the *source* system is less costly, difficult, or hazardous to operate than the *target* system. Furthermore, if multiple similar robots have to perform the same task, it is more cost-effective if one robot learns to perform the task and transfers its knowledge to the other robots. Experimental results demonstrate the effectiveness of the proposed approach in improving the tracking performance of a UAV transferring knowledge between different-scale UAVs.

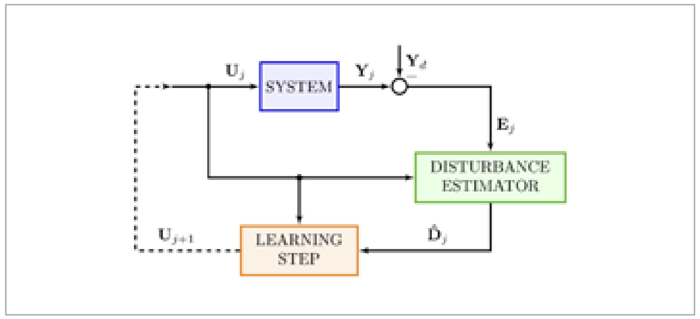

Fig. 3 - Block diagram of the proposed architecture.

ENGINEERING BALLISTIC CAPTURE FOR AUTONOMOUS INTERPLANETARY SPACECRAFT WITH LIMITED ONBOARD RESOURCES

Gianmario Merisio - Supervisor: Prof. Francesco Topputo

Current deep-space missions heavily count on ground-based operations. Although reliable, ground slots will saturate soon, so hampering the current momentum in space exploration. EXTREMA (short for *Engineering Extremely Rare Events in Astrodynamics for Deep-Space Missions in Autonomy*) is an ERC-funded project enabling self-driving spacecraft, thereby challenging the current paradigm under which spacecraft are piloted in interplanetary space. Deep-space guidance, navigation, and control (GNC) applied in a complex scenario is the subject of EXTREMA. Among others, the project aims to engineer ballistic capture (BC) in a totally autonomous fashion. Successfully freeing deep-space probes from human supervision will significantly reduce the overall operation costs. EXTREMA is erected on three pillars. Pillar 1 is about autonomous navigation. Pillar 2 concerns autonomous guidance and control. Pillar 3 deals with autonomous BC. The project has been awarded an ERC Consolidator Grant in 2019.
Self-driving spacecraft are machines capable of traveling in deep space and autonomously reaching their destination. These systems are used to engineer BC, thereby proving the effectiveness of autonomy in a complex scenario. BC mechanism is suited for limited-control platforms, which cannot afford to enter into orbits about a planet because of the lack of proper means. The object of this study is to attain BC in autonomy. The spacecraft assumed already in deep space has to acquire BC at Mars without relying on any information provided from the ground. Mars is chosen without loss of generality due to its relevance in long-term exploration.
This PhD research presents at first a characterization of BC corridors, streams of trajectories guaranteeing capture that can be targeted far away from the central body (see Figure 1). From a different perspective, corridors are time-varying manifolds supporting capture that are approximately in 1:1 mean-motion resonance with the target body. Targeting of corridors with a strongly constrained platform (e.g., CubeSat) is facilitated by the corridor stretching in backward time. This translates into a compression of the dynamics when propagated forwardly. Indeed, characteristic dimensions of corridors range from approximately 9.0e3-by-6.9e4 km up to 4.2e4-by-1.8e6 km over a time span roughly 40 to 560 days before the capture epoch.
Then, an autonomous ballistic capture (ABC) algorithm tailored for spacecraft with reduced computational capability that could potentially see the implementation onboard of interplanetary autonomous CubeSat is discussed. The algorithm is composed of two major segments. The first is carried out on ground and aims to prepare a BC corridor database. The second segment is carried out on board and foresees the CubeSat (or a spacecraft in general) computing new BC sets from which desired corridors are synthesized. The ABC algorithm envisages a novel methodology to construct families of ballistic capture orbits and compute the backbone of capture sets.
The problem of correcting the initial condition of a reference capture orbit is stated and discussed (see Figure 2). Attention is given to steps including the flow expansion, the definition of the 8 necessary boundary conditions, and their linearization. A three-point boundary value problem is formulated and solved with the multiple shooting technique. Families of capture orbits are easily generated by solving a sequence of linear systems, so reducing the computational burden typically required for finding BC orbits via classical approaches. The algorithm is proven successful in the generation of families of orbits belonging to various capture sets.
An alternative approach to present-day practices for designing BC orbits is also presented. The devised procedure leverages on the novel concept of a capture set backbone from which initial conditions belonging to capture sets performing many revolutions about the target are inferred. Construction of the backbone is made possible by exploiting the dynamical information embedded within Lagrangian descriptors propagated on a short finite horizon. The computationally demanding problem of designing orbits granting long-term temporary capture is unburdened by maximizing an energy-based descriptor on selected 1-dimensional sections at a constant initial pericenter radius.
Overall, the results presented in this PhD research aid in answering the research question of Pillar 3 and, consequently, the EXTREMA big research question. Achieving BC at Mars without any a priori instruction is anything but trivial, in particular for limited-capability spacecraft akin to CubeSats. Nevertheless, the advancements discussed in this work will hopefully foster the necessary knowledge to ultimately engineer autonomous BC.

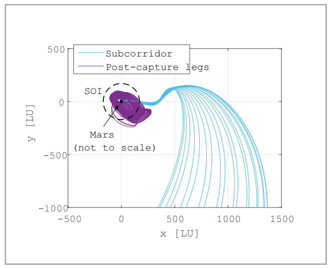

Fig. 1 - Ballistic capture corridor.

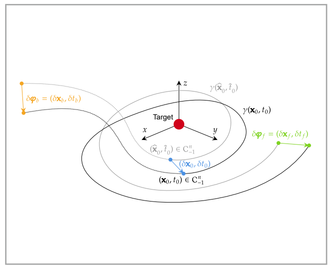

Fig. 2 - Correction of capture orbit.

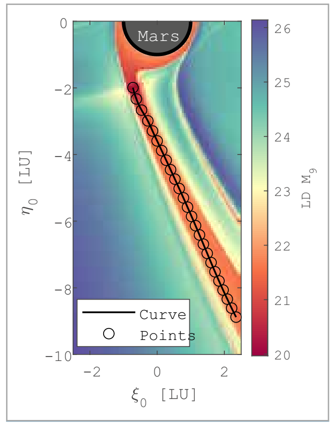

Fig. 3 - Backbone inspected against energy-based Lagrangian descriptor field.

MULTIRECEIVER RADAR TECHNOLOGIES FOR SPACE SURVEILLANCE AND TRACKING

Marco Felice Montaruli - Supervisor: Prof. Pierluigi Di Lizia

In the last decades, the growing in-orbit population of resident objects has become one of the main concerns for space agencies and institutions worldwide, and several initiatives have been promoted to tackle this issue. In this context, Space Surveillance and Tracking (SST) activities are in charge of maintaining an accurate and complete catalogue of orbiting objects, by also providing services such as collision avoidance, satellite re-entry and fragmentations analysis.
On ground-based sensors are mostly used for this purpose, and they can be distinguished in laser, optical and radar. Among them, surveillance means are fundamental, as they can acquire the measurements of an observed target with no transit prediction. In particular, surveillance radars allow to fully characterise the orbit of an unknown target from a single transit, through an Initial Orbit Determination (IOD) process based on the acquired measurements, which are slant range, Doppler shift and angular profile. However, the accuracy of the latter is generally coarse, preventing from a sufficiently accurate IOD result.
This thesis shows the advantage which may derive from an adaptive beamfoming technique in multireceiver surveillance radars devoted to SST-related activities, through the definition of the Music Approach for Track Estimate and Refinement (MATER) algorithm, which provides two main advantages: a finer accuracy in angular track estimation and the possibility to reconstruct the angular profile also when multiple sources are simultaneously detected, which is fundamental in fragments cloud and proximity operation monitoring. MATER algorithm is described as follows.
First, the signal Direction of Arrival (DOA) is computed with the MUltiple SIgnal Classification (MUSIC) technique, which exploits the signal correlation matrix. The DOA estimation result, for a specific time, is represented in Fig. 1, where it is possible to see both the correct DOA solution (the one with the red dot above) and the ambiguous ones, which may occur because of the sensor array configuration. For catalogued objects, at each observation epoch, the available ephemerides are exploited in the DOA estimation process to save computational time and to solve the ambiguity in the solution, and the angular track is obtained through a time regression of the estimated DOAs. For uncatalogued objects, the DOA ambiguity cannot be solved a priori, and tailored procedures have been developed to identify the best candidate among the computed angular tracks, based on either geometrical, or statistical, or signal processing considerations. The identified DOAs are clustered through the Random Samples Consensus algorithm (RANSAC), and the angular profile is returned after a quadratic regression in time.
Numerical simulations prove the robustness of the process, which returns an angular track accuracy between 1e-03 and 1e-02 deg, but may deteriorate depending on the impinging signal power, the number of samples integrated to generate each estimation and the related integration time length.
Nevertheless, MATER represents a remarkable step forward in favour of the surveillance radars contribution to SST-related activities, as demonstrated by tests on real case scenarios.
Particular attention is devoted to fragments cloud monitoring. Specifically, the fragmentation epoch identification problem from a single fragment observation is dealt with, which is of paramount importance in first epochs right after the event, to apply break-up models and to properly plan observations. Given the IOD accuracy, the uncertainty associated to the fragment orbital state cannot be neglected, and a stochastic approach is introduced. The resulting FRagmentation Epoch Detector (FRED) algorithm ranks a set of fragmentation epoch candidates according to the statistical matching between the Minimum Orbital Intersection Distance (MOID) and the relative distance distributions, and the optimal candidate is returned. Figure 2 shows the fragmentation epoch candidates distributions as a two-dimensional plot relating time and MOID, while Fig. 3 represents the matching between the MOID and the relative distance distributions (red and blue respectively). In the latter figure it is possible to appreciate that the relative distance distribution is much more stretched than the MOID one, as it is time-dependent.
The convergence to the correct solution strongly depends on the mutual geometry between fragment and parent orbits, the fragment orbital state accuracy and the time elapsed between the event and the observation, but FRED always performs better than an alternative deterministic metrics. MATER allows to exploit such an approach, but the associated non-zero mean and non-Gaussian error of measurements would prevent from stable and reliable results.
Nevertheless, in operational applications, the detected fragment may be later tracked with additional sensors to derive a more accurate orbital state to be used in FRED algorithm.

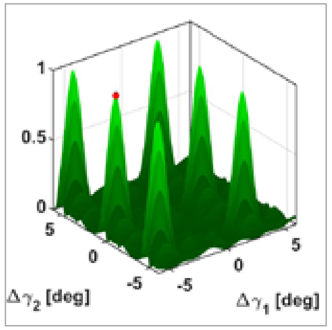

Fig. 1 - MUSIC DOA estimation

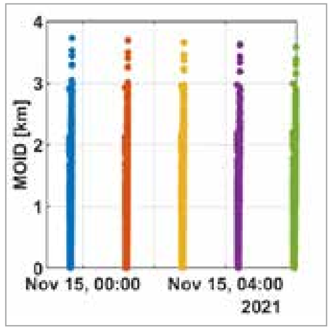

Fig. 2 - Fragmentation epoch candidates

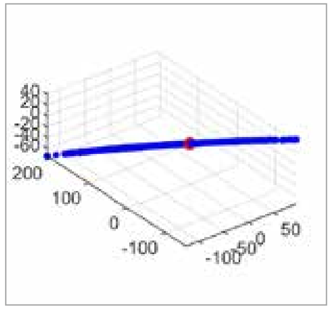

Fig. 3 - Matching between the MOID and the relative distance distributions

ROBUST DESIGN OF LOW-THRUST TRAJECTORIES THROUGH DIFFERENTIAL DYNAMIC PROGRAMMING ENHANCING THE EFFECTS OF ORBITAL PERTURBATIONS

Marco Nugnes – Supervisor: Prof. Camilla Colombo

Several future space missions will be equipped with low-thrust engines as main propulsion subsystem. This is true not only for planetary missions such as orbit raising, de-orbiting, Geostationary Transfer Orbits (GTOs), but also for interplanetary missions and large satellite constellations. The advantage in using low-thrust systems grants a higher final operational mass at the expense of a longer time of flight. Indeed, the main task of a space mission is to host a dedicated payload, which is associated to a set of scientific instruments to accomplish multiple objectives. The higher is the final operational mass the higher is the number of payloads to be set onboard of a single satellite. In the last 10 years the advancement in technology allowed to develop different types of new electric engines: solar engines, Hall effect thrusters, and plasma thrusters. The use of low-thrust engines completely changes the design problem of a spacecraft trajectory. When chemical engines, characterised by high thrust level, are involved in the design, the spacecraft trajectory design is solved considering multiple ballistic arcs separated by impulsive manoeuvrers.
The introduction of low-thrust engines turns the control policy from discontinuous manoeuvres to continuous laws. The design of a continuous control law requires the solution of a non-linear optimal control problem. One of the many techniques used to solve this problem is Differential Dynamic Programming (DDP) that couples the main advantages of classic direct and indirect methods. Despite its strong mathematical formulation the DDP technique did not find many applications over the past and the state representation was always chosen in terms of Cartesian coordinates. It is interesting to apply this technique to spacecraft trajectory design problems written in terms of orbital elements. Indeed, orbital elements represent a natural set to describe orbit mechanics because they provide a more physical insight into the problem. The variation of orbital elements can be rapidly associated to a geometrical representation of the spacecraft trajectory, whereas a variation of the position or the velocity vector in terms of Cartesian coordinates cannot be visualised until the full trajectory is plotted.
The aim of this research is to investigate the coupling between the optimisation techniques of DDP with the use of orbital elements as dynamic formulation and to apply the algorithm to space mission trajectory design problems. A novel mathematical theory has been devised which describes the bottlenecks in the application of the DDP together with the orbital elements and proposes an efficient solution through a continuation scheme to solve the optimal control problem. Interplanetary and planetary problems do not behave in the same way because of the different magnitude of the reference time used for the adimensionalisation of the time vector. The consequence is that a larger number of nodes is required for planetary problems to achieve the same time step used for the interplanetary ones. The larger number of nodes can considerably increase the simulation time making the DDP algorithm not efficient. A second important issue, which is very common in orbital mechanics problem, is the association between time discretisation and the nodes on the spacecraft trajectory. The discretisation is not uniform meaning that there is an overcrowding of nodes close to one apsidal point so that the distance between two successive nodes changes. There is the possibility that the continuity assumption required for the system dynamics is no longer valid because of the large distance between two consecutive nodes. A Sundman transformation is introduced to change the independent variable from time to the eccentric anomaly to make the mesh discretisation uniform. This important tool improves the convergence properties of the DDP algorithm when applied to planetary problems.
Another topic investigated is the possibility to leverage the effect of orbital perturbations as accelerations that can be engineered in the space mission design and not see them as disturbing factors. This second objective is set by the COMPASS ERC project which funded this research. The formulation of a cost function to optimise the maximum shadow time experienced by a spacecraft is devised. This subject is very hard because all the existing eclipse algorithms are based on osculating orbital elements while during a trajectory optimisation problem the orbital elements are changing with time. The main idea to build the eclipse cost function is to define an inner conical region associated to the maximum allowed shadow time. This region is equivalent to a path constraint because the spacecraft is not allowed to enter the area if the maximum shadow time requirements must be satisfied. The cost function represents the minimum distance of the spacecraft from the surface of the constraining region and it admits values different from zero only when the spacecraft is inside this region. Therefore, the minimisation of the cost function is equivalent to push the spacecraft outside the forbidden region that implies to respect the eclipse time requirements.

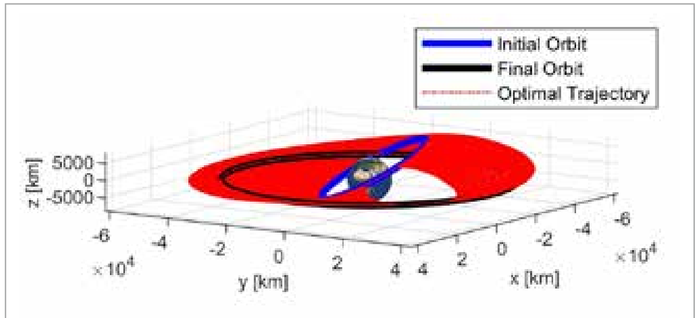

Fig. 1 - Optimal GTO to GEO transfer considering 600 revolutions.

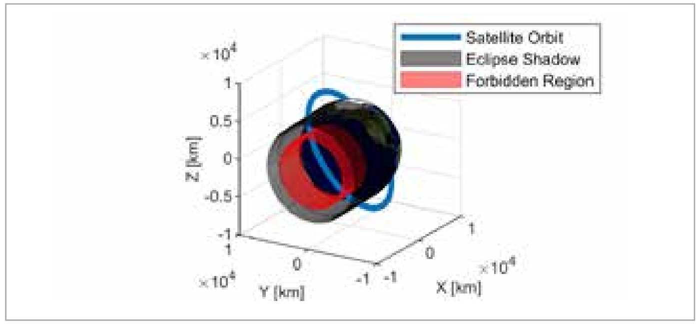

Fig. 2 - Graphical representation of the constraining cone to solve the minimum shadow time problem.

SPACECRAFT RELATIVE NAVIGATION WITH ELECTRO-OPTICAL SENSORS AROUND UNCOOPERATIVE TARGETS

Margherita Piccinin - Supervisors: Prof. Michèle Lavagna

Spacecraft relative navigation is a crucial and yet challenging capability for missions ranging from science and exploration to on-orbit-servicing and active debris removal. Traditional approaches vastly rely on the target's cooperation or on the ground acquisition of knowledge of the target's characteristics, then exploited on-board. Today, the achievement of an autonomous navigation is becoming a primary task, enabling new complex mission objectives that require low latencies and thus can not completely rely on ground commands, as is typically done. To accomplish this task, future missions will embark sensors suites composed by multiple Electro-Optical instruments. In fact, in the last decade, the technological development of space sensors as uncooled microbolometers, multispectral cameras and laser scanners, made them portable also on small platforms and apt to be employed for navigation purposes, as opposed to complex scientific instruments. Differentiating the input measurements to navigation not only would raise robustness and accuracy, which are keys for autonomy, but would also increase flexibility, allowing to widen the operational ranges.
This research work focuses on the exploitation of Electro-Optical sensors for enhancing autonomous relative navigation in proximity of an uncooperative target.
Different types of sensors are examined, probing the advantages and limitations of their stand-alone employment and proposing methods to engage them in synergy for the navigation. Monocular cameras working in the visible band are considered at first, being the most common solution adopted for relative navigation. To explore benefits and boundaries of such approach, particularly challenging applications are considered, as of use to understand when other sensors may come into place. As a result, multispectral navigation is proposed to overcome visibility and illumination-related issues proper of the visible band, identifying from analyses the Long Wave Infrared Band as interesting for a multispectral navigation. Secondly, the navigation performance achievable with currently available thermal infrared cameras is studied. The operative conditions in which thermal-based navigation is advantageous with respect to visible imaging are defined and a multi-modal navigation is proposed. Moreover, visible-infrared images fusion is implemented and compared with the two stand-alone techniques of visible and infrared images. Finally, classical and Deep Learning methods based on LiDAR scanners are developed for pose estimation, offering structured information of the target geometry. The possibility of an integration with a classical vision-based approach is also proposed. The research work successfully finds key elements and guidelines for an exploitation of the different kind of sensors in various scenarios. The proposed methods can increase accuracy, robustness or enable operations for new mission concepts.
The Thesis also poses its accent on the verification and testing of the proposed navigation techniques. In particular, the topic of generating representative synthetic data and of their validation with real or experimental data is argued for the three sensors. The lack of prior tools is mostly challenging for thermal cameras, therefore an innovative pipeline for generating synthetic thermal images is proposed and implemented. Experimental activities including calibration of sensors in GNC facilities are carried-out. Such activities allowed tests of the navigation algorithms, comparing the performance achieved with respect to synthetic data. This Thesis offers an overview and initial framework for the concurrent exploitation of visible cameras, thermal cameras and LiDAR sensors, making a step forward to overcome major challenges of proximity relative navigation with uncooperative objects.

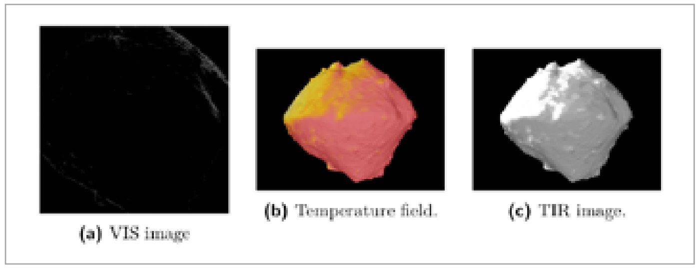

Fig. 1 - Results of the generation of synthetic multispectral images, with proposed physics-based simulator.

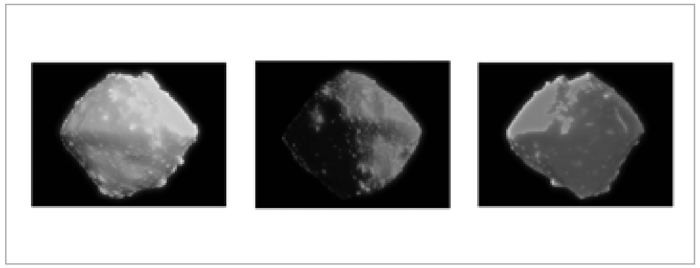

Fig. 2 - Study of multispectral image-based relative navigation with unknown asteroid target, with visual and thermal images fusion at different lighting and thermal conditions.

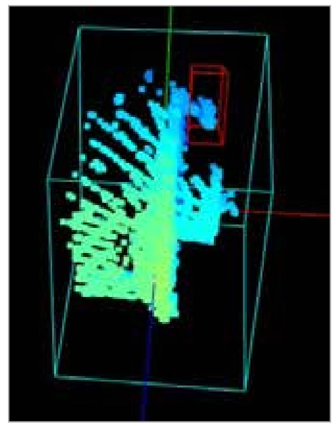

Fig. 3 - LiDAR-based relative pose estimation during capture of uncooperative spacecraft, tested on experimental data.

MULTIDISCIPLINARY GUIDANCE AND CONTROL SYNTHESIS METHODS FOR SMALL SATELLITES

Jacopo Prinetto - Supervisor: Prof. Michèle Lavagna

The interest in small-sat and CubeSat missions is constantly increasing during the lasts years, as well as the complexity of the scenarios in which such class of satellites is employed and the performances that they shall guarantee in term of both attitude and orbital control.
This growing interest is motivated on one side by the fact that small-sat can potentially reduce the costs and development time of a mission when compared with larger satellites, and on the other side by the fact that small-sat open the possibility to exploit innovative mission concepts with fractionated of repeated payload, increasing the scientific or economic return while minimizing the single-point-failures that can affect large monolithic satellites.

The research work presented here focuses on the development and testing of multidisciplinary guidance and control synthesis methods for small satellites. The multidisciplinary approach, that will be extensively recalled in this work, become almost essential when small-sat guidance and control problems are addressed, indeed the hardware performance of such satellites are limited by their size and the reduced heritage. In particular, the performance of these satellites are typically limited by some critical elements, namely the propulsive units, the available power and energy and the computational performances.

In this research work, two novel semi-analytical guidance algorithms for the center of mass and attitude motion are developed, presented and tested in mission scenarios of different complexity to prove their validity. In particular, the guidance algorithm for the center of mass motion is focused on the solution of the continuous control problem of a thrusting spacecraft, to be suitable for both electrical thrusters and low thrust-to-weight ratio chemical propulsive units. The algorithm is also employed in a small-sat multi injection mission scenario, adopting a novel routing problem approach. The attitude guidance algorithm is focused on the optimization of highly constrained attitude maneuvers. The constrains implemented arise both from hardware limitations and from the imposition of forbidden/desired pointing directions thought the exploitation of keep-in and keep-out cones. These last constraints are representative of scenarios in which some pointing directions are desired, such as the antenna to ground visibility during the maneuver, or the maximization of solar panels exposition to the sun, or in which some pointing directions are forbidden, such as payload and/or navigation instrument Sun/Earth/Moon avoidance. The algorithm is then coupled with a controller suitable for small-sat on-board implementation and tested in some realistic scenarios. As last step, the effect of flexible behavior of small-sat on the pointing performances is investigated through the adoption of a proper multi-body formulation of the equation of motion of the flexible small-sat.

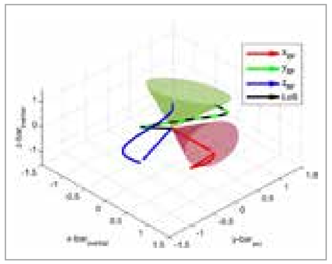

Fig. 1 - Optimal slew maneuver with keep-out cones

GUIDANCE AND NAVIGATION ALGORITHMS FOR AUTONOMOUS MULTIROTOR UAVS

Gabriele Roggi - Supervisor: Prof. Marco Lovera

The interest and the possible applications of Unmanned Aerial Vehicles (UAVs) have been increasing quickly in the last few years. At the current state, the vehicles can be either teleoperated on an actuator set-point or waypoint level or execute a flight path planned on a ground control station, constantly under direct line of sight with an operator. At the same time, the platform relies on Global Navigation Satellite System (GNSS) information for its navigation. The presented way of conducting operations displays some critical issues. First, in the case of teleoperation, the stress level on the operator is quite high and this can potentially lead to errors or damages to the platform. Communication constraints between the operator and the UAV could further complicate things. Then, operations are limited by the availability of GNSS signal, thus excluding indoor or other challenging environments. Consequently, in order to deploy their full potential, these machines have to navigate autonomously without any user intervention or the need for any external infrastructure. In this framework, autonomous drones could take decisions without relying on downlinked data in a time-efficient way and could execute high-level commands and reach complex objectives without the need for a human operator who translates the goals of the mission into position waypoints.
A first part of the work covers the development, simulation and experimental validation of guidance and navigation algorithms for this kind of machine.
First, the three different platforms, designed in collaboration with the Politecnico di Milano spin-off company ANT-X, are presented. One of them is shown in Figure 1.

Fig. 1 - ROG-3 autonomous platform.

Then, different software solutions, capable of large-scale indoor GNSS and collision avoidance in cluttered environments, are discussed in detail. Extensive simulation and experimental testing have been performed for validating of the proposed approaches.
Finally, the results obtained during the Leonardo Drone Contest (LDC) autonomous drone competitions, are shown, demonstrating robustness and reliability of the proposed software and hardware architectures outside the laboratory environment (see Figure 2).

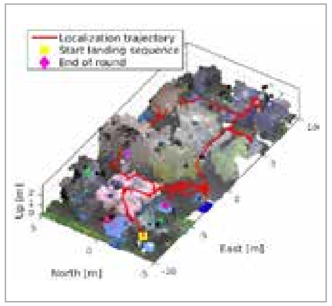

Fig. 2 - Trajectory followed by the drone during the Leonardo Drone Contest autonomous drone competition. The map (point cloud) has been generated on the UAV during flight and it has been employed for path and trajectory generation.

The second part of the dissertation tackles the problem of the systematic characterization of vision systems. In this framework, we have proposed the Allan Variance (AVAR) time domain technique to model the types and magnitude of various noise terms affecting the stereo visual odometry (VO) position measurements. Through suitable computations, a state space representation of the errors, which can be used in sensor fusion framework, is obtained. The retrieved model is then employed for validation through a Kalman predictor. This analysis has been conducted on an experimental dataset collected using a multicopter UAV equipped with stereo vision (like the one in Figure 1). The runs of the experiment have been designed following the Design of Experiments (DoE) technique. In this framework, the model sensitivity to changes in the environmental and flight conditions is also discussed.
Finally, in the third part of the thesis, the problem of guidance and navigation for performing autonomous landing in different scenarios is addressed. In particular, the proposed solutions tackle some of the problems of an autonomous emergency landing in case of faults or malfunctions in an indoor environment and Air-to-Air Automatic Landing, i.e., the landing of a small drone on top of a larger one (see Figure 3) during flight.

Fig. 3 - 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.

In the former scenario, the UAV needs to identify, approach and land at a safe site without any intervention. In particular, we have considered the problem occurring in an indoor GNSS-denied environment similar to the one of the LDC competitions. Furthermore, the problem has been split in two sub-problems, i.e., landing zone detection and path planning, solved separately.
In the latter scenario, we have considered a non-cooperative approach for performing the task using vision for tracking and landing on the target drone. To this aim, a Kalman Filter (KF) is designed to estimate the target state using information coming from a camera mounted on the smaller drone. At the same time, a Quasi Time Optimal (QTO) control law and a hybrid logic are used to perform the landing.

FLIGHT SIMULATOR TRANSFER OF TRAINING EFFECTIVENESS IN HELICOPTER MANEUVERING FLIGHT

Paolo Francesco Scaramuzzino - Supervisor: Prof. Giuseppe Quaranta

Pilot training and flight simulators play a crucial role in rotorcraft safety. However, to spread the use of flight simulators in helicopter pilot training, it is necessary to minimize the chances of insufficiently realistic training settings and negative transfer of skills. This thesis contributes to this key point by providing indications for the development of helicopter training simulator criteria. Therefore, this thesis has the following ambitious goal:

Contribute to an enhanced understanding of the future requirements for helicopter pilot training in flight simulators.

To this end, this research considers two representative helicopter tasks, hover and autorotation, and analyzes them in detail to understand the relation between transfer of training and simulator fidelity, especially as related to the quality of the cueing system and the mathematical model. Therefore, this thesis answers the following main research questions:

1) How does simulator objective fidelity, due to variations in the quality of the cueing systems, affect the initial training of the hover maneuver?
2) How do variations in the controlled helicopter dynamics affect the recurrent training of the autorotation maneuver?

The hover and autorotation maneuvers are most relevant in different phases of the training syllabus (either ab-initio or recurrent training), allowing to identify differences in terms of requirements for basic and advanced simulator training, as well as for task naïve learners and experienced pilots.

This thesis aims to contribute to an enhanced understanding of the future requirements for helicopter pilots training in flight simulators, providing indications for the development of guidelines for such novel training when the helicopter is flown in two of its most characteristic modes of operation: hover and autorotation.

Transfer-of-Training experiments are one of the few available techniques that can be used to explicitly measure simulator training effectiveness. Quasi transfer studies, also known as Simulator-to-Simulator Transfer experiments, employ tasks where participants alternate between different simulators or where some change in task or configuration is performed in the same simulated environment.

In contrast, real flight transfer studies investigate whether certain skills can be acquired in a simulator and successfully transferred to actual flight. The quasi-transfer paradigm relies on the assumption that simulators act as a valid replacement for the actual aircraft. Although this is a strong assumption, it is corroborated by experimental evidence. Furthermore, a quasi-transfer design avoids the costs, hazards, and scheduling hindrances (e.g., interruptions due to bad weather) of a true transfer and offers the possibility of safely investigating dangerous situations such as engine failures. Another issue arising from true-transfer studies is the reliability of the performance measurements in the real-world setting. Moreover, although the pilot appears to be the only constant element in the two control systems, i.e., pilot-vehicle and pilot-simulator, there may be inevitable psychological differences in a pilot's mindset between the two settings. This is not necessarily a disadvantage from a training perspective, because relieving the trainee of the stress and the workload deriving from auxiliary duties (e.g., safety and flight regulation aspects, communication, periodic systems monitoring, etc.) enables him to devote more resources to learning.

For this thesis, three quasi-transfer-of-training experiments was conducted to test the effectiveness of the training programs formulated according to the analysis of the training tasks. A first quasi-transfer-of-training experiment with task-naïve learners trained for the hover maneuver demonstrates that desktop trainers may be a valid alternative to high-fidelity simulators if supported by a suitable training program.

Two quasi-transfer-of-training experiments with experienced helicopter pilots trained for an autorotation maneuver demonstrate that positive transfer of skills occurs from a relatively hard to a relatively easy helicopter dynamics, but not the opposite, suggesting that starting the training with more difficult to control helicopter dynamics fosters the development of skills that can be easily adapted to easier conditions.
The simulators used in this thesis are the Max Planck Institute Cyber-Motion Simulator and Computer Based Trainer and the Delft University of Technology SIMONA Research Simulator, which are shown in the figure below. One of the core elements of a flight simulator is the flight mechanics model, which replicates the response of the actual aircraft to pilot's control inputs. Different flight mechanics models have been used in this thesis, ranging from an identified model of the Robinson R-44 helicopter, suitable for hover and low-speed simulation, to a physics-based model with six rigid-body degrees-of-freedom, quasi steady flapping dynamics, and uniform inflow. The physics-based model developed in this thesis for a conventional helicopter (one main rotor and one tail rotor) is generic. Therefore, it can be used to represent different helicopters by simply changing the input parameters of the model (e.g., rotor radius, helicopter weight, etc.). The physics-based model was validated against available trim flight test data for the Messerschmitt-Bölkow-Blohm Bo-105 helicopter in straight level flight and tested in the simulator with experienced and qualified helicopter pilots. Although the model exhibits a good match with flight test data for most of the trim variables, the use of a uniform inflow model causes an underestimation (in absolute value) of the lateral cyclic pitch. Trim in steady autorotation and stability derivatives in level flight and steady autorotation of the developed model were verified against those of other models of the same helicopter due to the lack of available flight test and identification data.

(a) The Max Planck Institute CyberMotion Simulator.

(b) The Max Planck Institute Computer Based Trainer.

(c) Delft University of Technology SIMONA Research Simulator.

Fig. 1 - Flight simulators used in this thesis.

ENHANCED AUTONOMY IN GNC FOR SPACECRAFT WITH LIMITED OBSERVABILITY OPERATING

Giovanni Zanotti – Supervisor: Prof. Michèle Lavagna

Autonomy in spacecraft Guidance Navigation and Control (GNC) is an ever-growing topic in both academic and industrial research, due to the vast possibilities that it can enable in terms of mission concepts and operational costs. The work presented in this thesis explores different strategies to support the enhancement of on-board autonomy in the GNC tasks in view of the future challenges that the lunar environment will present, considering scenarios without complete observability imposed by reduced sensor utilisation or by the constraints of a small-sized navigation constellation. Three different scenarios are investigated, studying, implementing and testing GNC architectures to address the problem of spacecraft autonomy in various dynamical conditions of proximity manoeuvring, natural motion and landing.

The objective of pushing towards spacecraft autonomy is indeed a key point to unlock the exploitation of more intelligent and adaptive platforms, which, related to the tendency to move more and more towards distributed and smaller systems, needs to be deeply investigated. Such approach, entailing small satellites in constellations or formation flying contexts, provide cheaper and more versatile solutions in general, but not in the operational costs, unless a higher level of autonomy is given to the systems. The GNC tasks are deeply involved in these considerations, recalling that the state-of-the-art for most of the spacecraft is to completely rely on ground intervention to run the Flight Dynamics routines, i.e. performing the Orbit Determination (OD) and scheduling and commanding the required orbital manoeuvres. The exploitation of small platforms however is accompanied, in general, with reduced sensor suites and computational power, reason for which specific low-observability navigation techniques are to be targeted, relevant also for larger platforms in contingency scenarios.

The next decades of space exploration will also be deeply influenced by the renewed interest in the Moon, target of many international programmes aiming at providing the basis for a stable human presence in this environment. Such activities will provide both scientific and technological advancements in the understanding of our natural satellites and in our capability to survive and remain on its surface. Two promising infrastructures that are currently being studied with joint international efforts are the Lunar Orbital Platform - Gateway (LOP-G) and a communication and navigation constellation around the Moon.

The former project will be a new orbital outpost to host astronauts in the cislunar environment. In particular the chosen trajectory on a Near Rectilinear Halo Orbit (NRHO) will represent an interesting playground for the validation of some autonomous relative GNC algorithms needed by possible chasing spacecraft looking to either reach the Gateway or fly in formation cooperatively with it. A lunar constellation will instead be a great opportunity in particular to increase the autonomy from ground-based navigation for both surface and orbital users, resulting in a lunar-centric Global Navigation Satellite System (GNSS) service.

The work presented in this thesis focuses on considering these two infrastructures as opportunities to study Earth-autonomous GNC strategies, which can contribute to the exploitation of such potential. Two scenarios of spacecraft flying in proximity to the LOP-G are presented first, where two missions of autonomous rendezvous and manoeuvring in formation flying are considered. The associated GNC schemes have been analysed considering a limited observability scenario where only relative angular measurements are retrieved to perform navigation. The recorded performance is promising and showing the boundaries of applicability of performing complex and mission critical tasks with such estimation architecture.
The third scenario instead provides first a strategy to help the design of a small-sized lunar constellation, entailing different objectives and users to assist. Then, various optimised constellations are tested including the orbital and landing users' filtering architectures, extracting insights on the state estimation achievable and its capability to support critical GNC tasks. Fig. 1 presents the GNC architecture employed for a Moon landing mission.
The results obtained showed navigation capabilities good enough to enable correct execution of missions in the low lunar orbital region including the complex task of performing a controlled landing at the South Pole. To provide a higher formulation robustness, the filters involved have been also deployed and run on embedded hardware, validating their implementation through Processor-In-the-Loop (PIL) testing.

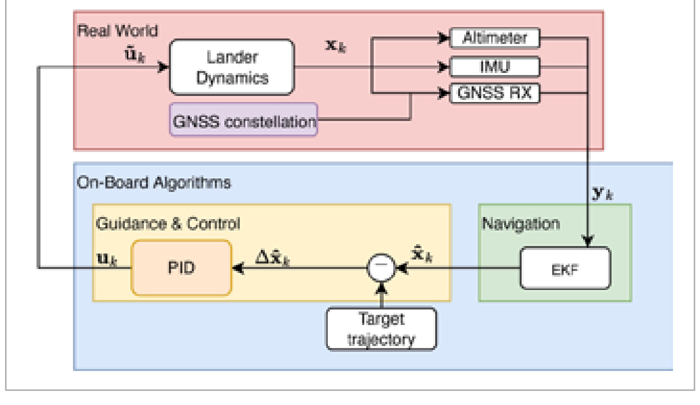

Fig. 1 - Architecture of the GNC scheme used for the landing analysis.