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

PhD Yearbook | 2019

DOCTORAL PROGRAM IN AEROSPACE ENGINEERING

Chair:
Prof. Pierangelo Masarati

The aim of the course is the acquisition of the high level competence 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 allows the graduates to compete in a European and international environment.
The course is three years long, 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, 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 has a background curriculum lacking some introductory knowledge required for the Doctorate, the Faculty Board will ask to recover such knowledge, with the assistance of the tutor.
The same Faculty Board will verify afterward 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 will take into consideration also the objectives and the core topics of the candidate's thesis. The program will also try to consider general cultural requirements as well as what is deemed to be more specifically related to 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 general in an external institution is allowed, and even strongly recommended. Its duration may range from a few weeks up to one and a half year. The related activities should be carried out in well known and qualified scientific institutions (universities, research centers, etc.), and well 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 vehicles, fixed wing vehicles and space vehicles.
In this context, a more specific competence can be gained either in a single 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, 28 years ago, the doctoral course on Aerospace Engineering graduated more than 100 PhDs.

DOCTORAL PROGRAM BOARD		
Prof. Alessandro Airoldi	Prof. Pierluigi Di Lizia	Prof. Pierangelo Masarati
Prof. Franco Auteri	Prof. Lorenzo Dozio	Prof. Marco Morandini
Prof. Franco Bernelli Zazzera	Prof. Aldo Frezzotti	Prof. Maurizio Quadrio
Prof. James Biggs	Prof. Luciano Galfetti	Prof. Giuseppe Quaranta
Prof. Carlo Bottasso	Prof. Alberto Guardone	Prof. Sergio Ricci
Prof. Camilla Colombo	Prof. Michèle Lavagna	Prof. Francesco Topputo
Prof. Giovanni Consolati	Prof. Marco Lovera	Prof. Riccardo Vescovini
Prof. Alessandro Croce	Prof. Filippo Maggi	Prof. Alex Zanotti
Prof. Luca Di Landro		

ADVISORY BOARD	
Valerio Cioffi, Leonardo Aeronautica	Marco Molina, Leonardo Elettronica, Difesa e Sistemi di Sicurezza
Gian Paolo Dallara, Dallara	Franco Ongaro, Estec
Luca Medici, Leonardo Elicotteri	Grazia Vittadini, Airbus

SCHOLARSHIP SPONSORS	
ERC	Leonardo
ESA	Marie Skłodowska Curie

ABSOLUTE AND RELATIVE 6DOF DYNAMICS, GUIDANCE AND CONTROL FOR LARGE SPACE STRUCTURES IN CISLUNAR ENVIRONMENT

Andrea Colagrossi – Supervisor: Michèle Lavagna

Future science and exploration missions will exploit cislunar environment as effective outpost to advance technology readiness in view of human presence beyond Earth. These ambitious space programmes entail modular large space infrastructures to be available in non-Keplerian orbits, to run manned and robotic activities in Moon vicinity. As ISS operations teach, in space outposts ask for complex logistic, which leans on rendezvous and docking/undocking capabilities between space segments and embrace different engineering disciplines. So far, no mission performed autonomous and accurate proximity operations but in LEO. Conversely, several flown missions were operational on non-Keplerian orbits, exploiting the increased knowledge about n-body dynamics modelling for trajectory design. However, existing studies deeply investigating the 6 DOF absolute and relative dynamics in non-Keplerian orbits are somewhat missing; this area of investigation is now mandatory to support the cislunar infrastructure design and implementation, assessing and addressing practical solutions for guidance and control strategies, which shall be applicable to reliably manage proximity operations of the lunar gateway.

The PhD research, starting from the well-known restricted n-body problem formulation, presents analyses and results obtained by adding a coupled orbit-attitude dynamical model and the effects due to the large structure flexibility. The cislunar environment is accurately modelled, assessing the fidelity of various modelling approaches. Thus, the most relevant perturbing phenomena, such as the Solar Radiation Pressure and the Sun's gravity, are included in the Earth-Moon system model as well. The absolute orbit-attitude dynamics in cislunar space is investigated with the purpose to highlight periodic motions that can be exploited to naturally stage large space structures in lunar vicinity.

Many kinds of planar and spatial families of orbits in the n-body environment are generated exploiting multiple-shooting algorithms. As example, orbit-attitude periodic dynamics in EML1 Lyapunov Orbits are reported in Figure 1. These naturally periodic solutions show three dissimilar rotational motions for a disk-like spacecraft, with moment of inertia ratio equal to 5. They are related to orbital motions with period equal to 12.1 d, 14.1 d and 18.88 d. The attitude dynamics analysed in the quaternion subspace allows to point out and uniquely characterise the various dynamical families, which have different behaviours according to the orbital period, the energy of the orbit, the dynamical bifurcations and the changes in the stability of the motion along the periodic family. The 6 DOF dynamical models are implemented to analyse absolute and relative dynamics in cislunar space. Moreover, efficient 6 DOF absolute and relative guidance and control methods are designed leveraging the non-Keplerian natural dynamics. In fact, the coupled orbit-attitude dynamics allows to compute orbit-attitude manifolds, which are of particular interest for relative dynamics during rendezvous and proximity operations: natural orbit-attitude trajectories can be exploited to easily guide a spacecraft (chaser) during its approach to the operational orbit of a target one. In Figure 2, the 6DOF relative dynamics is shown on a stable manifold approaching the orbit-attitude state of a possible target in vicinity of the apolune region of an EML1 Halo Orbit. Figure 2(a) shows the classical manifold trajectories approaching to the target orbit. The relative trajectories in figure 2(b) have a spiral motion toward the target that naturally bring the chaser at close distance from the matching point (~ 1 km). The attitude dynamics over a natural manifold, in figure 2(d), is always matched with the one on the target's orbit. In practice, orbit-attitude manifolds have no relative attitude component: the chaser can be controlled to have a zero-relative orientation with respect to the target at the beginning of the rendezvous phase.
Then, it will naturally have an absolute rotational motion that is continuously matching the target attitude up to the docking point.
A final controlled 6DOF motion can complete the natural proximity operations. For this purpose, the PhD research work presents the possibility to connect natural drift rendezvous trajectories with a final controlled close proximity path. Relative Guidance and Control functions to be operated in cislunar space under the framework of energy optimal applications are developed and tested in relevant scenarios, as the one reported in Figure 3. The outcomes of the PhD research work are intended to highlight relevant results and drivers for cislunar outposts design, with the purpose to better leverage the coupled 6 DOF natural dynamics in computing effective and efficient trajectories, while addressing functional and performance requirements. On board resource limitations and system reliability are always highlighted in the analyses. Different case studies for large space structures on selected non-Keplerian orbits in the Earth-Moon system are discussed to point out some relevant conclusions for the potential implementation of such a complex space infrastructure.

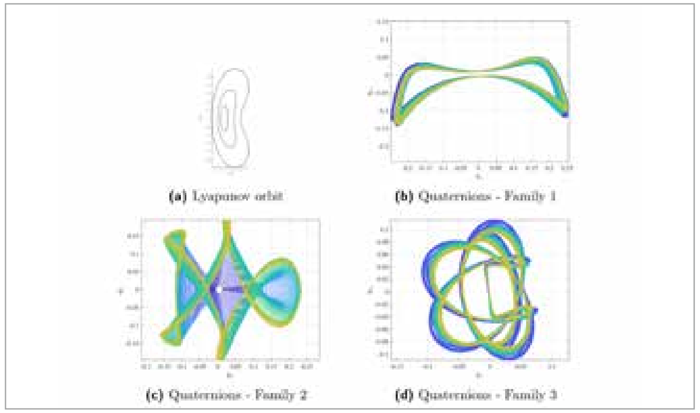

Fig. 1 - Family of Lyapunov ordbit-attitude periodic dynamics - Quaternion subspace, components 1 and 2. (EML1 Lyapunov Orbits: $T_{t1}\cong 12d$, $T_{t2}\cong 14$ and $T_{t3}\cong 19d$ - $I_{max}/I_{min}=5$).

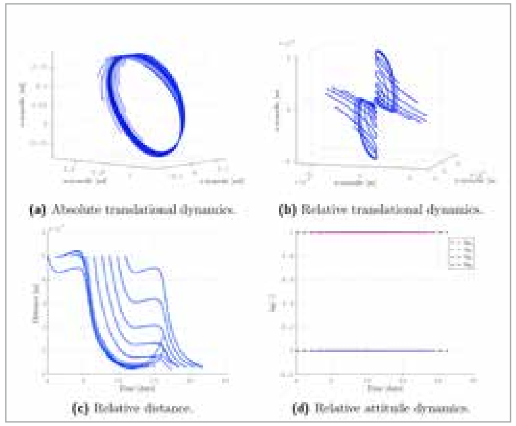

Fig. 2 - Natural approaching 6DOF relative dynamics on an EML1 Halo orbit.

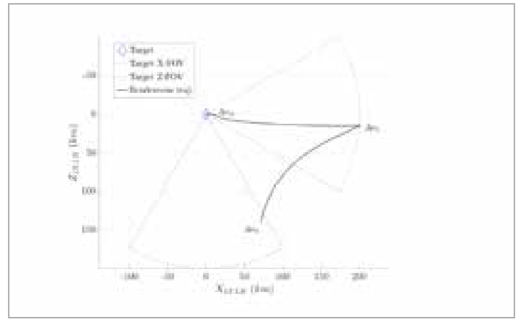

Fig. 3 - Proximity Operations in LVLH Frame, x-z view: Closing and final approach phase.

AUTONOMOUS NAVIGATION FOR CLOSEPROXIMITY OPERATIONS AROUND UNCOOPERATIVE SPACE OBJECTS

Vincenzo Pesce - Supervisor: Michèle Lavagna

Spacecraft autonomous relative navigation is an arduous and attractive problem for future space missions. In particular, autonomy is becoming indispensable, allowing to cope with the inability to rely on commands from ground control stations (due to communications latencies and black-outs), but providing increased mission frequency, robustness, and reliability. In this thesis, innovative techniques for relative state estimation in case of uncooperative known and unknown objects, using cameras, are proposed. Several mission scenarios are examined, considering the consequent effects on the architecture of the estimation technique, its robustness and implementability. An innovative approach for vision-based relative state estimation using a mono-camera is presented along with numerical and experimental results. The novelty of this approach lies in the pose acquisition algorithm, based on a customized implementation of the RANSAC algorithm which exploits the Principal Component Analysis (PCA) and the knowledge of a simplified target model, and in the navigation filter, exploiting a linear H-∞ Filter for the translational motion and an innovative 2nd Order Non-linear Filter on the Special Orthogonal group (SO(3)) for the rotational part. Moreover, this work offers an extensive comparative analysis between different filtering techniques for relative attitude estimation. A numerical validation campaign and performance assessment are carried considering different simulation scenarios. Representative target/chaser relative dynamics, target geometries and vision-based measurement are reproduced. Simulation results show the capability of the proposed pose acquisition algorithm to provide an accurate initialization for the tracking step (position and attitude errors lower than 0.5m and 2.5° in most of the cases). The sensitivity analysis on the acquisition step highlights a dependence between relative angular velocity and acquisition time. Specifically, higher relative angular velocities imply longer time to initialize the pose parameters. Furthermore, the pose tracking functionality and the navigation filter are validated through statistical simulations, considering different orbital scenarios. Satisfactory results are obtained for all the presented cases for both position and attitude estimation. In fact, steady state relative position and attitude RMSE are lower than 3cm (except in the HEO case) and 1° respectively. Finally, sensitivity analyses are performed to demonstrate the algorithm robustness against measurement noise and error sources. A preliminary experimental validation campaign is also presented to test the image processing algorithm considering realistic images. Exploiting the facility for vision-based autonomous GNC validation at PoliMi-DAER, the algorithm is tested under controlled, realistic illumination conditions and relative approach trajectory. A representative mock-up is manufactured to reproduce the optical properties of a real spacecraft. The results of the preliminary experimental validation campaign show that the image processing algorithm is able to correctly perform pose acquisition and tracking even with real images. In the same framework, relative navigation in a cislunar environment is analyzed, considering the case of a passively cooperative target and a chaser equipped with stereo-camera. In particular, we assumed to know the position of feature points on the target, representative of optical markers. An EKF is developed, using a linearized, ephemeris-based model to describe the relative translational dynamics and a classical combination of the Euler equations for target and chaser for the rotational dynamics. A proper observation model, considering a stereo camera, is adopted. A preliminary numerical validation is presented and promising results are obtained. Then, a novel estimation technique combining Radial Basis Function Neural Network (RBFNN) and an adaptive form of a Kalman Filter is presented and applied to relative navigation scenarios. The proposed neural-network performs an on-line estimation of the disturbances acting on the spacecraft, which are included in the prediction step of the filter. The on-line learning algorithm exploits the state estimation worked out by the filter itself to update the neural network weights. Moreover, an innovation-based recursive filter architecture is employed. Finally, the problem of navigating, mapping and planning around a small body (uncooperative unknown target) is tackled exploiting Partially Observable Markov Decision Process (POMDP). Focusing on the SPC mapping method, we develop cost functions that quantify the 'orbit goodness' in the sense of map improvement. These mapping accuracy measures are then used to guide the orbit selection process. We rely on a reduced policy space where orbits are selected from a representative family of common orbits around small bodies. All the different approaches and algorithms presented in this dissertation provide satisfactory and promising results, representing possible answers to the main challenges of vision-based proximity relative navigation with uncooperative objects.