جامعـــة خليفـــة
Khalifa University

Research Project Proposal for PhD Students

Project Title	Design of low-energy trajectories for the robotic exploration of the giant planets

Project Supervisors			
Main Supervisor	Name: Elena Fantino		
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Project Specification

Abstract/Summary

The objective of the project is to design the trajectory of a multi-moon robotic mission from arrival at the target planet (a giant planet) to completion of a serial tour of its major moons.

Problem Statement, Challenges and Potential Benefits

The outer planets (Jupiter, Saturn, Uranus and Neptune) are of particular interest in terms of what they can reveal about the origin and evolution of our solar system. They are also local analogs for the many extra-solar planets that have been detected over the past twenty years. The study of these planets furthers our comprehension of our neighbourhood and provides the foundations to understand distant planetary systems. Robotic missions are essential tools for this scientific goal. Current plans include two missions to Jupiter and a mission to Saturn. Once the spacecraft has achieved orbit around the planet, the major challenge is to identify fuel- and time-efficient strategies to position the spacecraft in scientifically-useful orbits around the moons and to transfer sequentially among them in an exploration tour. Furthermore, the design of the tour must comply with the strict requirements imposed by the hostile particle environments and by the extreme scarcity of solar radiation for electrical power generation. The communication link with the Earth adds further geometrical and time constraints to trajectory and maneuver design. This project will deal with all the above challenges. It will build upon the state of the art in this field, it will make use of the most advanced astrodynamics tools, and it will develop from previous investigations of the PI and her project collaborators on this topic.

A traditional dilemma exists between duration and propellant cost of the lunar tour, i.e., fast, hence radiation-safe, but expensive solutions versus cheap, gravity-assisted, but slow (hence not radiation compliant) trajectories. This project will address these issues. A lunar tour will be designed based on direct (hence fast) low-energy transfers between consecutive moons and within the Hill region of each moon aiming at a closed, repeatable tour. Impulsive maneuvers, which are known to make the direct transfers expensive and unfeasible, will be optimized and the result will be used as the initial guess for the construction of a series of low-thrust transfers in the inter-moon phases of the tour. Optimizations, trade-offs between cost and duration, advantages and drawbacks of 2D and 3D orbits will be analysed and the issues of technological feasibility (e.g., how to produce the high levels of electrical power to operate the thrusters) will be addressed. The project will be developed using modern methods of astrodynamics and celestial mechanics and new developments from recent research. It will be subdivided into the following activities

- Design of the mathematical objects required in the design of Low-Energy Transfers (LETs)
  The dynamical model is the Circular restricted three-body problem (CR3BP) .
  - Generation of families of 2D (Lyapunov) and 3D (Halo) periodic orbits around the collinear libration points of each planet-moon CR3BP [
  - Computation of their stable and unstable invariant manifolds
  - Computation of transit and non-transit orbits
  - Design of inter-moon transfers

  The orbital transfers between consecutive moons will occur through the L_1 and L_2 gateways of the planet-moon CR3BPs and will be computed using the above objects (periodic orbits, invariant manifolds, transit orbits).
- Justification, verification and implementation of two-body approximations in inter-moon space
  - Computation and optimization of direct transfers with impulsive maneuvers
  - Analysis of planetary orbital configurations, identification of time and geometrical constraints on the trajectory
- Design of intra-moon transfers
  - Computation of heteroclinic connections between periodic orbits around L_1 and L_2 of a planet-moon CR3BP. Evaluation/optimization of propellant consumption (impulsive maneuvers)
  - Computation of homoclinic orbits to/from a periodic orbit around L_1/L_2 of a planet-moon CR3BP. Evaluation/optimization of propellant consumption (impulsive maneuvers)
  - Characterization and selection of intra-moon transfers based on observation parameters (approach distance to the moon, relative speed, transfer time, illumination conditions) and system requirements (geometry of communication architecture)

- Design of inter-moon transfers with low-thrust (LT) maneuvers
- Study of the replacement of the maneuvers with gravity assists at the moons: feasibility and benefits.

Desirable Outcomes and Deliverables
Learning outcomes: orbital mechanics, propulsion, optimization
Developed numerical codes (in Fortran language)
Peer-reviewed journal publications (e.g., Acta Astronautica, Journal of Guidance, Control and Dynamics), presentations at international conferences (e.g., IAC 2018 in Germany, IAC 2019 in USA, 27th ISSFD in Australia (2019), IAC 2020 in Dubai).

Pre-requisites Required of Student
MSc Degree in relevant area
Mathematics
Space Dynamics
Programming skills (Fortran, C, C++, Matlab)

Key References (max. 10)
[1] Colasurdo, G. et al., 2014: "Tour of Jupiter Galilean moons: Winning solution of GTOC6", Acta Astronautica 102, 190 - 199
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[5] Fantino, E. Castelli, R., 2017: "Efficient design of direct low-energy transfers in multi-moon systems", Celestial Mechanics & Dynamical Astronomy, 127, 429-450, DOI: 10.1007/s10569-016-9733-9
[6] Fantino, E. Castelli, R., 2016: "Two-body approximations in the design of low-energy transfers between Galilean moons", in Astrodynamics Network - Astronet-II. The final conference (Gómez G. and Masdemont J. eds.), 77-86, Springer, ISBN: 978-3-319-23984-2
[7] Fantino, E., Gómez, G., Masdemont, J.J., Ren, Y., 2010: "A note on libration point orbits, temporary capture and low-energy transfers" Acta Astronautica 67/9–10, 1038–1052
[8] Gómez, G.,Koon, W.S., Lo, M.W., Marsden, J.E., Masdemont, J.J., Ross, S.D., 2004: "Connecting orbits and invariant manifolds in the spatial restricted three-body problem", Nonlinearity 17/5, 1571
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Research Project Proposal for PhD Students

Project Title	Low-thrust spacecraft trajectory design and optimization

Project Supervisors			
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Project Specification

Abstract/Summary

This study belongs to the area of Astrodynamics and Space Mission Design. The proposed investigations are part of a project on the design of spacecraft trajectories for the next space missions in the neighbourhood of the Earth and in interplanetary space. The project consists in the development of concepts, methods, and algorithms to deal in a transversal way with mission design problems from different contexts (planetary, geocentric, interplanetary) and originating from different space mission needs. The topic of this PhD Thesis proposal is the development of an optimal control method and associated code for the design of low-thrust spacecraft trajectories.

Problem Statement, Challenges and Potential Benefits

This PhD proposal focuses on the design and optimization of orbital transfers with low-thrust maneuvers. These are the low-cost alternative of impulsive maneuvers. Their relevance in space mission design has increased in recent years owing to the technological advances in electrical propulsion and propellantless vehicles (solar sails). The range of applications of these technologies has widened considerably as space exploration has reached new frontiers (the inner solar system with the Messenger and Bepi Colombo missions, the outer solar system with the New Horizons probe, the planetary systems of the giant planets with missions like EJSM/Laplace) requiring higher Delta-V capabilities.

Designing and optimizing a low-thrust trajectory is an optimal control problem. To be able to develop an efficient method to identify the optimal thrust direction is challenging, and many researchers rely on commercially available optimizers. However hand, developing *ad hoc* methods and approaches allows to investigate more efficient optimization methods, gives full control on the solution and is open source. This PhD thesis will develop through the following steps:

- State of the art on impulsive (high-thrust) maneuver design and optimization
- Study of quasi-optimal steering laws (e.g., thrusting parallel to the velocity vector, transversally, etc.) as in Pollard (1997, 2000), Ruggiero et al. (2011) to modify the orbital elements of a Keplerian orbit both in 2D and in 3D
- State of the art on low-thrust trajectory design (optimal control)
- Design and development of an optimal control tool for low-thrust trajectory design
- Application: geocentric orbit transfers, transfers between moons of Jupiter (as part of a lunar tour)

Desirable Outcomes and Deliverables

Learning outcomes: multi-body dynamics, trajectory design, maneuver design, low thrust, optimization
Developed numerical codes (in Fortran language)
Peer-reviewed journal publications, presentations at international conferences

Pre-requisites Required of Student

MSc in a relevant discipline
Mathematics
Space Dynamics
Programming skills

Key References

Battin, R. H.: An Introduction to the Mathematics and Methods of Astrodynamics, AIAA Education Series (2001)

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J. Prussing and B. Conway, Orbital Mechanics. New York, New York: Oxford University Press, 1993.
Fantino, E., Flores, R. M., Di Carlo, et al.: On geosynchronous inclined orbits for high-latitude communications, Acta Astronautica 140, 570-582 (2017). DOI: 10.1016/j.actaastro.2017.09.014