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Welcome!

The “AstroNet-II International Final Conference” is one of the last milestones of the Marie-Curie Research Training Network on Astrodynamics “AstroNet-II”, which has been funded by the European Commission under the Seventh Framework Programme.

Since January 2012, 17 young scientists have been involved in the network, working on astrodynamics problems related to: trajectory design and control, attitude control, structural flexibility of spacecraft and formation flying.

Now, with the network coming to its end, it is time to communicate to an international specialised audience the work that has been carried out during these four years. Together with the presentations of the recruited fellows, we will have the opportunity to hear about the work of other scientists in the field from all over the world, as well as a number of invited talks delivered by relevant people in Astrodynamics.

The meeting takes place in Tossa de Mar, an ancient fishermen’s village located half way between the city of Barcelona and the French border. This small village became an emblematic tourist destination after the stay - during the spring of 1950 - of Ava Gardner for the recording of the movie “Pandora and the Flying Dutchman”. Still now, the village of Tossa remembers this event with a statue of “Pandora”.

We are currently negotiating with Springer the publication of the book of Proceedings of the Conference.

Scientific committee:
Dr. Franco Bernelli, Dr. James Biggs, Dr. Juan Luis Cano and Dr. Josep J. Masdemont.

Local organizing committee:
Dr. Josep J. Masdemont, Dr. Gerard Gómez, Zubin Olikara, Fabrizio Paita.
## Schedule

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<td>ESR - Paita</td>
<td>C. Brunskill(*)</td>
<td>ESR - Caubet</td>
<td>S. Greenland(*)</td>
<td>M. Ceriotti(*)</td>
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<td>12:00-12:30</td>
<td>ESR - Zamaro</td>
<td>C. Brunskill(*)</td>
<td>F. Topputo(*)</td>
<td>ESR - Iorfida</td>
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<td>12:30-13:00</td>
<td>V. Martinot</td>
<td>F. Topputo(*)</td>
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<td>16:30-17:00</td>
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<td>J.L. Cano</td>
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<td>19:00-20:30</td>
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José Rodríguez-Canabal Memorial

By the end of the 70’s - more than 30 years ago - a small group of the Barcelona Dynamical Systems Group put in contact for the first time with what at that moment was called the ESOC Mission Analysis Office. The reason was the realisation of a Study Contract for the European Space Agency.

In our first visit to ESOC for the Kick-Off meeting of the contract, a young man came for us at the reception and introduced himself as Pepe; he was Dr. José Rodríguez-Canabal, a staff member of the Mission Analysis Office. Since this first meeting, and during many years that unfortunately finished on 11th October 2013, we always found in José professional advice, support, help and over all kindness. It is by these reasons that we remember him.

Dr. Rodríguez-Canabal was an Aerospace Engineer that graduated at E.T.S.I. Aeronáuticos of the Universidad Politécnica de Madrid. In 1972, under the supervision of Prof. R.S. Bucy, he finished his PhD in Control Theory at the University of Southern California. After his PhD he moved to Toulouse, were he worked at CNRS, and in 1973 he got a position at ESOC, from which he retired in 2010.

During his professional career, Dr. Rodríguez-Canabal worked in many of the most relevant missions launched or participated by the European Space Agency, including: Cluster II, Giotto, Lisa, Rosetta, SOHO, and Venus Express. During this Memorial we will hear about his contributions from his colleagues at ESOC.

But we all remember Pepe not only because of his high professionalism but because of his kindness and friendly personality. We are very proud to have also as invited speakers of this Memorial some of his best friends.

Speakers:

- Walter Flury (ESA/ESOC), “35 years of mission analysis at ESOC”
- Miguel Belló (Deimos Space), “Lessons learned”
- Guy Janin (ESA/ESOC), “The Office No. 411”
- Javier Jiménez (Univ. Politécnica Madrid), “José Rodríguez-Canabal: The early years”
- Jaume Pagès (Universia), “José Rodríguez-Canabal: A personal approach”
- Johannes Schoenmaekers (ESA/ESOC), “Interplanetary trajectory design for Rosetta and Solar Orbiter”

Chairman: Carles Simó (Universitat de Barcelona)
Monday, June 15

9:00–10:00
Earth Observation Satellites: Deimos 1 and Deimos 2
Miguel Belló
Deimos Space

This talk is a short description of the Earth Observation satellite systems with special attention to the different applications in the field of agriculture, climate change, intelligence, disaster monitoring, forestry, etc.

10:00–10:30
A Trajectory Generation and Tracking System for Reusable Launch Vehicles during TAEM
Luca de Filippis
Deimos Space

In this presentation a new trajectory generation and tracking system for the Terminal Area Energy Management phase of a Reusable Launch Vehicle is presented. During this phase the vehicle has to glide at low Mach to reach the point close to the runway where automatic approach and landing starts. The trajectory generator is based on the concept of Energy Corridor management and it is composed of two main elements: a trajectory propagator and a ground track generator. The trajectory tracker, on the other hand, is an NDI based guidance algorithm that exploits data coming from the generator to obtain the steering commands. Imposing a dynamic pressure profile as function of the altitude, a heading path is selected in order to steer the vehicle toward the runway, putting to zero cross and down track errors.

10:30–11:00
Control of Satellite Relative Motion using Low Thrust Nonlinear Time-Delay Feedback
Claudiu-Lucian Prioroc
University of Turku

The development of a stabilizing control method for the relative motion between two satellites using continuous low thrust is described. The relative motion of two satellites is considered in the two body problem with $J_2$ perturbation and it is described by the Clohessy-Wiltshire equations. The satellites orbits are considered to have slightly different periods and inclinations, thus the relative motion between them will not be bounded. To stabilize the relative motion, time delay feedback control is used. The time delay feedback control eliminates the necessity of having a pre-defined reference relative motion to
be tracked by the follower satellite, by using the previous relative orbit as a reference for tracking. First we consider the stability in the sense of Lyapunov. Once the Lyapunov function is found, a first order sliding mode time delay feedback controller is developed to stabilize the relative motion, based on the free variable transformation, Lyapunov transformation and considering that the $J_2$ perturbation is bounded. Numerical simulations are used to compare the performance of the developed nonlinear time delay feedback controller with linear feedback time delay control as well as with PD controller. Also it is shown that by using the time delay feedback control one can design artificial reference relative orbits that can be tracked by using feedback control laws. Numerical simulation results prove the effectiveness of bounding the relative motion for long periods of time using the proposed stabilizing method.

11:00–11:30  
*Coffee Break / Outreach ESR-ER Videos*

11:30–12:00  
**On Distributed Control Strategies for Spacecraft Formation Flying**  
Fabrizio Paita  
*Institut d’Estudis Espacials de Catalunya*

In the present session we discuss several aspects related to distributed control strategies for spacecraft formation flying, both for translational and rotational motion.

Specifically, in the first part of the talk we deal with formation acquisition and maintenance. Starting from a consensus model introduced by F. Cucker and S. Smale in 2007, we construct a distributed control which allows the spacecraft of the formation to asymptotically achieve the same velocity. The value of the latter can be customized by employing a leader spacecraft, thus making the formation behave as rigid body moving around a reference trajectory.

By testing our control under the presence of a central force field we show that the efficiency of the control strongly depends on the relative accelerations between the single spacecraft and the selected reference orbit, with the former “falling” towards the latter over long periods of time (regardless of the surrounding conditions).

Instead, in the second part of the presentation, we tackle the problem of attitude synchronization. In particular, we introduce a PD-like continuous control based on the quaternion formalism and, after proving analytically that the formation asymptotically synchronize under this control, we discuss the dependence of the synchronization process in terms of the initial relative conditions, the dimension of the formation and the structure of the underlying communication graph (with no limitations on the torque).
One of the paramount stepping stones towards the long-term goal of undertaking human missions to Mars is the exploration of the Martian moons. Since a precursor mission to Phobos would be easier than landing on Mars itself, NASA is targeting this moon for future exploration, and ESA has also announced Phootprint as a candidate Phobos sample-and-return mission.

Orbital dynamics around small planetary satellites is particularly complex because many strong perturbations are involved, and the classical circular restricted three-body problem (R3BP) does not provide an accurate approximation to describe the systems dynamics. Phobos is a special case, since the combination of a small mass-ratio and length-scale means that the sphere-of-influence of the moon moves very close to its surface. Thus, an accurate nonlinear model of spacecrafts motion in the vicinity of this moon must consider the additional perturbations due to the orbital eccentricity and the complete gravity field of Phobos, which is far from a spherical-shaped body, and it is incorporated into an elliptic R3BP using the gravity harmonics series-expansion (ER3BP-GH).

In this presentation, a showcase of various classes of non-keplerian orbits are identified and a number of potential mission applications in the Mars-Phobos system are proposed: these results could be exploited in upcoming unmanned missions targeting the exploration of this Martian moon. These applications include: low-thrust hovering and orbits around Phobos for close-range observations; the dynamical substitutes of periodic and quasi-periodic Libration Point Orbits in the ER3BP-GH to enable unique low-cost operations for space missions in the proximity of Phobos; their manifold structure for high-performance landing/take-off manoeuvres to and from Phobos surface and for transfers from and to Martian orbits; Quasi-Satellite Orbits for long-period station-keeping and maintenance. In particular, these orbits could exploit Phobos occulting bulk and shadowing wake as a passive radiation shield during future manned flights to Mars to reduce human exposure to radiation, and the latter orbits can be used as an orbital garage, requiring no orbital maintenance, where a spacecraft could make planned pit-stops during a round-trip mission to Mars.
Monday, June 15

12:30–13:00
**Capitalising Astrodynamics Tools over Decades**
Vincent Martinot  
*Thales Alenia Space*  
(Invited by IEEC)

Astrodynamics tools in the industry are developed and enhanced along with the studies/programs that require their use, and not out of the box. This represents a significant effort that needs to be capitalized over years and it is a real challenge when considering in particular:

- The changing environment of these tools in terms of hardware/software on which they are used.
- The evolution of the development environment (programming language, revision management system).
- The information technology background of the newly formed engineers.
- The management of the supporting documentation (user manual, developer manual), ...  

The way this challenge is managed in the industry will be illustrated through the use of examples related to a framework for the mission analysis of Earth-bound missions and for the mission analysis of interplanetary missions.

13:00–15:00
*Lunch*

**José Rodríguez-Canabal Memorial**

**35 Years of Mission Analysis at ESOC**
Walter Flury  
*ESA/ESOC*

**Lessons Learned**
Miguel Belló  
*Deimos Space*

**The Rosetta Mission: Flight Operations**
Vincente Companys  
*ESA/ESOC*
Monday, June 15

The Office No. 411
Guy Janin
ESA/ESOC

José Rodríguez-Canabal: The Early Years
Javier Jiménez
Univ. Politécnica Madrid

José Rodríguez-Canabal: A Personal Approach
Jaume Pagès
Universia

Interplanetary Trajectory Design for Rosetta and Solar Orbiter
Johannes Schoenmaekers
ESA/ESOC

20:30–
Dinner
Tuesday, June 16

9:00–10:00

**Developing a Transport in Cislunar Space**

Kathleen C. Howell  
*Purdue University*  
(Invited by University of Turku)

The vicinity near the Earth-Moon libration points is of interest in support of future crewed and robotic missions. This region has been proposed for both storage of propellant and supplies for any lunar missions, as well as potential locations for the establishment of space-based facilities for human missions. Beyond the near-vicinity of the Moon itself, however, applications are being pursued throughout an expanded Earth neighborhood anywhere within lunar orbit. Thus, further development of an available transport network in cislunar space is valuable. The existence of periodic orbits throughout the region serves as a framework and the connections between various families allows movement throughout the region. This investigation has been based upon establishment of a fundamental set of orbit family structures and a developing network of links. The latest results in this development include methodologies and a catalog of the transfers between Earth-Moon $L_1$ and $L_2$ orbits in the spatial problem. Maneuver-free transfers are incorporated as well as transfers that require relatively small levels of delta-v. To demonstrate the persistence of such transfers in a higher-fidelity model, several solutions are transitioned to a Sun-Earth-Moon ephemeris model with the inclusion of solar radiation pressure and lunar gravity harmonics. The defining characteristics are preserved in the higher-fidelity model, validating both the techniques employed for this investigation and the solutions computed within the catalog.

10:00–10:30

**Global Representation of Invariant Manifolds in the CR3BP with Differential Algebra**

Alexander Wittig  
*Politecnico di Milano*

The concept of differentiable manifolds is a mathematically well defined and tool from the field of topology with many applications in the study of dynamical systems. In the field of aerospace engineering manifolds are used frequently in the preliminary design of trajectories in restricted three body system. To this end, an efficient computer representation of the manifold is required. Classical techniques are based on the pointwise numerical integration of approximate initial points on the manifold and yield a grid of points along on manifold. However, this representation as a finite set of points is devoid of all the analytical structure inherent in the mathematical definition of manifolds.
In this talk, I will introduce an efficient computer representation of invariant manifolds that follows closely the mathematical definition, in particular preserving the analytical structure of the manifold. The computation of invariant manifolds in the circular restricted three body problem will be used as an example to illustrate the construction of a global covering of the invariant manifold using differential algebra techniques combined with automatic domain splitting.

The resulting manifold representation features extremely fast and accurate evaluation of arbitrary points on the manifold as well as associated information such as tangent and normal vectors to the manifold. It can thus be employed efficiently inside e.g. numerical optimization loops that require information on the position of a given point relative to the manifold such as e.g. its distance.

10:30–11:00
Aspects of Invariant Manifold Computation and Applications
Zubin Olikara
Institut d’Estudis Espacials de Catalunya

In this talk we present an overview of on-going work on the computation of invariant manifolds and their applications in celestial mechanics. We begin by introducing tools for generating invariant manifolds with a particular focus on semi-analytic techniques based on polynomial algebra. The first application considered is the end-of-life disposal of Sun-Earth libration point spacecraft. We show a simple maneuver scheme using the unstable manifold and zero-velocity surfaces can be used to prevent returns to the Earth vicinity over a long period of time. The second application concerns the computation of natural connecting orbits. We provide examples in a perturbed two-body problem (switching resonant orbits), a three-body problem (connecting libration point orbits), and a four-body problem (system-to-system connections). For the third application we consider motion in the vicinity of a uniformly rotating tri-axial ellipsoid, which serves as a simple model of an asteroid. We then show how the model can be adapted for understanding motion within barred galaxies.

11:00–11:30
Coffee Break / Outreach ESR-ER Videos

11:30–12:15
Bringing Research to the Marquet
Chris Brunskill
Catapult UK
(Invited by University of Surrey)
12:15–13:00
**Computation of Ballistic Capture Orbits and Applications**
Francesco Topputo
*Politecnico di Milano*  
(Invited by Politecnico di Milano)

In this talk, the problem of computing ballistic capture orbits is discussed, and an overview on possible applications is given. The talk will focus on the method used to derive the stable sets, which are sets of initial conditions that generate orbits satisfy a simple definition of stability. The methods to compute these sets in the circular and elliptic restricted three-body problems will be shown, as well as their implementation into a three-dimensional, full-ephemeris n-body problem. The relation between these sets and the stable manifolds of the Lagrange point orbits will be discussed. Moreover, the manipulation of the stable and unstable sets to achieve orbits with prescribed behavior will be given. Applications involve interplanetary trajectory design, lunar missions, and asteroid retrieval scenarios.

13:00–15:00
*Lunch*

15:00–16:00
**Non-gravitational Forces in the Orbital and Rotational Motion of Small NEAs**
Tomasz Kwiatkowski
*Astronomical Observatory of A. Mickiewicz University*  
(Invited by University of Zielona-Gora)

The dynamics of the orbital and rotational motion of small NEAs is dependent not only on the gravitational interaction of the the asteroid with the planets and the Sun, but also on small non-gravitational forces, like the solar radiation pressure, the Yarkovsky and YORP effects, as well as the meteoroid impacts. A short review of the current knowledge of those effects will be presented, with examples of how they can be used to derive physical properties of small NEAs.
Tuesday, June 16

16:00–16:30
**Two-body Approximations in the Design of Low-Energy Transfers between Galilean Moons**
Elena Fantino, Roberto Castelli
*Universitat Politècnica de Catalunya, VU University Amsterdam*
(Invited by IEEC)

Over the last two decades, the robotic exploration of the Solar System has reached the moons of the giant planets. In the case of Jupiter, a strong scientific interest towards its icy moons has motivated important space missions (e.g., EJSM-Laplace, or JUICE). A major issue in this context is the design of efficient trajectories enabling satellite tours, i.e. visiting the several moons in succession. Concepts like the Petit Grand Tour and the Multi-Moon Orbiter have been developed to this purpose, and the literature on the subject is quite extended.

Two models are often set in opposition: the two body problem (with the patched conics approximation and gravity assists) on one side, and the three-body problem (low-energy transfers) on the other. In this contribution, we deal with the connection between two moons, Europa and Ganymede, and we investigate a two-body approximation of trajectories originating from the stable/unstable invariant manifolds of the two circular restricted three body problems, i.e., Jupiter-Ganymede and Jupiter-Europa. We develop ad-hoc algorithms to determine the intersections of the corresponding elliptical arcs and the magnitude of the maneuver at the intersections. We provide a means to perform very fast and accurate evaluations of the minimum cost trajectories between the two moons. Eventually, we validate the methodology by comparison with numerical integrations in the full four-body problem.

16:30–17:00
*Coffee Break / Outreach ESR-ER Videos*

17:00–17:30
**Rigorous Results on the Relegation Algorithm and Applications via Algebraic Manipulation**
Marco Sansottera
*University of Milan*
(Invited by University of Roma Tor Vergata)

The relegation algorithm, introduced by Deprit et al., represents a generalization of the classical Birkhoff normal form. The method has been successfully adopted in the artificial satellite theory, e.g., for finding initial conditions for perturbed frozen orbits around inhomogeneous fast rotating asteroids and for the averaging of the tesseral effects. The relegation algorithm has been introduced essentially as a formal algorithm, as in the usual spirit of celestial
mechanics, but rigorous convergence estimates are still lacking. In the present work we reformulate the algorithm and produce rigorous convergence estimates. Furthermore, simple applications via algebraic manipulation will be presented. This is a joint work in collaboration with M. Ceccaroni.
Efficient Modelling of Small Bodies Gravitational Potential for Autonomous Proximity Operations
Andrea Turconi
University of Surrey

Maintaining spacecraft in proximity of asteroids and comets requires extensive orbit determination campaigns and relies on a concept of operations with the ground in the loop. Apart from some autonomy planned for the very last legs of landing and touch-and-go trajectories, nowadays all the orbital manoeuvres have to be carefully planned in advance thanks to a model of the gravitational potential that becomes more and more detailed along the mission but whose knowledge remains on the ground.

Recent developments in on-board navigation paved the way for autonomous proximity operations. Thanks to on-board navigation systems future spacecraft will have, directly on-board, the knowledge of their relative position and velocity with respect to the small body. Simple gravity models are then required in order to be easily stored and handled on board.

In this research we identified a class of models that can represent well some characteristics of the dynamical environment around the asteroid. In particular we chose to fit the positions and Jacobi energies of the equilibrium points generated by the balance of gravity and centrifugal acceleration in the body fixed frame. In this way these models give also a good estimate of the condition of stability against impact for orbital trajectories.

Making use of these approximate models we show autonomous guidance laws for achieving body fixed hovering in proximity of the asteroid while ensuring that no impact will occur with the small body. The proposed control law is made of two components in the directions parallel and normal to the instantaneous velocity. The parallel component is used to achieve the target energy level thanks to a Lyapunov controller. The normal component is used to direct the motion towards the target position and to compensate the deviations caused by the components of gravitational, centrifugal and Coriolis forces which are normal to the velocity. Assuming relative navigation data as an input and considering the associated uncertainties of the autonomous navigation systems previously mentioned, we discuss the performance of the proposed control laws.

Formation Flying Guidance for Debris Observation, Manipulation and Capture
Thomas Vincent Peters
GMV

The presentation will treat GNC aspects of a debris removal mission, with a main focus on guidance. First debris types and the current state of debris
will be briefly discussed. Next, a short overview of debris capture and removal options will be provided. The most promising options will be discussed more in-depth. Following this introduction, mission phases of the debris removal mission are outlined. These are the mid- to short-range rendezvous, inspection, synchronization and capture. For each of the phases, examples will be provided from recent projects and engineering issues will be discussed. Finally, some alternatives to synchronization are examined.

18:30–19:00  
*General Assembly*

19:00–20:30  
“*Soap Bubbles*” by Anton Aubanell

20:30–  
*Dinner*
Wednesday, June 17

9:00–10:00
**Electro-Optical Attitude Sensors Basic Concepts and Application in the GNC of Spacecrafts**
Franco Boldrini
*Selex*
(Invited by Politecnico di Milano)

10:00–10:30
**Autonomous Guidance and Control Technology for Earth Observation and Interplanetary Small Satellites**
Junquan Li
*Clyde Space Ltd.*

This presentation is a summary of my Astronet II Marie Curie ER research work at Clyde Space Ltd, UK. The first year of this work involved the study of an FPGA based Attitude Control System design for an Earth observation nanosatellite, and a study of Pulsed Plasma Thruster technology for LEO satellite formation flying. The second year of this work covered autonomous guidance and control technology for interplanetary small satellites. This was based on non-affine control design for solar radiation pressure propulsion systems, used for spacecraft formation flying at libration points and for displaced orbits hovering near the Earth or Sun.

The first part of this presentation presents a deep space formation flying mission using microsatellites with pulsed plasma thrusters and solar sails as propulsion systems. The circular restricted three body problem with consideration of solar gravitation was used as the equation of motion. Formation flying near Earth-Moon triangular libration points uses short period trajectories as relative references. Simulation results using a nonaffine control strategy are provided to demonstrate the effectiveness of the proposed propulsion systems for formation flying near triangular libration points.

The second part of this presentation is a study of spacecraft missions for access to the polar regions of the Earth, which are useful in terms of monitoring, provision of communications and resource exploration. Biasing satellite coverage provided to northern latitudes also has commercial advantages. This work will study orbit and attitude stability criteria for a solar sail spacecraft that could serve this region and possible strategies for acquisition using the limited resources to miniaturized spacecraft without a propulsion system. A coupled orbit and attitude stability analysis for a spacecraft using solar radiation pressure for displaced orbits will provide validation based on stability and controllability criteria.
10:30–11:00
**Different ASRE approaches to Solve Nonlinear Optimal Control Problems with Application to Spacecraft Coulomb Formations**
Mohammad Mehdi Gomroki
*Middle East Technical University*

Suboptimal solutions of nonlinear optimal control problems are addressed in the present work. In the Approximating Sequence of Riccati Equations (ASRE) method, the nonlinear problem is reduced to a sequence of linear-quadratic and time-varying approximating problems. For this purpose, the nonlinear equations are written in State Dependent Coefficient (SDC) factorization form. Two different ASRE approaches are discussed and their implementation procedures will be explained. To implement and compare these two techniques, spacecraft Coulomb formations are considered. The effectiveness of the approaches as well as their comparison is demonstrated through numerical simulations.

11:00–11:30
*Coffee Break / Outreach ESR-ER Videos*

11:30–12:00
**A Motion Planning Method for Spacecraft Attitude Manoeuvres Using Single Polynomials**
Albert Caubet
*University of Strathclyde*

Smooth attitude slew manoeuvres can be obtained using trajectory planning techniques. In the proposed method, the attitude trajectory is shaped by a polynomial, determined by matching selected boundary conditions and a certain manoeuvre time. Through inverse dynamics, the torque profile can be estimated. In the general case with arbitrary boundary conditions, the attitude is parameterised with quaternions. The rest-to-rest special case is shown to be an eigenaxis manoeuvre, thus it is better expressed with axis-angle parameters. Also, a spin-to-spin case with reduced attitude is presented using Euler angles for path planning. The problem of time minimization (within the set of trajectories defined by the given polynomials) is addressed, and a method for analytically estimating the minimum time of a manoeuvre is proposed. As a trajectory planning method, constraints such as limits on torque, velocity, acceleration, jerk and reaction wheel speed can be checked. Obstacle avoidance can be implemented by introducing path points introduced in higher order polynomials. For the attitude problem, this method is specially suited to spacecraft with flexible appendages, which require smooth motions to avoid short-period oscillations. The computational efficiency of using polynomials
for trajectory planning, even with some degree of optimisation, is relatively
high, thus it can be implemented on-board for real-time computation. This
method can also be applied to the problem of docking with an uncooperative
spacecraft, planning a trajectory for the translational coordinates in the Eu-
clidean space. The different optimisation considerations of this scenario are
discussed.

12:00–12:30

Novel Approach on the Optimisation of Mid-Course Corrections
along Interplanetary Trajectories
Elisabetta Iorfida
University of Surrey

The primer vector theory, firstly proposed by Lawden, defines a set of
necessary conditions to characterise whether an impulsive thrust trajectory is
optimum with respect to propellant usage, within a two-body problem context.
If the conditions are not satisfied, one or more potential intermediate impulses
are performed along the transfer arc, in order to lower the overall cost. The
method is based on the propagation of the state transition matrix and on the
solution of a boundary value problem, which leads to a mathematical and
computational complexity.

During this presentation, a novel approach is proposed. It is based on a
polar coordinates transformation of the primer vector which allows the decou-
pling between its in-plane and out-of-plane components.

The out-of-plane component is solved analytically while for the in-plane
ones a Hamiltonian approximation is made. The novel procedure reduces
the mathematical complexity and the computational cost of the problem of
Lawden and gives also a novel and different perspective about the optimisation
of the transfer trajectory.

12:30–13:00

Solar Surfing the Earth-Sun RTBP
Ariadna Farrés
Universitat de Barcelona

In this talk we want describe the some of the possibilities that Solar sails
give when we navigate in the Earth–Sun system. We consider the Restricted
Three Body Problem (RTBP) as a model, including the Solar radiation pres-
ture (SRP) due to the Sail. It is well known that the extra effect of the SRP
gives birth to a family of 2D “artificial equilibria” parametrised by the sail
orientation.

We will describe the linear dynamics around the equilibria close to the
classical Lagrange points $L_1$ and $L_2$ and how to use this information to surf
along the family of equilibria in a controlled way. We will illustrate these techniques with several example missions.

13:00–15:00
*Lunch*

15:00–
*Social Activities: Trip to Girona / Camí de Ronda*

20:30–
*Dinner*
Detumbling GEO objects is a critical component of many space debris remediation or satellites servicing missions being envisioned. A touchless method of controlling the relative spin and attitude of the passive space objects is discussed. Here active electrostatic charging is employed via a primary electron gun on the host spacecraft. The electron emission is aimed at the passive space object to charge it negatively, while the servicer is charged positively. This creates milli-Newton level forces if the spacecraft are 3-4 craft radii apart. Recent research has been investigating modulating this electrostatic force field to control the relative spin and orientation without requiring physical contact. The Multi-Sphere-Method (MSM) is being developed to facility faster-than-realtime charged astrodynamics simulations. Terrestrial experimental results are discussed to validate these models, and illustrate the performance of closed-loop 1-D attitude control. Further, early results of studying three-dimensional charged relative attitude motion are presented illustrating how the natural relative motion of spacecraft can be exploited to remove most of the rotational energy.
performances evolved from requirement verification to flight prediction, whose objective is to provide a more accurate estimation of the expected performance during the day of flight, made weeks in advance or a few hours before launch. For instance, the availability of a measured mass, centre of gravity and Inertia or launcher performance reduces the uncertainty levels and hence improves the accuracy of the flying qualities performance estimation. An overview of the Mission Analysis, Flight Mechanics and GNC activities performed by DEIMOS Space will be given from design up to flight.

10:30–11:00

**Bifurcations and Halo Orbits**

Marta Ceccaroni  
*University of Roma Tor Vergata*

Halo orbits are three-dimensional periodic orbits around the collinear Lagrange points in the restricted three-body problem, resulting from the interaction between the gravitational pull of two planetary bodies and the Coriolis and centrifugal accelerations acting on a spacecraft. Robert W. Farquhar, suggested to use the Earth-Moon L2 Halo as a communications relay station for an Apollo mission to the far side of the Moon, as it would enable continuous view of both the Earth and the hidden Moon. Yet, the establishment of a bridge for radio communication, is a significant problem for future space missions planning to use the outer side of the Moon as a launch site for space explorations or as an observation point.

An analytic investigation of the bifurcation thresholds for halo (and other periodic) orbits around the collinear points $L_1$ and $L_2$ of the circular, spatial, restricted three body problem is here presented.

Following a standard procedure, the dynamics is first reduced to the center manifold by constructing a normal form adapted to the synchronous resonance. Introducing a detuning, measure of the displacement from resonance, the energy is expanded in power series, leading to an explicit formula of the energy level at which the bifurcation takes place for arbitrary values of the mass ratio.

The energy threshold can be lowered exploiting solar radiation pressure, which, in some cases enables the further bifurcation of other families of periodic orbits.

11:00–11:30

*Coffee Break / Outreach ESR-ER Videos*
11:30–12:15

**Dynamics and Control Problems for Advancing Nanosatellite Capability**

Steve Greenland  
*Clyde Space Ltd.*

This talk will give an overview of actual and future nanosatellite missions, based on those in development at Clyde Space and University of Strathclyde such as Earth-solar limb hyperspectral imaging, quantum key distribution for secure telecommunications, and enabling ubiquitous low data rate information services. The talk will discuss relevant engineering challenges around the orbit and attitude dynamics in the system design and guidance navigation and control of these missions. For example, the development of practical deorbit and aerodrag control, optical stabilisation, and ad-hoc network design are all current challenges for the next generation of nanosatellite. From these, possible opportunities to enhance hands-on elements in future ITN networks in the future will be identified, using facilities such as the NANOBED missions lab at the University of Strathclyde, and links into industrial bases like Clyde Space Ltd.

12:15–13:00

**Relevant Applications of Differential Algebra in Astrodynamics**

Pierluigi di Lizia  
*Politecnico di Milano*  
(Invited by Politecnico di Milano)

The vast majority of numerical algorithms in astrodynamics is largely based on pointwise or linear techniques. The linear assumption significantly simplifies the problem, but the accuracy of the technique drops off in case of highly nonlinear systems and/or long time propagations. Differential Algebra provides a method to overcome this limitation and to implement efficient arbitrary order techniques. Differential algebra (DA) replaces the operations between single numbers by operations on polynomials. Consequently, the implementation of DA in a computer environment allows the user to very efficiently obtain the Taylor expansions of arbitrary functions to arbitrary order, including the expansion of the flow of an ordinary differential equation at any given time. This paves the way to interesting applications in space-related problems.

The aim of the presentation is to provide an overview of relevant applications of DA in astrodynamics. The applications include nonlinear uncertainty propagation: due to the possibility of obtaining high-order expansions of the flow of spacecraft dynamics, DA is used to develop efficient algorithms for nonlinear covariance propagation and fast Monte-Carlo simulations. These algorithms can then be embedded into efficient tools for nonlinear filtering,
collision probability computation, and robustness analysis. In addition, DA can approximate the solution manifold of implicit equations in Taylor series. This allows engineers to obtain Taylor expansions of the solution of boundary value problems with respect to boundary conditions, which enables the development of high-order optimal feedback control schemes.

13:00–15:00
Lunch

15:00–16:00
The ESA-SSA Program: the NEO and SST Segments
Fabrizio Bernardi
SpaceDyS
(Invited by University of Roma Tor Vergata)

The European Space Agency has started since 2008 an optional program called Space Situational Awareness (SSA). The SSA program deals, generally, with the hazard coming from space for the Earth living beings and for the space assets. In particular the SSA program is split into three segments:

- SW  Space Weather that deals with the hazard coming mostly from the Sun activity that can affects the proper functioning of the Earth satellites and on ground infrastructures
- SST  Space Surveillance and Tracking that deals with the hazard coming from the space debris population for the space assets
- NEO  Near Earth Objects that deals with the hazard coming from possible impacts of natural objects (asteroids and comets) with the Earth

This presentation will discuss the SSA NEO and SST segments activities performed so far and the perspective for the future years.

16:00–16:30
Leveraging Discrete Variational Mechanics to Explore the Effect of an Autonomous three-body Interaction added to the Restricted Problem
Natasha Bosanac, Kathleen C. Howell, Ephraim Fischbach
Purdue University

With improved observational capabilities, an increasing number of binary systems have been discovered both within the solar system and beyond. In this investigation, the dynamical environment of the binary is modeled using
a three-body interaction added to the inverse-square pairwise gravitational forces of the circular, restricted three-body problem. Discrete variational mechanics is employed to compute periodic orbits and determine the natural parameters at which interesting shape characteristics emerge due to the presence of this additional force contribution. By comparison to the stability and existence of equilibrium points, such analysis facilitates exploration of the effect of an additional three-body interaction and the conditions for reproducibility in the natural gravitational environment.

16:30–17:00
Coffee Break / Outreach ESR-ER Videos

17:00–17:30
Integrability studies of systems in celestial mechanics
Maria Przybylska
University of Zielona-Gora
(Invited by University of Zielona-Gora)

Recently very strong necessary integrability conditions were formulated in the framework of the differential Galois theory. Conditions of this type enable to select values of physical parameters for that system can be integrable. Short review of results of such an analysis for selected systems from celestial mechanics will be given. Among others two body problems in curved spaces, anisotropic Kepler problem, planar three body problem, generalized planar three body problem when bodies attract mutually with the force proportional to a certain integer power of the distance between bodies, generalised two fixed centers problem, satellite in geo-magnetic field, dumbbell and point mass problem will be considered.

17:30–18:00
Disposal Options for Lisa Pathfinder
Willem van der Weg
University of Zielona-Gora

In this talk we will briefly review the end-of-life options considered in a recent ESA study for Libration Point Orbit missions. Because of the unstable nature of the orbits around libration points $L_1$ and $L_2$ in which spacecraft operate care must taken when their operational lifetime comes to an end. In our study we surveyed a number of options, including: controlled Earth impact, lunar capture, lunar impact, and disposal by bringing the spacecraft into an orbit around the Sun slightly inside or outside of the Earth’s orbit around the Sun. In particular, we will discuss this last disposal method in
more detail for the case of Lisa Pathfinder. In addition, we show some results on handling the uncertainty of the solar radiation pressure, and its influence on the disposal strategy.

18:00–18:45
Asteroid Threat Mitigation, Defending Earth from a Space Danger

Juan Luis Cano, Mariano Sánchez
Deimos Space

In recent years and with the advent of dedicated observation programmes to discover new asteroids, as the Spaceguard Survey in USA, we have realised that the Earth orbit is regularly approached by thousands of small bodies every year ranging from kilometres to negligible sizes. Whereas the very small bodies do produce no substantial problems to life on Earth (maybe just some meteoroidal activity), the larger sizes (above tens of meters) can certainly imply effects ranging from local phenomena, as the ones experienced in Chelyabinsk in February 2013, to dramatic impacts affecting large areas and even provoking global damages (as in the case of the K-T extinction event). Solar dynamic models and observations of these bodies have permitted the derivation of Near Earth Object (NEO) population models and as a consequence the characterisation of the probability that the Earth encounters a minor body of a given size in a given time frame. Frequencies of once per century have been assessed for objects as the one occurred in Chelyabinsk (15-20 m). Such studies and the large number of bodies detected in recent years have prompted the question of how to avoid the danger posed by those with probabilities of impact, giving rise to a new discipline in the space sector which has been denominated Planetary Defense. International efforts are currently put in place to fully characterise the threat, design response actions to mitigate that threat and policies of international cooperation for such type of events whenever they can be foreseen. The seminar will address the presentation of the mitigation actions currently considered as well as the expected interaction with the threatening NEOs. A study case on the 2011 AG5 asteroid (now considered a no-threat case) will be presented.

20:30–
Social Activities: Gala Dinner & Surprise
Friday, June 19

9:00–10:00

Analytical and Semi-analytical Integration: The Role of Polar-nodal Variables
Martín Lara
GRUCACI, Universidad de la Rioja
(Invited by IEEC)

In the last two decades numerical methods seem to have completely eclipsed analytical and semi-analytical methods for practical application. In spite of that, analytical and semi-analytical integration may still play a role in the propagation of space orbits. Indeed current space debris mitigation guidelines may require the design of End-of-Life disposal strategies guaranteeing some safe condition for hundreds of years. In these cases, combinations of semi-analytical integration with global optimizers have disclosed as suitable strategies. But analytical integration is also an option for onboard orbit propagation when reduced power consumption is a critical requirement, as for micro and nano satellite missions.

In all cases, the efficiency in evaluating the analytical expressions is closely related to the variables used in the formulation of the theory. Thus, while the construction of the theory is naturally approached in action-angle variables, the resulting analytical expressions are customarily reformulated in non-singular variables in order to make the theory as much general as possible. Yet, the evaluation of long Fourier series in non-singular variables may notably degrade the performance of the theory. On the contrary, when using polar-nodal variables the analytical expressions adopt a compact form of straightforward evaluation. Still, the case of almost equatorial orbits must be treated separately, but a simple set of non-singular elements which are trivially derived from the polar-nodal variables may be used for dealing properly with this case. Therefore, the lack of universality of the polar-nodal formalism is easily fixed with the introduction of a flag in the code, and is largely compensated by the notable simplifications that the periodic corrections accept in the case of almost-equatorial orbits.

10:00–10:30

Vision-based Navigation around Small Bodies
Pawel Kicman
GMV

The talk is focused on the vision-based navigation around small bodies, starting with general overview of methods used in space. The focus of the talk is placed on the body relative navigation methods that are mainly applicable for use around asteroids and small moons. The algorithms applicable
for relative and absolute navigation are reviewed and presented. The detailed analysis of absolute navigation with reference to the body surface is analysed. The results section contains comparison of positioning accuracy between simulated and real images obtained in the PANGU, and GMV optical laboratory, respectively.

10:30–11:00
Astrodynamics of Trojan Asteroids from a Perturbative Approach
Rocío I. Páez
University of Roma Tor Vergata

Trojan motion is a classical subject of Celestial Mechanics, from both analytical and numerical points of view. A clear understanding of the natural behavior close to the equilateral Lagrangian points is essential to exploit such dynamics in future missions. Its main problem is due to the existence of singularities corresponding to close encounter between the Trojan body and the primary. While numerical approaches can easily overcome this issue, analytical treatments face convergence problems that pose obstructions to representing Trojan motions in terms of series expansions. The talk will focus on introducing the Trojan problem as a particular case of the Restricted 3-Body Problem. We will present a set of basic tools of Perturbation Theory, used to the study of problems in Celestial Mechanics via a Hamiltonian Formulation and reduction to normal forms by Lie transformations. We will also show some novel approaches for bypassing the convergence problem, and future aims about Trojan stability.

11:00–11:30
Coffee Break / Outreach ESR-ER Videos

11:30–12:15
Unconventional Solar Sailing
Mateo Ceriotti
University of Glasgow
(Invited by University of Strathclyde)

The idea of exploiting solar radiation pressure (SRP) for space travel, or solar sailing, is more than a hundred years old, and yet most of the research thus far has considered only a limited number of sail configurations. However solar sails dont have to be inertially-pointing squares, spin-stabilised discs or heliogyros: there is a range of different configurations and concepts that present some advantageous features. In this presentation, I will be showing and discussing some non-conventional solar sail configurations and applications.
One of the concepts tries to overcome the fact that a solar sail produces a very small acceleration, which is furthermore constrained in direction. If the sail is complemented by a small traditional electric thruster, the resulting hybrid-propulsion spacecraft is more efficient than traditional propulsion, and capable of missions which would be unrealistic otherwise: examples are stationary polar spacecraft and geostationary orbits displaced above/below the equatorial plane.

Conventional Earth-orbiting solar sails often have strong demands on the attitude control system: attitude actuation can be avoided completely if the sail is not flat but pyramidal and hence heliostable (passively pointing at the sun). The sail can then be used to change the orbit altitude with a clever mechanism to open/close it timely. If instead a heliostable sail is released in an undamped oscillatory attitude motion synchronised with the orbit, then the orbital energy can be changed entirely passively.

Solar radiation pressure can also be used to actively control the attitude of large spacecraft. SRP can be used to create artificial-equilibrium attitudes that are different than the traditional ones due to gravity gradient, and to create homoclinic and heteroclinic connections between equilibria.

The main motivation behind all these novel configurations is to overcome some of the engineering limitations of solar sailing, however the resulting concepts pose some intriguing orbital and attitude dynamics problems, which will be discussed.

12:15–13:00
**The Full Problem of Two and Three Bodies: Application to Asteroids and Binaries**
Elisabet Herrera-Sucarrat
*MathWorks*
(Invited by University of Surrey)

13:00–15:00
_Closure & Lunch_
List of participants

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