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**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: dynamics and control, fluid mechanics, systems and equipment, flight mechanics, passive structural safety, intelligent and automated systems, structures and materials.

In this respect, some examples of professional skills achieved in the course of the past 24 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.

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# ROBUST OPTIMIZATION OF A THERMAL ICE PROTECTION SYSTEM IN UNCERTAIN CLOUD ENVIRONMENTS

**Bárbara Arizmendi Gutiérrez – Supervisor: Alberto Guardone**

In-flight icing occurs when aircraft traverse environments of high moisture and the air temperature is below the freezing point. The existing water, which is present in the form of clouds, impacts over the surfaces and freezes. Ice shapes of different complexity progressively accrete. This unpredictably alters the normal operation of aircraft and their components. It always entails negative effects, which can compromise the performance and in the worst cases safety. Unfortunately, there are several records of accidents and serious incidents that were caused by icing. Luckily, and for nearly one hundred years, aircraft manufacturers and researchers from public and private entities have worked on the study, development and deployment of systems for the protection against this threat. These are the so-called Ice Protection Systems (IPS). These aim to maintain the critical components free from ice formations and guarantee their expected performance. Among these technologies are Electro-Thermal IPS (ETIPS) that exploit the Joule effect to generate heat. In this way, outgoing heat fluxes are supplied to melt ice to warm up the impacting liquid water and evaporate it. The later operation is called Anti-Ice (AI), whose aim is to prevent or delay the formation of ice. One of its main drawbacks is the large electrical power consumption. Besides, if not enough power is

supplied in AI operation, the residual non-evaporated water may freeze downstream, forming runback ice shapes. Runback ice equally poses a threat for safety and performance and these formations are difficult to be voluntarily removed.

The process of designing these systems requires the evaluation of the requirements of thermal power for the adequate evaporation of water. Moreover, the distribution of the thermal power across the protected parts, in case of modular systems, must be designed. The distribution of heat fluxes must ensure adequate protection in the event of any of the expected icing conditions. Within an encounter of icing conditions, the cloud properties are uncertain. In the vast majority of flights, these quantities are not measured and not controlled. The allocation of resources for the worst-case scenario is over-conservative and might compromise the integrity of the materials. The present numerical study describes an effort towards a more efficient use of the resources for the operation of a wing or engine nacelle AI-ETIPS in a robust manner. That is, accounting for the effects of the uncertainties in the cloud parameters and the consequences these entail in the possible runback ice formations. Additionally, it is sought to reduce the likelihood of severe ice accretions.

To this end, first, a numerical model is constructed to represent the operation of an airfoil AI-ETIPS. This model is based on a previous research effort. The aero-thermodynamic model iteratively solves the conservation equations in control elements. It accounts for all the identified relevant mass and heat fluxes. It is a steady-state model that represents mild ice encounters that extend horizontally, that is, flights through stratiform clouds. The model is loosely coupled to an aerodynamic Eulerian CFD solver and a Lagrangian particle tracking solver for the evaluation of the impinging mass rates. To account for the effects of viscosity, an integral boundary layer is included into the model. Several key improvements are deployed to enhance the completeness and robustness of the reference model. These include freezing terms for the prediction of runback ice formation mass rate. In this way, the possible existence and severity of runback ice formations can be assessed. The results obtained are in good agreement with experimental measurements.

The model validation is followed by a comprehensive optimization study for given cloud and flight conditions. The case study regards an airfoil equipped with an AI-ETIPS consisting of seven independent heating

elements. The heat fluxes distribution across the different heaters is optimized for the minimization of the thermal power consumed. Besides, it is constrained to the avoidance of runback ice formations. The constraint is handled by means of the penalty method. The optimal solution lays in the boundary of feasibility and therefore, the penalties introduced are investigated. Genetic Algorithms (GA) are chosen for optimization due to their versatility, maturity, effectiveness and ability to cope with noise and multiple minima. This is caused by the introduction of the penalty into the objective function, which may change the monotony of the objective function. Crossover and mutation search paradigms in GA are also investigated. The optimized layout of heat fluxes is shown to be able to more efficiently evaporate the impacting water. That is achieved mainly by minimizing the convective losses in different ways. With regards to the GA, a very slow convergence is observed as well as a convergence to possible different minima in the different runs.

Uncertainty Quantification (UQ) methods are used to address the lack of information of cloud properties and their effect in the magnitude of runback ice formations. To this end, uncertainties are treated in a probabilistic manner. Non-intrusive forward propagation

techniques across the numerical model are deployed into a case study. The related quantities of interest present inherent non-smooth features. Therefore, two different well-established UQ methods are deployed with different computational costs. Expensive Monte Carlo Sampling techniques (MCS) are used due to their versatility and limited requirements from the perspective of the QoI. Besides, Generalized Polynomial Chaos Expansions (gPCE) are implemented, which are able elaborate estimations of the statistics of the QoI requiring a reduced number of function evaluations. Two different layouts of heat fluxes are evaluated to study the effects of power into the statistical quantities. It is concluded that gPCE is able to elaborate estimations of the low order statistics of the QoI. In addition, a straightforward analysis of variance is also reported in this work to assess the effects of the uncertain quantities in the variance of the QoIs.

The last part naturally brings together the combination of the optimization and UQ techniques. Two objective functions are sought to be minimized. The first regards the thermal power consumed by the AI-ETIPS and the second one is a counterpart robustness function of the total freezing mass rate. This function includes low order statistical quantities from the

runback ice metrics. By minimizing it, the likelihood of severe runback ice formations is reduced as well. These two objectives are often compromised, meaning that improvements in one lead to worsening of the performance in the other objective. Hence, there is not a unique optimal design but a set of designs arranged in a Pareto frontier. In this work, the two objectives are treated separately. The algorithm Non Dominating Sorting Genetic Algorithm - II (NSGA-II) is used for optimization. GAs are one of the preferred options for multi-objective optimization problems. Moreover, this particular algorithm was found as efficient and effective in the literature when compared with other alternatives. Due to the computational cost to evaluate the measure of robustness, the optimization runs are only partially converged, but still they are capable of obtaining fronts of solutions that present improvements in performance with respect to the initial random population. The population size is also investigated to assess its effects on the final set of optimized solutions. The approach allows to find more efficient layouts that reduce either the power consumption or probability of severe runback ice formations when compared with an intuitive baseline configuration.

## DEVELOPMENT OF AN ABLATION MODEL FOR RAREFIED FLOWS WITH APPLICATION TO METEOROID ENTRY

**Federico Bariselli - Supervisor: Aldo Frezzotti**

About 100 tonnes of small meteoroids enter the terrestrial atmosphere every day. As a meteoroid interacts with the atmosphere, its surface temperature can reach several thousands of Kelvins, causing its ablation. Among the various strategies for the observation of meteors, radio-based techniques have proved to be a simple yet valuable tool for collecting large amounts of data. Ground radio stations can detect free electron densities in the meteoroid trail, which are initially produced by the hyperthermal collisions of the ablated species with the incoming freestream. Therefore, the ability to predict the ionisation intensity and the rate of dissipation of the plasma trail becomes essential for the correct interpretation of the radio signal. However, the current models are drastically simplified; they use zero-dimensional approaches and disregard nonequilibrium phenomena, such as rarefied gas effects. This work aimed at providing a detailed description of the degradation process of a meteoroid and the physico-chemical dynamics driving the ablated vapour around the body and in the extended plasma trail. Each improvement in the modelling is expected to impact not only the comprehension of the physical problem but also the estimates on mass fluxes and the statistical outcome of the collected observational data. First, we described the nonequilibrium collisional processes around millimetre-sized meteoroids, at certain selected

conditions along the entry path. These conditions were chosen in agreement with the trajectory and flow regime analysis. Particular attention was given to the production of free electrons, from which the intensity of the radio signal depends. We carried out the investigation in the framework of the Direct Simulation Monte Carlo (DSMC) method, where we included specific models to tackle both gas-surface interactions and gas-phase encounters. With respect to classical meteor theory, the introduced evaporation boundary condition can take into account condensation fluxes and the backscattering of molecules at the wall. Moreover, a database of elastic and reactive cross sections was developed for the ablated vapour. This set of data may be useful to scientists as a reference database for future theoretical and numerical studies. Collisional processes and shielding effects proved to be meaningful for events below 100 km or intense ablation rates, and they could be even more significant for bigger meteoroids. Ionisation comes mainly from the hyperthermal encounters between air and vapour, rather than from thermalised metal-metal collisions. A second phase of the work dealt with the experimental characterisation of the material response of some meteorite samples. These experiments allowed testing the evaporation model and yielded insight into the ablation mechanisms. We presented the results

from two campaigns, carried out in the VKI Plasmatron wind tunnel and the NASA Ames laser ablation facility, so to span a range of evaporation conditions. Both tests confirmed strong degassing of light species and oxidation, and they indicated that accurate ablation modelling requires describing the mechanical removal of the molten layer into the hypersonic flow. Geochemical characterisation of the recovered material demonstrated the successful use of these type of facilities to reproduce fusion crusts similar to those collected on the ground. Finally, measurements of the surface temperatures, coupled with thermal response modelling of the material, helped in refining the understanding of the surface energy balance. Despite the simplicity of the numerical model, simulations and pyrometry data were found to agree reasonably well in laser experiments, while they needed a tuned contribution of the oxidation heat flux in the Plasmatron tests. Then, we studied the processes which lead to the extinction of the plasma trail. For this purpose, we employ the simulations obtained using the DSMC method as initial conditions to carry out detailed chemical and multicomponent diffusion calculations of the extended trail (up to several kilometres) using a Lagrangian approach. In this approach, a fluid element reactor marched along assigned streamlines, calculating multicomponent mass diffusion in the radial direction and detailed chemical

reactions. Chemical reactions had negligible effects in the neutralisation process of underdense trails, which were dominated by mass diffusion. Also, a constant diffusion coefficient, as used in standard models, was sufficient to reproduce the numerical profiles. The influence of chemistry and differential diffusion could be enhanced in overdense meteors. Therefore this aspect deserves future investigation. Finally, we linked the dissipation of the electrons to the reflected radio echo, so to estimate the resulting signal in the framework of the classical underdense meteor theory. On the whole, the procedure presented represents a standalone methodology, which can provide meteor physical parameters at given trajectory conditions, without the need to rely on standard lumped models. Finally, in light of the experimental results, we presented a numerical procedure that allows studying melting in the presence of a rarefied gas phase. In these flows, the condensed phase can be treated as a continuous medium, whereas a kinetic treatment is needed for the gas. We proposed a computational approach in which both phases are simulated by particle schemes: the DSMC method for the vapour and the Smoothed Particle Hydrodynamics (SPH) method for the solid and the liquid. This approach is computationally more intensive, as it proposes to describe the dynamics of the three phases comprehensively. In

this case, a two-way coupling between phases was pursued, at the expense of other possibly relevant phenomena such as evaporation or chemical nonequilibrium of the gas, which were not taken into account. We showed the details of the thermal and dynamic coupling methodology, along with some verification test cases in simplified configurations. Finally, as a proof-of-concept, we considered the melting of a solid cylinder immersed in a rarefied hypersonic stream. The dynamics of the molten layer under the influence of the external flow was analysed.

# ANALYSIS, DESIGN, AND OPTIMIZATION OF ROBUST TRAJECTORIES FOR LIMITED-CAPABILITY SMALL SATELLITES

Carmine Giordano – Supervisor: Francesco Topputo

Since the beginning of the space era, satellites have always been equipped with chemical propulsion engines, characterized by a high value of thrust and a good control authority. However, in recent times, the space exploration is going in the direction of exploiting small platforms in order to get scientific and technological return at significantly lower costs, employing low thrust limited-capability spacecraft, needing reduced propellant mass.

For traditional spacecraft, the correction maneuvers are considered to be a minor problem, since changing the trajectory is relatively easy with a single, short burn; on the other hand, adjusting the orbit can be problematic for low-thrust spacecraft, since a long burn is needed, even for paltry deviations. Therefore, orbit determination and the subsequent correction maneuvers cannot be considered a minor problem and preliminary trajectory design has to take them into account. Thus, a shift in mission analysis paradigm becomes necessary. For this reason, in this work, a novel trajectory design and optimization technique, naturally embedding navigation features and correction maneuvers has been developed, implemented, and assessed.

Traditionally, the preliminary mission analysis is performed in a sequential approach, exploiting two consecutive steps: 1) the nominal trajectory to the

target is sought, trying to minimize the propellant mass; 2) a navigation assessment is performed in order to evaluate the flyability of the nominal trajectory and it is composed by two sub-phases: a) the knowledge analysis, used to estimate the achievable level of accuracy in the spacecraft state knowledge; and b) the navigation cost estimation, which computes the navigation cost needed to allow the spacecraft to reach the target. This two-step approach can lead to sub-optimal solutions, requiring a gratuitous amount of propellant. This behavior is taken to extremes when small satellites are considered. As a matter of fact, some trajectory can be wrongly tagged as infeasible using this approach. Thus, a holistic approach, able to comprehend the whole navigation assessment inside the optimization process, has to be devised to relieve this effect. This integrated approach is depicted in Figure 1. In a single step, it is able to optimize the deterministic and the stochastic costs, while evaluating the

statistics associated to the trajectory. However, this general concept can be hardly used as a comprehensive method for the robust stochastic mission analysis, due to the diverse characteristics and mission profiles of the deep-space exploration missions. For this reason, in this work, three mission scenarios, selected among the trend topics in space missions, are used as test case in order to specialize the general problem and assess the performances of the integrated approach.

The scenarios selected as test-bench for the revised approach are: (1) a spacecraft subject to a strongly nonlinear dynamics, executing impulsive maneuvers; (2) a satellite controlled by continuous low-thrust, following a spiral trajectory in a simpler environment; (3) a probe performing some fly-bys in a planetary system.

Scenario (1) can be used to represent spacecraft flying on Lagrange points orbit manifolds and it can well describe the trajectory of the CubeSat

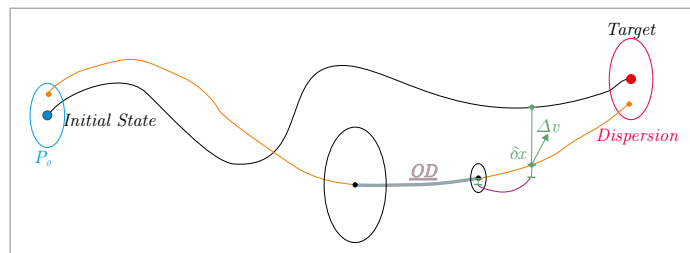


Fig. 1 - Revised approach for the preliminary mission analysis.

LUMIO. LUMIO was one of the winners of ESA's SysNova. It was later considered for further implementation and completed successfully the Phase A in February 2021. LUMIO space segment is composed by a 12U CubeSat, flying a halo orbit at Earth–Moon L2. The spacecraft is equipped with a novel miniaturized optical instrument capable of detecting light flashes in the visible spectrum produced by meteoroid impacts. LUMIO will be released on a low lunar orbit and it will reach the operative orbit autonomously. In this work, the focus is placed on this transfer phase. Thus, an optimization problem has been implemented, minimizing the total costs, while assuring that the uncertainty ellipsoid of the final state is inside a desired bubble. In this case, the stochastic quantities are estimated by employing a new combination of the polynomial chaos expansion together with the conjugated unscented transformation (labelled as PCE-CUT), able to give an accurate, but fast, estimation of knowledge and dispersion. The trajectory correction maneuvers are computed by using the differential guidance. Some first guesses, obtained by patching low lunar orbit states with trajectories from the halo propagated backward, are used to feed the optimization algorithm. For this scenario, it can be found that the solution having the best deterministic value is not the one having the best

performances when stochastic costs are considered. Indeed, up to a 10% of fuel can be saved considering the integrated approach, instead of the sequential one.

Scenario (2) can be used to describe a low-thrust deep space trajectory. An example for this kind of dynamics can be the transfer phase of the CubeSat M-ARGO. M-ARGO is planned to be the first standalone ESA deep-space CubeSat to rendezvous a near-Earth asteroid (NEA). This concept was developed by ESA and then studied for the Phase A, by GomSpace Luxemburg and Politecnico di Milano. In this case, the thrust should be treated like a Gauss-Markov process and, for this reason, linear propagation is considered to propagate the uncertainties. The trajectory from Sun-Earth L2 to the asteroid 2000 SG344, being one of the baseline trajectories for M-ARGO, is used as test-case. In this case, the integrated approach minimization is able to reduce the propellant consumption by a 3%.

Scenario (3) is representative of ESA mission JUICE, planning to perform a tour of the Jovian system. The work on this Scenario has been conducted during a visiting period in ESA/ESOC. In this Scenario, since some intermediate targets should be respected in order to accomplish scientific or engineering objectives, an innovative guidance algorithm, able to fulfill goals along the trajectory, called

target guidance, was implemented and tested. The combination of the integrated approach together with the target guidance is able to save 5% of  $\Delta v$  by cutting half of the stochastic costs.

In conclusion, the integrated approach, embedding stochastic features in the trajectory optimization, is able to reduce the overall propellant mass in all the mission scenarios proposed in this work, while satisfying the required constraints.

# NUMERICAL AND EXPERIMENTAL INVESTIGATION ON THE CRUSHING BEHAVIOUR OF AUXETIC LATTICE CELLS PRODUCED WITH ADDITIVE MANUFACTURING TECHNIQUE

Kadir Gunaydin – Supervisor: Antonio Mattia Grande

In aerospace, automotive and military applications, lightweight structures such as sandwich structures have an important role in the impact and blast situations due to their feasible crush resistance specifications. For crashworthy structures, different types of sandwich structures have been proposed with different cores such as foams, lattices and trusses. Lattice cores have come forward regarding crashworthiness, and one of the most promising lattice structures is auxetic cellular solid structures. Auxetic lattice structures are special structures experiencing negative Poisson's ratio so that they behave differently from conventional materials; they shrink under compressive loads and expand while tensile loads are applied. Among them, chiral structures are one of the prominent auxetic structures that show close to the Poisson's ratio of -1. Poisson's ratio of the chiral cellular solids is independent of its constituent material; however, besides the topology of the cellular solids, the constituent material is important for determining the mechanical performance for compression and crush applications. Therefore, the manufacturing method is explicitly playing a significant role in cost, production challenges, and performance. Commercially offered metal-based honeycomb structures are continuously produced from an aluminum sheet by means of cutting and bending metal rolls. The development of additive manufacturing

(AM) processes in recent years provides an opportunity to produce arbitrary typologies with less limitation comparing to conventional production methods. Two different AM methods have been used in this study. One of them is fused deposition modeling (FDM), which uses polymer material, and the other one is the electron beam melting (EBM) additive manufacturing process that uses an electron beam to melt metallic powders. In this study, material characterization studies were conducted to understand the constituent material behavior of lattice cells and to obtain constitutive equations. Moreover, experimental and numerical crush analyses were conducted to determine efficient auxetic topology for energy absorption applications, and an application study was deployed.

A comparative compression investigation of anti-tetrachiral and modified re-entrant lattices was conducted in-plane direction. Lattice structures were manufactured using FDM and crushed at the quasi-static condition. Non-linear finite element (FE) models of both structures were established, and the FE results were systematically compared with the experimental results in Figure 1. The onset of densification phases of both structures was determined numerically.

Results indicate that deformation modes strongly affect the force-deflection response of both designs.

In this manner, failure zones and buckling deformations were identified to find a relation with theory to modify geometries. The anti-tetrachiral design exhibits higher specific energy absorption than modified re-entrant hexagonal lattices. Beyond the auxetic characteristics, deformation mechanism of the anti-tetrachiral lattices provides an opportunity to construct an excellent crush absorption in-plane direction thanks to its high shear strength stem from its unique deformation mechanism. Furthermore, after concluding that the wrapping mechanism of chiral auxetic structures is more efficient than re-entrant structure mechanism, different type of chiral structures such as trichiral, anti-trichiral, tetrachiral, anti-tetrachiral, hexachiral and regular hexagonal are crushed numerically. As a result, hexachiral structure was selected for applications. The application study was devoted to the understanding of

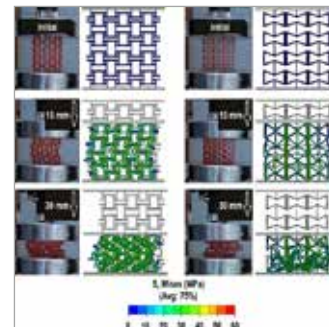


Fig. 1 - The experimental and numerical crush comparison of anti-tetrachiral and re-entrant lattices

the energy absorption characteristics of filled hexachiral auxetic lattices cylindrical composite tubes subjected to a uniaxial and lateral quasi-static load.

Composite tubes without filler material were initially subjected to uniaxial and lateral quasi-static crushing load.



Fig. 2 - Crushing of hexachiral filled composites in A) lateral B) uniaxial direction

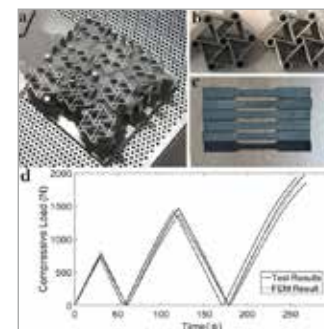


Fig. 3 - a) powder cake b) asbuilt and sandblasted chiral cells c) asbuilt and sandblasted tensile specimens d) compressive load profile test and numerical analysis result comparison

The identical experiments were then performed on hexachiral lattices and hexachiral lattices filled composite tubes. As a result, the SEA capability for the axial quasi-static crushing of the hexachiral lattices filled composite tubes experienced a 45% decrease in comparison with the hollow composite design. In contrast – and quite remarkably - a 450% increase in comparison with the hollow composite configuration was captured.

In addition to the application study, a hexachiral unit cell was produced using EBM technology and Ti6Al4V materials. To understand the effect of EBM AM method on mechanical properties specimens were produced in different directions, which are perpendicular (90°), 45° oriented and parallel (0°) to the powder deposition direction. Chiral lattice unit cells are produced where their flatwise surface is parallel to the powder deposition direction to have higher mechanical performance and prevent additional inner support structure usage. As a result, a compression load profile is used to investigate hexachiral unit cell displacement limit by applying large displacements without experiencing permanent deformations, degradation or failures. EBM produced chiral cells and tensile specimens, and experimental and numerical results can be seen in Figure 3. The outputs of the study can be used for special crashworthy applications such as

helicopter landing gears, automotive crashbox systems, filling lattices for spacecraft shell structures.

## SIMULATION AND DETECTION OF ICE FORMATION AND SHEDDING ON ROTORCRAFT

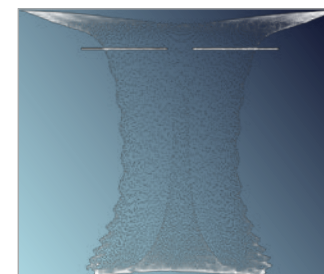
**Myles Morelli – Supervisor: Alberto Guardone**

In-flight icing is a peculiar phenomenon. Clouds of supercooled liquid water droplets exist within the atmosphere that are in an unstable state while undisturbed. However, when brought into contact with aircraft at sub-zero temperatures, these supercooled water droplets freeze on impact leading to the formation of ice. Ice induced geometric modifications on aerodynamically sensitive surfaces such as wings or rotors presents a serious issue to flight safety. Operating in the presence of icing clouds is therefore inherently dangerous and ill-advised without prior assessment of the effects of ice accretion. Accordingly, this influences the decision to provide icing clearance by the regulatory authorities. Moreover, the altitude in which rotorcraft operate coincides with the icing envelope where the likelihood of encountering supercooled water droplets is highest. Subsequently, rotorcraft are particularly vulnerable to the icing environment which makes understanding the phenomenon critical. Understanding this safety-critical issue for rotorcraft however is non-trivial, as this PhD research goes on to present. The scarce knowledge of both rotorcraft ice shapes and of their detection is disconcerting. Numerical modelling techniques represent a powerful tool to investigate the physics of rotorcraft icing and to assist in the design of new ice detection and protection technologies. Progress in the multidisciplinary field

of computational rotorcraft icing requires knowledge of research disciplines such as computational fluid dynamics, particle in cell techniques, phase change modelling, and mesh deformation strategies. This PhD research presents original research in each of these aforementioned disciplines associated to computational rotorcraft icing. The core of the PhD research is divided into three main technical parts and aims to: (i) introduce a conceptual framework for ice modelling and detection in a non-inertial, rotating framework; (ii) develop and validate novel three-dimensional numerical tools suitable for simulating rotorcraft aerodynamics and icing; (iii) analyse high-fidelity rotorcraft icing simulations while addressing the limitations identified within the literature. The first part of the PhD research is devoted to the conceptual design phase of an acoustic ice detection system. An acoustic characterization of glaze and rime ice structures is introduced to quantify different ice shape noise signatures which directly transcend from the iced performance characteristics. The feasibility of the detection technique is assessed on a two-dimensional oscillating Sikorsky 2110 airfoil based on the experimental model from *Phase-I of the High Fidelity Icing Analysis for Rotors* consortium. The second part of the PhD research is committed to the development and validation of three-dimensional

rotorcraft icing tools, namely; (i) efficient and robust mesh deformation strategies for aircraft icing, (ii) open-source rotorcraft computational fluid dynamics software, (iii) influence of rotor-wing interactions on predictions, and (iv) novel particle tracking techniques. Firstly, radial basis function mesh deformation techniques and data reduction schemes are introduced to address the issues intrinsic to the moving ice boundary. Radial basis functions provide a suitable cost-effective approach to ensure high-quality mesh deformation for challenging iced geometries and multi-step ice accretion. While the data reduction schemes presented, facilitate the use of radial basis functions even on large datasets. Secondly, this PhD research provides the first open-source and validated rotorcraft Computational Fluid Dynamics code by developing the well established SU2 solver. The incorporation of a new core feature to accommodate the blade kinematics of rotorcraft has been introduced. Thirdly, the flow physics associated to complex interactional behaviour of rotors and wings can be unlike that of isolated components and thus requires additional investigation. To this purpose, the turbulent flow field around a wing-tip mounted propeller configuration was simulated and validated using the model and test conditions released by the *Workshop for Integrated Propeller Prediction*. Fourthly, new techniques are

introduced concerning Lagrangian particle tracking in mesh with arbitrary motion as well as across non-conformal boundary interfaces to enable the simulation of clouds containing individual supercooled water droplets in complex rotorcraft flow fields as shown in Fig.1. The third part of the PhD research is dedicated to establishing state-of-the-art rotorcraft icing codes to help understand complex icing physics which can be difficult to comprehend using already existing icing analysis approaches. An original high-fidelity approach for the modelling of rotorcraft icing using new and entirely three-dimensional techniques is introduced, harnessing the previously developed numerical tools. The new approach is demonstrated on the experimental SRB-II model rotor in forward-flight developed at the Anti-icing Material International Laboratory in the Universit e du Qu bec  a Chicoutimi, Canada.



**Fig. 1 - Simulation of a cloud of supercooled water droplets in the flow field of a rotor in hover.**

Overall, the numerical predictions are in good agreement with the experimental data. Subtleties in the modelling techniques, which subsequently have a significant impact on the final ice shapes, are highlighted. Additionally, the instantaneous pressure fluctuations of the iced rotors are analysed to provide an early insight into the potential use of computational aeroacoustic codes further down the line.

# AI-AUGMENTED GUIDANCE, NAVIGATION AND CONTROL ALGORITHMS FOR PROXIMITY OPERATIONS OF DISTRIBUTED SYSTEMS

Stefano Silvestrini – Supervisor: Michèle Lavagna

Future science and exploration missions will implement innovative mission concepts to embark on daring endeavors exploiting cooperating intelligent systems. The concept of Distributed Space Systems boosts the achievable mission objectives due to the flexibility and adaptivity that the system inherently possesses. For instance, large synthetic instrumentation can be built by dedicated configurations of the system or very close-approach fly-by with small bodies can be performed; moreover, the single-point failure, typical of large satellites, is generally avoided in Distributed Systems and Formation Flying architecture. All these features are achieved at the cost of a significant increase in the on-board autonomy. Due to the relative distances involved, each agent composing the system needs to be able to react to unforeseen events rapidly and autonomously, such as collisions. To this end, it is critical that each spacecraft is capable of planning, navigating and controlling itself in unknown or partially-known environment, without ground-intervention. The research work presented here focuses on the development and testing of a full Guidance, Navigation & Control system aided by Artificial Intelligence techniques. The enhancement provided by Artificial Intelligence techniques allow the system to fly in uncertain environments by incrementally learning its mathematical modeling. The Thesis

develops a number of methods to recover the underlying dynamics by simply measuring relative state and processing it with an Artificial Neural Network. This dynamic representation is then used to plan control action and enhance the navigation and control synthesis. In particular, three methods for dynamics reconstruction are developed, together with their mathematical foundation. The three approaches integrate the Artificial Neural Network at different levels: from fully integrated, where the dynamics is completely encapsulated into an Artificial Neural Network, to partially integrated in which the network learns either the unknown dynamical accelerations or reconstructs the unknown parameters of the analytical expression. Such reconstruction scheme is used in two different planning and control algorithms:

Neural-Artificial Potential Field method and Model-Based Reinforcement Learning. The former is a fast and light algorithm that easily handles collision avoidance but lacks of planning; the latter is able to generate plans and control the spacecraft based on the learnt dynamics. Despite all the promising features of the neural-aided APF algorithm, two major drawbacks have been identified: on one hand, the APF may lead to instability depending on the tuning and type of required maneuvers; on the other hand, it does not optimize the maneuver control, potentially leading to high  $\Delta v$  cost, without a-priori estimate of the control effort. For this reason, an innovative strategy for the guidance and control of distributed formation has been developed. In particular, the method solves the shortcomings that arise from the partially known

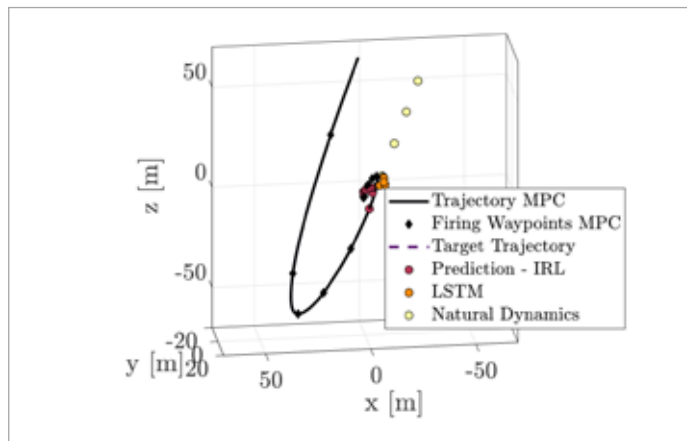


Fig. 1 - Inverse Reinforcement Learning for safe proximity maneuvers.

dynamical environment as well as the lack of knowledge of future trajectories of neighboring satellites during coordinated maneuvers. Given the distributed planning architecture, each spacecraft does not know how the rest of the system is evolving. For this reason, it has been necessary to develop an AI-based routine coupling Long-Short Term Memory and Inverse Reinforcement Learning to predict the behavior of external agents, being either in free-motion or controlled-motion, as shown in Figure 1.

The algorithms, when compared to classical methods, showed superior performance and constant increase in relevant Guidance, Navigation & control metrics (navigation accuracy, maneuvers  $\Delta v$ , etc.). Finally, in order to increase the Technology Readiness

Level of the algorithms, the work presents the Processor-In-the-Loop testing campaign executed with relevant hardware: a micro-controller unit and a single-board computer with similar computational power with respect to flight-hardware. In detail, the algorithms have been tested numerically and in Processor-In-the-Loop (PIL) simulations using a single core TMS320C28x 32-Bit CPUs @200 MHz of TI C2000-Delfino MCUs F28379D unit and a AM335x 1GHz ARM® Cortex-A8 mounted on a BeagleBoneBlack board. An end-to-end autocoding procedure has been developed to transition from Model-In-the-Loop simulations to Processor-In-the-Loop validation. The tests were deemed successful by evaluating the execution times, resource utilization and achieved accuracy, as shown in

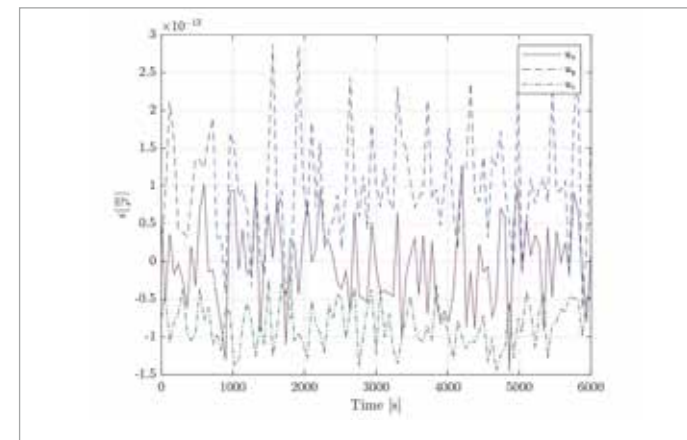


Fig. 2 - Numerical discrepancy for the model predictive control output during PIL test.

Figure 2 for instance. The outcome of the Thesis is a complete framework to integrate different AI-based techniques to enhance existing, well-established, algorithms. Employing Artificial Neural Networks for spacecraft operations can help in bridging the gap between space exploration and distributed autonomous flight. Being computationally light, online Artificial Neural Network aided algorithms can be deployed in micro-satellites, where the computational power is limited. The methodology described here can easily be extended to other mission scenarios, where the flexibility and adaptivity of the system is critical.