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PhD Yearbook | 2020

DOCTORAL PROGRAM IN AEROSPACE ENGINEERING

Chair:
Prof. Pierangelo Masarati

The aim of the course is the acquisition of the high level competences 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. The level of the course provide 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 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.

Since its foundation, more than 35 years ago, the doctoral course in Aerospace Engineering awarded more than 140 PhDs.

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MISSION ANALYSIS AND OPERATIONAL ASPECTS FOR A LUNAR EXPLORATION ARCHITECTURE

Lorenzo Bucci – Supervisor: Michele Lavagna

The work is focused on the analysis of a future lunar exploration architecture, coupling analytical techniques, trajectory design tools, and operational aspects. Recently, a renewed interest was observed toward the exploration of the Moon, particularly with NASA's intention to bring astronauts back to the lunar surface by the year 2024, the first after the end of the Apollo program. All over the world, space industries and agencies have manifested the intention to develop lunar orbiters, landers, rovers, thus fostering new research ideas and international partnerships.

At the time of the Apollo program, a set of constraint and aspects (technical and political) required robust transfer strategies and parking orbits, eventually leading to a quasi-Hohmann transfer from Earth to the Moon, and the use of circular low lunar orbits for the modules, likely at the expense of the overall fuel budget. Libration point orbits, although already envisaged by pioneering works, were not considered for the first human landing on the Moon. In recent times, a great deal of attention was given to libration point orbits in the Earth-Moon system. These orbits, non-Keplerian in nature, possess appealing features in terms of cheap access, low eclipse times, low station keeping requirements, and Earth visibility. Moreover, the tidal lock of the Moon rotation with its orbital motion causes its surface to keep the same relative geometry with respect to libration points orbits, rendering them particularly suitable for lunar surface access.

The core of the research was the investigation of the rendezvous problem in non-Keplerian orbits, which is a key feature of any future lunar exploration architecture. The most flexible solution involves ascent from lunar surface to a circular low lunar orbit, in order to avoid timing issues and have a flexible parking orbit from which to start the rendezvous sequence.

Delays in the initial manoeuvre can be compensated by a small Delta-V penalty; furthermore, a sensitivity analysis highlighted how the system constraints (steering rate, thrust-to-mass ratio, vertical altitude clearance) have an impact on the ascent Delta-V and a further optimization of the system design leads to benefits in the trajectory analysis and related budgets. Since the lunar surface is nearly fixed with respect to libration point orbits, a pattern of accessibility can be found, identifying the regions with cheapest and most expensive access cost, in terms of Delta-V. The pattern was thoroughly analysed, deriving the link between rendezvous location and lunar surface site, highlighting the most suitable ascent trajectory to obtain the cheapest transfer. The main reason of the different accessibility cost was identified in the plane change manoeuvre, which must be performed when arriving from those sites which do not allow ascent to an optimal low lunar orbit.

By employing dynamical systems theory, the use of unstable, central, and stable manifolds was discussed for the non-Keplerian rendezvous strategy. The coupling between operational requirements, safety, and fuel minimisation lead to the use of central manifold for the hovering phase; the study showed the possible use of the stable manifold for the terminal rendezvous, although noticing that the large time scales might not be suitable for practical application. A stochastically-optimal trajectory was eventually derived, taking into account the actual flight dynamics operations of a space mission. The technique was proved to be effective, showing the benefit of the coupling between operational constraints and trajectory analysis already from early design phases.

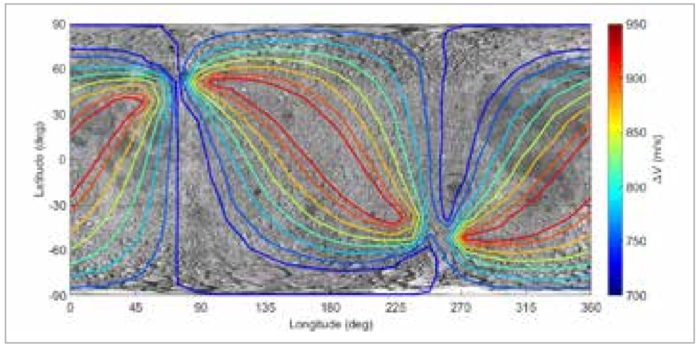

Fig. 1 - Lunar surface accessibility map. Total Delta-V from a 9:2 resonant Near Rectilinear Halo Orbit.

Furthermore, the dissertation investigated disposal options from cislunar environment, focusing on techniques to leave non-Keplerian lunar orbits. Among the different options, Moon collision can be easily achieved, exploiting unstable manifolds of the departure orbit, and tuning their non-linear component through the Delta-V. The drawback of this option is that some sites on the lunar surface shall not be targeted, and a massive use of such strategy will inevitably lead to debris pollution. The targeting of an Earth atmospheric re-entry is concluded to be poorly feasible for operational reasons. In order to achieve transfers with limited Delta-V, weak stability boundary transfers can be exploited, but these require long time of flight and present a high sensitivity to the initial manoeuvre. Eventually, the disposal in heliocentric orbit is a promising option. The study showed how dynamical systems theory, and massive trajectory computation, allow to identify regions in the phase space (manoeuvre, direction, epoch) where heliocentric orbits can be obtained with limited Delta-V budget.

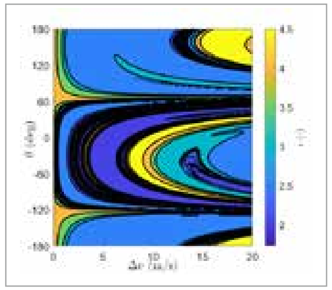

Fig. 2 - Finite time Lyapunov exponents map for heliocentric disposal. Black regions indicate chaotic transitions between solutions.

Moreover, the results of the study were validated with a Monte-Carlo procedure, proving its effectiveness. This investigation analysed transfer trajectories, rendezvous strategies, and disposal possibilities for a lunar exploration architecture. The term *architecture* is employed, instead of *mission*, considering that in such environment there will be synergies between multiple vehicles, both on the surface and in orbits, thus going beyond the concept of a single-objective *mission* design. The introduction of operational aspects, such as manoeuvre execution error, orbit determination issues, vehicle constraints, etc., proved to be beneficial for the design of such architectures, showing how trajectory analysis and fuel budgets can be further optimised with an overall gain, at the expense of a little increase in complexity in the design process.

END-TO-END ANALYSIS OF CCPS SIZE EVOLUTION IN SOLID ROCKET MOTOR FLOWS

Stefania Carlotti - Supervisor: Filippo Maggi

The combustion of aluminum contained in the energetic material of solid rockets starts from metal agglomeration at the burning surface and ends up with the expansion of molten droplets through the nozzle. Globally, the formation of these condensed (liquid and solid) combustion products is detrimental in terms of performance and environmental impact. On one hand, most of the specific impulse losses is attributable to two-phase flow, since particles could be well out of equilibrium with respect to the gaseous flow due to lag effects caused by the nozzle expansion. Indeed, the larger the particles, the higher their thermal and kinetic inertia, and the lower the real performance with respect to the ideal ones. On the other, recent studies highlighted that alumina particles represent a favorable substrate for heterogeneous reactions, involving significant ozone depletion effect. The rate seems to be strongly influenced by particle size and favored by the long residence time of fine dust in the upper atmosphere. Size and composition of those particles play a key role in the definition and in-depth comprehension of the previously described problems. However, condensed particles experience a variety of phenomena while they are carried through the nozzle by the gaseous mixture, greatly modifying their chemical and physical properties. Thus, the characterization and modelling of alumina particulate is not straightforward, and innovative diagnostics are required to support the description of the most important features.

The dissertation thesis targets the development of an end-to-end unified framework of techniques for the characterization and modelling of the alumina particle size distribution (PSD) in solid rocket motors.

The statistical development of the PSD is experimentally investigated starting with the characterization of the incipient agglomeration under a zero-cross flow condition. Indeed, quench bomb tests, performed at the Space Propulsion Laboratory (SPlab) of Politecnico di Milano enables to collect and post-process particles right after the release from the burning surface. Laser diffraction analysis is then employed to define the initial particle size distribution. Tests are performed under several combustion chamber pressures and aluminum mass fraction loadings, highlighting the influence of these parameters on the resulting PSDs.

The definition of the final state of the particulate requires the design, qualification and implementation of an innovative intrusive device for particles collection downstream of rockets nozzle exit. This activity is part of EMAP (Experimental Modeling of Alumina Particulate in Solid Booster), an ESA-TRP project led by the German Aerospace Center (DLR) and involving the Swedish Defence Research Agency (FOI) and the SPLab. The project aims at characterizing the rocket exhaust plume from a sub-scale SRM, resembling the exhaust conditions of Ariane 6 boosters. A rocket plume collector (RPC) is designed, merging the supersonic collection methodology and the gas scrubber technique, which segregates the particles from the gas with a quenching liquid sprayed by sprinklers. The detailed analysis is supported by a quasi 1-D solver based on a set of steady-state compressible equation in the form proposed by Shapiro. Hence, the nominal operative point of the RPC is by parametrically varying and opportunely tuning some selected parameters. On the same nominal geometry, a hybrid 2D axial-symmetric mesh is generated and the turbulent flow field is solved using the DLR TAU CFD code to verify the validity and robustness of the implemented code. Despite some discrepancies due to the multidimensional processes not treated by the 1D code, same trends and averaged values of the variable of interest are obtained, suggesting the robustness of the implemented engineering approach for design purposes.

Specific activities are carried out to support the implementation and assess the behavior of the whole system. From a modelling viewpoint, an off-design verification is conducted by means of a sensitivity and an uncertainty analysis. The former is based on the Elementary Effects Method of Morris, while the latter considers a coupled aleatory-epistemic approach in the Monte Carlo framework. The probability boundaries of the system are identified, and possible failures quantified by considering eventual variations of relevant parameters with respect to the nominal conditions. Strong counteracting effects, cancelling each other out, can be identified and lead to a global high working efficiency of the system. Simultaneously, preliminary experimental activities are needed for the instrument qualification. Among them, cold flow experiments, performed at the vertical wind tunnel (VMK) of the Supersonic and Hypersonic Technology Department of the DLR, are carried out at a representative Mach number (M=3) to verify the fluid dynamic behavior of the device in steady state regime and the capability of the system of capturing a representative population of particles seeding the flow without physical alteration.

Final hot flow tests campaign requires the integration of subscale solid rocket motors in the base model of the VMK. Same formulations studied for the incipient agglomeration tests are investigated under several combustion chamber pressures, expansion ratios and aluminum loading fractions, highlighting the influence of those parameters on the collected particles. Firstly, laser diffraction methodology analysis enables to obtain the volume-, surface- and number-based distribution as well as relevant diameters such as the Sauter diameter D(3,2) and De Brouckere Mean Diameter D(4,3). Secondly, Scanning Electron Microscope (SEM) enables to cross check the results obtained by the previous methodology and provides information on the morphology of the particles under analysis. Additionally, Xray diffraction (XRD) is employed to obtain the chemical composition of the residues, identifying and quantifying, if possible, crystalline forms.

The achieved experimental results serve both as boundary conditions and for mutual verification purposes of a parallel numerical activity. In fact, the subscale SRMs employed during the hot flow campaign and their discharge in the atmosphere are numerically investigated by means of reacting two-phase flow simulations. This activity is carried out at the Spacecraft Department of DLR, by means of the DLR TAU code. The multiphase simulations feature the lagrangian particle tracking method, the Sabnis break up model and the Troyes reaction mechanism, as well as the experimental PSD at the burning surface as input. Hence, (1) valuable information concerning the real region of interest of the novel experimental technique are obtained. Indeed, influence of the afterburning process and of the thermal and kinetic lags of the particles on the gaseous flow are assessed. Moreover, (2) the size of the alumina particulate is tracked and compared to the experimental outcomes of the particles collection in plume campaign. Despite of several modelling assumptions, the numerical diameters confirm the experimental results and can be in turn given as input to the RPC simulation to finally obtain a cross check on the behavior of this innovative diagnostics. (3) This final set of simulation enables to verify that the collection methodology and the internal fluid dynamic do not lead to particles distribution modification, confirming the high-fidelity experimental collection process, the reliability of the numerical simulations and the successful end-to-end analysis of CCPs size evolution in SRMs.

TOWARDS SAFE AND RELIABLE ON-ORBIT OPERATIONS WITH MANIPULATORS

Francesco Cavenago – Supervisor: Mauro Massari

Space robotics is considered one of the most promising technologies for future on-orbit servicing (OOS) missions, like active debris removal, maintenance of space systems, repair, assembly, inspection, refueling, etc. However, after the first studies almost 40 years ago, the use of spacecraft equipped with manipulators is still very limited. The reason lies in the high complexity involved in this kind of missions, especially if the system is wanted to be autonomous. In order to carry out successful and reliable robotic operations in orbit, many challenges have to be faced and a further development of the robotic technologies must be pursued.

Advanced algorithms are required to go through very different and demanding phases. First, the space robot has to rendezvous with a target object, which could be uncooperative and thus require the acquisition of information about the motion and physical properties. Then, an effective coordinated control of the spacecraft-manipulator ensemble is necessary, including trajectory generation and robust control schemes for both systems. A stable interaction between the robot and the target must be guaranteed during physical contact due to grasping and manipulation tasks. Moreover, unexpected collisions may occur since the robot is required to operate very close to other objects, and thus a reaction strategy should be implemented to avoid severe damages and the failure of the mission. These are only some of the challenges involved in an on-orbit autonomous robotic missions with manipulators. In this thesis, the attention is focused on the relative pose estimation problem and the physical contact handling, especially the unexpected collision handling.

A high-order numerical extended Kalman filter (HNEKF) and an unscented Kalman filter (UKF) are developed in the differential algebra (DA) framework to address the relative states estimation. HNEKF and UKF are filtering techniques in which the prediction step relies on a fully nonlinear mapping of the means and covariances, and thus they provide superior performance in nonlinear estimation problems with respect to linear filters. In the first technique, the nonlinearities are included in terms of high-order Taylor expansion. The latter one is based on the unscented transformation: carefully-chosen sample points are propagated through the true nonlinear system in order to propagate the expected value and covariance. Despite of the advantages of both filters, the need to derive analytically and integrate the so-called higher-order tensors for the HNEKF, and the need to integrate multiple points each time instant for the UKF, make them difficult to use for onboard application due to the computational complexity. However, these problems can be easily solved using DA techniques. By substituting the classical implementation of real algebra with the implementation of a new algebra of Taylor polynomials, any function *f* of *n* variables can be easily expanded into its Taylor polynomial up to an arbitrarily order *m* in the DA framework. This has a strong impact when the numerical integration of an ordinary differential equation (ODE) is performed by means of an arbitrary integration scheme. Starting from the DA representation of the initial conditions and carrying out all the evaluations in the DA framework, the flow of an ODE is obtained at each step as its Taylor expansion in the initial conditions. This eliminates the need to calculate the higher-order tensors at each time step by solving a complex system of augmented ODE for the HNEKF, and reduces the multiple integrations of the UKF to an easier evaluation of a Taylor polynomial in different sample points. The performance of the two DA nonlinear filters is assessed numerically through Monte-Carlo-based simulations, and it is compared not only in terms of accuracy, but also in terms of computational weight. Indeed, a key point for the success of OOS missions is the development of efficient algorithms capable of limiting the computational burden without losing out the necessary performance. To this aim, the DA-based HNEKF, which was developed inside the Ariadna study “Assessment of Onboad DA State Estimation for Spacecraft Relative Navigation” in collaboration with ESA, has been also implemented on a BeagleBone Black platform, which is deemed to be representative of the low computational capability in orbit.

As regards the physical contact handling, the problem can be split into different phases: the detection, the isolation, the identification and the reaction. In the first phase, some significant signals are monitored, and when they cross a predefined threshold, an alarm is risen. Then, in the subsequent two phases, the part of the robot involved in the impact is identified and the contact force is estimated. Finally, in the last phase, the robot is commanded to react properly to the contact. Note that this scheme is valid for both planned and unexpected contacts. In order to address the first three phases jointly, the well-known momentum-based observer, initially developed for fixed-base robots, is extended to floating-base robots and analyzed considering space-related issues. This observer computes the linear, angular and joint momentum residuals which turn out to be the estimates of the external generalized forces acting on the floating base and the disturbance joint torques due to the contact. Then, the residuals can be used to estimate the external wrench acting on the robot. The main drawback of the method is the need of a fast and accurate reconstruction of the base linear velocity, which is difficult to obtain in real space applications. Therefore, a new observer is proposed based on a centroid-joints formulation of the space robot’s dynamics. The most important feature of this observer is the complete decoupling of the angular and joint momentum residuals from the base linear velocity. These residuals can be used to reconstruct the external wrench leading to a more practical and better-performing solution. Indeed, the proposed method requires only the knowledge of the base angular velocity and control moments, and the joint positions, velocities and torques, which can be acquired at high frequency and feature relatively low noise. Moreover, the angular and joint momentum residuals can be used to isolate the contact rapidly and accurately. Both observers have been validated on the On-Orbit Servicing Simulator (OOS-Sim) hardware-in-the-loop facility at the DLR. Afterwards, another technique for the detection and isolation is also presented, which is based on monitoring the components of the robot’s total momentum. The performance is evaluated numerically and a discussion of the pros and cons with respect to the observer is reported in the thesis.

Finally, a compliant reaction controller is proposed to face unexpected collisions. The controller uses the information from the developed observer to move away from the obstacle reaching a safe position and configuration, while keeping a desired attitude. Thanks to the developed strategy, multiple impacts and the build-up of the contact force, which can lead to damages and instability, are avoided. The controller is demonstrated to be input-to-state stable, namely the error on the states is bounded during the contact and goes to zero when the contact ends. The performance is assessed through a simulation example, considering a 7 degrees-of-freedom robotic arm on a 6 degrees-of-freedom moving spacecraft, equipped with thrusters and variable speed control moment gyros.

ORBIT DETERMINATION OF RESIDENT SPACE OBJECTS USING RADAR SENSORS IN MULTIBEAM CONFIGURATION

Matteo Losacco – Supervisor: Pierluigi Di Lizia

In the last decades, the number of man-made objects orbiting the Earth has dramatically increased. In about 60 years of space activities, more than 5000 launches have turned into around 42000 tracked objects in space, of which about 23000 remain in space and are regularly tracked by the US Space Surveillance Network. Among all these objects, only a small fraction (about 1950) are operational satellites. About 24% of the catalogued objects are satellites, while about 18% are spent rocket upper stages and mission related objects. The presence of satellites and upper stages is a source of new objects itself. Since 1961, more than 500 in-orbit fragmentation events have generated a population of so called “space debris” whose estimated numbers are impressive: about 34000 objects larger than 10 cm, 900000 objects from 1 cm to 10 cm, and 128 million objects from 1 mm to 1 cm. The presence of space debris unavoidably jeopardizes the operative mission of active satellites. The consequences of a possible collision between an operative satellite and space debris may result into the satellite failure or, in the worst-case scenario, satellite destruction and fragments generation. This hazard calls for the crucial adoption of countermeasures aiming at reducing mission related risks. Specific space programmes were started to build the expertise required to manage the challenges posed by the space traffic control problem, such as collision risk assessment and re-entry predictions. All these programs rely on the accurate estimation and prediction of the state of the orbiting objects, which are derived from tracking actions by dedicated optical, radar and laser sensors.

This thesis investigates the possible role of the novel Italian multibeam BIstatic RAdar for LEo Survey (BIRALES) for space surveillance. The first part of the thesis offers a detailed description of the sensor. The radar couples a single beam pulse compression system and a multibeam continuous wave system that provide slant range measurements coupled with Doppler shift data and multiple signal to noise ratio (SNR) profiles that are generated every time an object crosses the sensor field of view (FoV). The availability of multiple SNR profiles theoretically offers the possibility of reconstructing the track of the transiting object in the receiver (RX) FoV, thus enabling initial orbit determination (IOD) with just a single passage. This possibility is hindered by the complex gain pattern of the multibeam system, characterised by multiple lobes per beam that introduce an ambiguity in the track reconstruction phase. The additional lobes, called grating lobes, can be seen as exact replica of the beam main lobe generated by the geometrical regularity of the RX. Their presence unavoidably complicates the reconstruction of the angular profile of the object, since the univocal correlation SNR peak-beam main lobe that a single gain lobe scenario would grant is in this case not possible. The context is further complicated by dependency of grating lobes on beam angular position and RX elevation. Starting from a detailed description of the grating lobes phenomenon, the proposed algorithm, termed Multibeam Orbit Determination Algorithm, operates in two phases. The first phase aims at reconstructing the angular path of the orbiting object in the RX FoV. The ambiguity introduced by the presence of several gain lobes per beam is solved by generating multiple candidate sequences, i.e. sequences of gain lobes that are compliant with the measured SNR peaks. These sequences are progressively analysed with a series of filtering actions, which identify the most realistic sequences and prune away unfeasible angular paths. Each identified candidate sequence is then refined with a least squares process, in which the parameters defining the angular path are tuned to obtain a matching between simulated and measured SNR profiles. The operation is done by exploiting the available slant range measurements and is repeated for all the identified realistic sequences. At the end, the sequence that guarantees the lowest residual is selected as best candidate sequence, and an estimate for the track of the object is obtained. This estimate is then coupled with the available Doppler shift and slant range measurements, and a least squares process is run to obtain an estimate of the state of the object at the epoch of the first available measurement. The thesis offers a detailed description of the proposed algorithm, highlighting strengths and criticalities.

The described method is then applied in the second part of the thesis, where an analysis of the potential of BIRALES sensor while performing simulated survey operations is offered. The first part of the analysis is dedicated to the assessment of the observation capabilities of the sensor while observing two different orbiting populations of unknown objects, namely NORAD and MASTER 2040 LEO populations. The analysis shows the limitations of the current bistatic configuration, which result into a low number of objects observed multiple times. The second part of the analysis offers a description of the performance granted by the proposed orbit determination algorithm. The accuracy of both angular path and state estimates is analysed and discussed. The proposed track reconstruction algorithm provides precise track estimates, and the occurrence of the critical scenarios is quite limited. On the other hand, the accuracy of the obtained track estimate strongly depends on the number of illuminated beams and on the regularity of the available SNR profiles. These aspects, in turn, affect the accuracy of the state estimate, which depends on both available measurements and estimated track.

Starting from the available observation capabilities and the achievable orbit determination accuracy, the third part of the thesis presents a detailed analysis of the cataloguing performance of the sensor. Three different scenarios of increasing complexity are simulated and investigated: catalogue maintenance, catalogue generation, and the general cataloguing problem. The core of the problem is the identification of a suitable correlation process capable of fully exploiting the available information. For the presented analyses, different formulations for covariance-based correlation methods are tested, and a specific cataloguing algorithm is presented and applied. The algorithm is structured as an iterative process in which correlation and orbit determination refinement are strictly connected. Three different formulations for the three investigated scenarios are applied and discussed, and the sensitivity of the algorithm to the available parameters is discussed in detail. The analyses confirm the evidences obtained while investigating the survey potential of the sensor, resulting in limited cataloguing performance for all the investigated scenarios.

The final part of the thesis is dedicated to the assessment of the performance of the developed orbit determination algorithm while processing data obtained during real observation campaigns. The results show a general decrease in the obtained state estimates accuracy of about one order of magnitude in position and at least a factor three in velocity with respect to what obtained with numerical simulations. Different sources of inaccuracy are detected, involving both the processed measurements and the available model for the multibeam gain pattern. On the other hand, the statistical analyses on the number of observed objects confirm the trend highlighted in the numerical simulations. Starting from these considerations, an analysis on possible upgrade configurations for the sensor is finally presented, showing the possible benefits granted by the combined use of a monostatic configuration and a larger FoV.

COMBINED CHEMICAL-ELECTRIC PROPULSION DESIGN AND HYBRID TRAJECTORIES FOR STAND-ALONE DEEP-SPACE CUBESATS

Karthik Venkatesh Mani – Supervisor: Francesco Topputo

Interplanetary CubeSats enable universities and small-spacecraft consortia to pursue low-cost, high-risk and high-gain Solar System exploration missions, especially Mars missions. Cost-effective, reliable, and flexible space systems need to be developed for CubeSats to embark on interplanetary missions. Primary propulsion systems become an integral part of interplanetary CubeSats since orbital manoeuvring and control become indispensable. CubeSat missions can be accomplished by a) in-situ deployment by a mother ship, and b) highly flexible stand-alone CubeSats on deep-space cruise. Stand-alone CubeSats have a high degree of flexibility and autonomy which widen the launch windows and introduce new paradigms in autonomous guidance, navigation and control.

The current work focuses on design and performance characterisation of combined chemical--electric propulsion systems that shall enable a stand-alone 16U CubeSat mission on hybrid high-thrust--low-thrust trajectories from Earth to Mars. The emphasis is on combined propulsion since they are two separate systems in the same spacecraft that are used in different mission phases. Hybrid transfer solutions that utilise chemical—electric propulsion achieve a balance between system mass and transfer time. The application case is the Mars Atmospheric Radiation Imaging Orbiter (MARIO), a 32 kg 16U CubeSat mission that shall demonstrate the capabilities to escape Earth, perform autonomous deep-space cruise, achieve ballistic capture, and be emplaced on an operational orbit about Mars.

Chemical propulsion design is based on the ΔV requirement of 445 m/s for Earth escape and Mars capture orbit stabilisation, thrust constraint of 3 N, and combined propulsion system mass constraint of 50% of the initial wet mass. The system utilises non-toxic green monopropellant, an Ammonium Dinitramide (ADN)-blend called FLP-106, to improve safety and performance over conventional propellants such as Hydrazine. The thruster operates at 2 MPa combustion pressure. The nozzle throat diameter is 0.75 mm, the expansion area ratio is 200 and an expansion half angle of 15°. Two thrusters are used and the total thrust yield is 3.072 N and the I_{sp} yield is 241.2 seconds. High-thrust trajectory analysis is performed to calculate the propellant consumption for the shortest time for Earth escape. The high-thrust trajectory is executed in multiple burns to raise the orbit and each thruster burn is split equally before and after the perigee. The overall flight time, including powered and ballistic flight, until reaching eccentricity e = 1 is ~33.03 days. The total propellant mass is 5.725 kg for the required ΔV. Four elliptical dome ended cylindrical tanks, with a total volume of 4640.4 cm^3, are used to accommodate the propellant. The tanks are designed for a burst pressure of 3.9 MPa and a nominal feed pressure of 2.2 MPa. A pressuriser tank with a volume of 492 cm^3 containing gaseous nitrogen at 28 MPa is designed to maintain the propellant tank pressure. The total feed system volume is 8U. The overall mass of the chemical propulsion system is 6.91 kg, which is 21.59% of the wet mass (32 kg).

Electric propulsion is utilised in executing low-thrust autonomous heliocentric transfer, achieving ballistic capture, and circularising the spacecraft trajectory to an operational orbit about Mars. The design is based on the requirements placed on maximum transfer time and maximum power consumption as well as the constraint on the combined propulsion system mass. A performance model of an iodine-propelled inductively coupled miniature radiofrequency ion thruster is implemented to calculate the variation of thrust, specific impulse and efficiency with input power. The thruster size is 2.5 cm. The initial mass flow rate is maintained at 48 µg/s and the grids are maintained at 2000 V potential difference for ion acceleration. The maximum thrust yield is 1.492 mN and the maximum I_{sp} is 3168 seconds, considering the maximum input power of 67 W. The thrust and I_{sp} increase/decrease with increasing/decreasing input power, which in turn depends upon the Sun—spacecraft distance. A power constrained low-thrust trajectory optimisation utilising the thruster performance model is pursued to calculate the transfer time, ΔV and the required propellant mass for fuel-optimal and time-optimal transfers. Low-thrust circularization is then performed to complete the mission design and to size the system. For the time-optimal transfer, the total time of flight is 1250 days with a continuous thrusting period of 1186.83 days. The cumulative ΔV is 5.837 km/s. The total propellant mass amounts to 5.87 kg for a time-optimal heliocentric transfer and low-thrust circularization. A thermoplastic propellant tank with dimensions of 20 cm × 10 cm × 6.5 cm is used to store the propellant. Including the PPCU and the feed system, the overall volume amounts to 3U. The overall system mass is 6.57 kg, which is 20.53% of the launch mass.

Preliminary systems design of MARIO is presented to provide an overview of the mission and the context for the research. The system architecture and flight systems design that includes information on subsystems such as power, communications etc. are presented. The configuration of the MARIO spacecraft and the system budgets are also presented. Reflectarrays along with high-gain antennas are utilised to establish long-distance low-bandwidth X-band communication link with the Earth. Two deployable solar arrays with a drive mechanism are utilised for continuous power generation. The spacecraft uses a modified 16U structure with aluminium shielding. A customised VIS and IR range camera is used along with a high-capacity processor for observation and on-board processing.

Concurrent optimisation of low-thrust trajectory and electric thruster operations is performed to achieve comprehensive optimal solutions for heliocentric transfers. Thruster control parameters such as input grid voltage, mass flow rate, and RF coil power along with trajectory control parameters such as azimuth and elevation thrusting angles in spacecraft body centred frame are concurrently optimised to achieve transfers with minimum flight time. The definition of this framework paves the way for autonomous and responsive thruster operations along the trajectory for achieving efficient transfers without human intervention. This shall enable a comprehensive design of autonomous interplanetary CubeSats.

Combined chemical—electric propulsion could lead to a major paradigm shift in solar system exploration efforts using CubeSats at high science-to-investment ratio.

GRID SEARCH APPLICATIONS TO TRAJECTORY DESIGN IN PRESENCE OF FLYBYS

Davide Menzio – Supervisor: Camilla Colombo

In the design process of a deep-space exploration mission, two phases can be distinguished: an interplanetary cruise and a final phase in planetary moon-system. In both cases, flyby manoeuvres have a positive impact on the overall mission cost and the scientific return.

This doctoral dissertation focuses on methods, techniques, and tools for modelling the trajectory in presence of flybys. Depending on the gravitational model used and the mission scenario foreseen, various part of the search space can be analysed, and different insights derived about the nature of the third-body interaction. The ability of one method to reveal insights on the dynamics depends on the choice of the performance parameters and control variables used to study the trajectory evolution under the effect of the dynamics. Optimisation is a necessary step to confirm/disprove the solution proposed in the preliminary design, derived in simpler dynamics, by evaluating its applicability in the full-body one. While, generally, the inference process is deductive and moves from the model to the data, under specific conditions, the inductive stream can be followed. The improved understanding of the dynamics might positively affect the design process.

This work deals with grid-search approaches for the identification of feasible flyby.

The complexity of the mission scenario of Multiple-Gravity Assisted trajectories makes difficult to perform a comprehensive search of feasible transfers in a multi-dimensional solution space that is further constrained by all the trajectory requirements. Graphical methods represent a special class of search technique, which appear particularly appealing for the possibility to provide insights on the flyby dynamics.

The main theme encompassing the dissertation regards the reduction of the computational effort associated to the scanning of the search space. This objective is carried out exploiting graphical methods applied to the design of interplanetary trajectories, on one side, to improve the understanding of the dynamics and, on the other, to revisit the design process, itself.

Conic approximation represents the baseline of the design of flyby trajectories. Branch and bound techniques are applied to construct the transfer orbit as a sequence of Keplerian arcs connecting two minor bodies, at a time, but remaining bounded to the dynamics of primary, larger body. Flybys resolves the velocity discontinuities at each conjunction with the secondary, smaller body.

The first analysis of this dissertation originated from the observation that grid resolution of each Lambert leg presents a significant portion of solution space with high delta-v. Therefore, the dissertation proposes to study the low delta-v region in the simpler dynamics of circular co-planar orbits of the planets. The hypothesis allows to determine analytically the location of the minimum delta-v and to characterise the shape around it through the solutions associated to tangential manoeuvre at departure and arrival with prescribed delta-v. The approach can be easily extended to multi-revolution trajectories.

The next step moves from the direct trajectory to the flyby one. A three-steps solution is proposed to reduce the computational effort of grid approaches. Firstly, the recombination of the search spaces associated to the pre- and post-encounter trajectories enables to reduce the cubic growth of cascade approaches into a quadric one. Secondly, the switch from an epoch-based parametrisation of the search space to an orbital elements formulation allows to obtain a more compact set to scan. In the end, pruning techniques are implemented identifying bounding regions in search space defined by delta-v levels and orbital elements variations derived for limiting cases of the flyby.

The simplicity of the patched conics method offers the great advantage to describe the spacecraft motion by invariant quantities, but at the same time presents a limited understanding on the chaotic nature of the interaction between two or more gravitational fields and constrains the trajectory design to high energy flyby. Differently from the two-body dynamics, in the three-body dynamics the total energy is the unique invariant of motion. Such condition prevents to describe the trajectory analytically and requires to numerically propagate the spacecraft trajectory from an initial state to study its evolution in the three-body dynamics. Studying the complete search space of the state vector can be computationally intensive, therefore mapping approaches have been developed to study the effect of the third body perturbation on an osculating orbit, approximating the dynamics.

Following this logic, the 3D Flyby map is developed to study the flyby effect in the three-body dynamics. Prograde and retrograde flybys can be distinguished, differently from what patched conics predicts, and in particular the formers are more efficient than the latter. Resonant flybys can be identified interpolating and refining the initial conditions of the Flyby map. A natural sequence of resonant flybys can be determined, differently from what patched conics theorises, a presents a specific direction in crank angle.

ORBIT PROPAGATION AND UNCERTAINTY MODELLING FOR PLANETARY PROTECTION COMPLIANCE VERIFICATION

Matteo Romano – Supervisor: Camilla Colombo

At the beginning of interplanetary missions, launcher upper stages may be left orbiting the Sun on trajectories that may bring them close to other planets, with the risk of impacting and contaminating them. For this reason, all interplanetary missions must comply to planetary protection requirements. These guidelines have the goal of limiting the probability of unwanted collisions between mission-related objects and celestial bodies that may host extra-terrestrial life forms or conditions favourable to their development.

The aim of this PhD research is to develop new techniques and numerical tools to improve the means currently employed in planetary protection analysis. The proposed approach focuses on different methods for numerical propagation, uncertainty sampling and uncertainty propagation to make the verification of compliance to planetary protection requirements more precise and affordable. In this work, particular attention is given to the main aspects affecting the reliability and affordability of planetary protection analysis.

In particular, the orbital propagation in the n-body dynamics which causes issues on a numerical level due to the occurrence of close approaches with celestial bodies is addressed by selecting methods for the integration of the trajectories and comparing them in various test cases. The effect of numerical integration errors on the overall planetary protection analysis is assessed, and a novel approach to deal with close encounters with planets is proposed. This method establishes a criterion based on the eigenvalues of the Jacobian of the equations of motion to detect when a fly-by occurs during the propagation: this provides a definition that avoids neglecting some of these events in the analysis, as a way to identify all possible conditions that affect the simulation and to contain their effects at the numerical level.

On the side of the estimation of impact probability, a novel application of the Line Sampling method is proposed as an alternative to the standard approach based on Monte Carlo simulation. During the research, the method was implemented and validated for planetary protection analysis and made more effective by developing new algorithms to increase its accuracy and efficiency: these novel techniques allow to extend the applicability of the method to more complex cases, where multiple impact events and very low probability levels are expected. The findings confirmed the higher accuracy of LS in estimating low probability levels: when compared to standard MC, the LS method was capable of correctly estimating the impact probability, reaching the same accuracy after fewer propagations, or, vice-versa, returning more accurate results when the same number of propagations was performed.

Finally, uncertainty propagation methods were also applied to planetary protection, to overcome the limitations of sampling methods. The use of Gaussian Mixture Models and of adaptive splitting of the distribution is proposed to accurately propagate the initial uncertainty characterising the state of a mission-related object into interplanetary orbits, and to estimate efficiently the probability of impacts.

SYSTEM IDENTIFICATION, CONTROL, AND DYNAMICS ANALYSIS OF A SMALL-SCALE COMPOUND HELICOPTER

Meiliwen Wu – Supervisor: Marco Lovera

Due to the urgent need for high-speed VTOL aircraft in military and civil areas, the aviation pioneers have proposed a number of configurations mixing the lift and thrust devices from the existing conventional helicopter and fixed-wing aircraft. These novel concepts have promoted the development of many compound aircrafts after decades of demonstration, theoretical research, and experimental process, e.g., tiltrotor, compound helicopter, tiltwing, liftfan, and vectored aircraft. Among the novel ideas, the compound configuration is a good option for helicopters to break speed limitations and improve maneuverability. However, the compound concept applied to a small-scale helicopter has not been investigated in detail.

This work intends to promote the concept of compound configurations on the small-scale helicopter platform. The study gives a comprehensive investigation of the dynamic characteristics of an innovative 9.5 kg small-scale compound helicopter (SCH), which involves the work of prototype platform establishment, nonlinear modeling, system identification, control design, flight experiments, and validation. In the study, an innovative small-scale compound helicopter is established by installing ducted fan, wings, and horizontal stabilizer components. Multiple configurations are considered: (1) The general helicopter; (2) The general helicopter installed a ducted fan; (3) The general helicopter installed ducted fan and wings (see Figure 1); (4) The compound helicopter controlled by elevator and aileron, etc. The main configurations were tested in autonomous flights from hover to 32 m/s forward speed.

In order to give an all-around dynamic investigation, first, linear models of hover and forward flight conditions are obtained by the frequency-domain identification method in CIFER software. In hover, the control signals before and after the gyro part were recorded and processed as identification inputs. Two linear models considering with and without the gyro dynamics are decided. In the forward flights, a closed-loop investigation method is introduced to analyze the dynamics features of the compound configurations.
Then, the PBSIDopt, a time-domain identification method, is applied to analyze the identification problem from a different perspective. The PBSIDopt algorithm can be calculated in a numerically stable and efficient way, but the drawback is that it is difficult to obtain parameters with physical meanings. For dealing with this problem, a combined method $PBSID_{opt}$-H_∞ is implemented to search for the closest model with a physical structure.
Meanwhile, an 11-state nonlinear mathematical model is established according to the first physical principles and is modified with the help of the identification results. The model is carefully checked in the time-domain.
Further on, a transition control strategy is established based on a multiple-feedback control scheme. The strategy allocates the ducted fan thrust and the main rotor lift at different speed conditions. The whole strategy is optimized by the up-to-date Structured H_∞ method. A decoupling algorithm is proposed to alleviate the adverse coupling effects brought by the cyclic control.
Finally, in the last chapter, the main dynamics features are extracted from the flight experiments, the closed-loop identifications, the hover identifications, and the nonlinear model. By using the flight experiments, the trim results of different configurations at the high-speed are extracted and analyzed. The angle and force distributions of the main rotor under trim conditions are calculated with the help of the nonlinear model. The overall dynamic messages, e.g., rotor time constants, damping derivatives, etc., are compared with that of the other small-scale helicopters and compound configurations.


Fig. 1 - Small-scale compound helicopter.

Results show that the identified models of CIFER and $PBSID_{opt}$ provide satisfactory predictions on the flight responses. The combined method $PBSID_{opt}$-H_∞ can extract structured parameters from the $PBSID_{opt}$ results, offering an efficient computational tool. The established nonlinear model is successful in simulating the flight responses and predicting the trim values of experiments below 27 m/s. The interference between the wing and main rotor should be carefully processed under conditions of large negative pitch angle. The designed transition control strategy gives a complete solution of realizing the autonomous flights with different compound configurations. The optimized controller obtained by the Structured H_∞ performs a smoother transition and more stable high-speed sections compared with the previous one. The decoupling algorithm constrains the off-axis responses substantially. The designed small-scale compound helicopter is successful in unloading 80 % ~ 90 % of the main rotor forces and reducing power consumption. From the low-speed to the high-speed, the rotor time constant decreases and the maneuver derivatives decline. The helicopter is more sensitive to disturbance in longitudinal.
The compound study can be applied to more complete compound platforms and consider more advanced control algorithms to perform better high-speed flight features in the future.