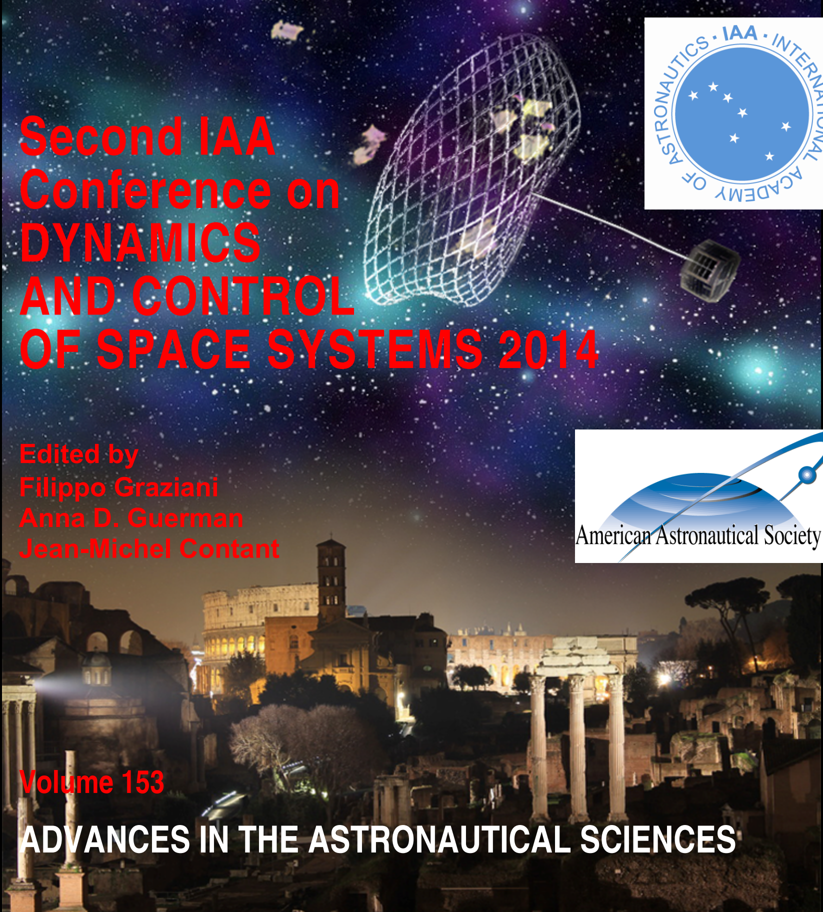
Quasi-optimal rotation deceleration of a dynamically asymmetric body in a resistive medium

Conference Paper · January 2015

4 authors, including:

Dmytro Leshchenko
Odessa State Academy of Civil Engineering and Architecture

Leonid D Akulenko
Russian Academy of Sciences



Second IAA Conference on DYNAMICS AND CONTROL OF SPACE SYSTEMS 2014

Edited by
Filippo Graziani
Anna D. Guerman
Jean-Michel Contant

Volume 153

ADVANCES IN THE ASTRONAUTICAL SCIENCES

IAA · INTERNATIONAL ACADEMY OF ASTRONAUTICS

American Astronautical Society

DYNAMICS AND CONTROL OF SPACE SYSTEMS DyCoSS'2014

EDITORS
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Dr. Anna D. Guerman — University of Beira Interior, Portugal
Dr. Jean-Michel Contant — International Academy of Astronautics, France

SERIES EDITOR
Robert H. Jacobs — Univelt, Incorporated, U.S.A.

Front Cover Illustration:

Rome, with its ancient history of glory and conquest, of technology and innovation, welcomes the 2nd IAA conference on Dynamics and Control of Space Systems. Cover picture by Ekaterina Skorova based on the photo of Mirko Di Mauro "Fori Imperiali."

Second IAA Conference on DYNAMICS AND CONTROL OF SPACE SYSTEMS 2014

Volume 153

ADVANCES IN THE ASTRONAUTICAL SCIENCES

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FOREWORD

This volume of the Series *Advances in the Astronautical Sciences* is dedicated to the second IAA Conference on Dynamics and Control of Space Systems – DyCoSS'2014 held in Rome (Italy), March 24-26, 2014 in Palazzo Rospigliosi, a 17th century building, located in the center of Rome, across from the Quirinale (official residence of the President of the Italian Republic), adorned by one of the largest private art collections in the city. More than 540 paintings, designs, and sculptures by several Italian artists decorate this magnificent palace.

The Conference was promoted by the International Academy of Astronautics (IAA) with the cooperation of the American Astronautical Society (AAS) and organized by G.A.U.S.S. Srl (Group of Astrodynamics for the Use of Space Systems). The aim was to join specialists in Astrodynamics, Space Flight Mechanics, and Space Structures.

The Conference Chairs were Filippo Graziani (Italy), Anna D. Guerman (Portugal), and Jean-Michel Contant (France) and the International Program Committee was formed by:

- Hyochoong Bang, Korea
- Franco Bernelli, Italy
- Chantal Cappelletti, Brazil
- Fabio Curti, Italy
- Harijono Djojodihardjo, Malaysia
- Antonio Elipe, Spain
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- Antonio Bertachini Prado, Brazil
- Georgi Smirnov, Portugal
- David B. Spencer, USA
- Paolo Teofilatto, Italy
- Othon Winter, Brazil
- Renato Alves Borges, Brazil

The local organization was supported by the G.A.U.S.S. Team with the following Local Organizing Committee:

- Filippo Graziani
- Chiara Massimiani
- Martina Carnio
- Marta Massimiani
- Marco Truglio
- Salvatore Paiano

- Aitor Conde Rodriguez
- Olga Ovchinnikova, press agent
- Nikolai Danylchyk, technical support

The program contained three parallel sessions alternated with four highlighted lectures on the hottest topics of space research. The 2nd IAA Conference on Dynamics and Control of Space Systems attracted an unexpectedly large number of scientists from all over the world: almost 130 participants attended and provided an interesting forum for research in the field.

The Opening Session began with a brief introduction of the conference by Prof. Anna Guerman and the welcome message from Prof. Filippo Graziani. Finally, Dr. Jean-Michel Contant, General Secretary of International Academy of Astronautics presented a talk "The International Academy of Astronautics and Astrodynamics: Past, Present and Future."

In the inauguration speech, Prof. Filippo Graziani, President of G.A.U.S.S., underscored the large number of high-quality papers submitted. These papers were organized in 16 thematic sessions; with about 15 papers in each session. The final program consisted of 144 presentations, even though during the conference only 111 papers were actually presented by the authors, while others were late withdrawals or "no shows." The present volume includes only the papers that were discussed during the DyCoSS'2014 sessions.

The work of thematic sessions of DyCoSS'2014 began on March 24 and continued to the afternoon of March 26. These sessions included presentations on Satellite Constellation and Formation Flying, Spacecraft Guidance, Navigation and Control, Attitude Dynamics and Control, Attitude Sensors and Actuators, Orbital Dynamics and Determination, Mission Design and Optimization, Space Structures and Tethers. A Panel Discussion on Space Surveillance marked the conclusion of this three-day event.

The Conference contributed to intensive discussions of the modern research, dissemination of the up-to-date information in the area and better contacts between the members of Space scientific community. A series of DyCoSS Conferences found its place in the tight calendar of the events in Space Systems as a stand-alone conference for Astrodynamics. We are confident that such an event will inspire a stronger cooperation in the space community and will be a research incentive in the Space field panorama.

Nothing of the above-mentioned would have been possible without the great effort of many colleagues. We are grateful to all members of the International Program Committee, the Local Organizing Committee and Palazzo Rospigliosi Manager, Gianluca Muto. We appreciated very much the dedication of the participants of DyCoSS'2014 (both the authors of papers and the audience in general) that made possible fruitful discussions at the conference sessions and beyond. Finally, we would like to express our gratitude to Mr. Robert Jacobs for his continuous support and to Univelt, Inc., for publishing this volume.

DyCoSS'2014 Co-Chairs:

Dr. Filippo Graziani
Dr. Anna D. Guerman
Dr. Jean-Michel Contant

CONTENTS

Part II

SESSION 1: SATELLITE CONSTELLATIONS AND FORMATION FLYING I

Chair: Harijono Djojodihardjo, Universiti Putra Malaysia (UPM), Serdang, Selangor, Malaysia

IAA-AAS-DyCoSS2-14-01-01

AAS 14 – 501

Guidance and Control for Spacecraft Planar Re-Phasing Via Input-Shaping and Differential Drag

Riccardo Bevilacqua and **David Perez**, Mechanical Aerospace and Nuclear Engineering Department, Rensselaer Polytechnic Institute, Troy, New York, U.S.A.

This paper proposes a solution to the problem of re-phasing circular or low eccentricity orbiting, short-distance spacecraft, by integrating existing analytical guidance solutions based on input-shaping and analytical control techniques for differential drag based on Lyapunov theory. The combined guidance and control approach is validated via numerical simulations in a full nonlinear environment using Systems Tool Kit. The results show promise for future onboard implementation on propellant-less spacecraft. [View Full Paper]

IAA-AAS-DyCoSS2-14-01-03

AAS 14 – 502

Self-Organising Low Earth Orbit Constellations for Earth Observation

Garrie S. Mushet and **Colin R. McInnes**, Department of Mechanical & Aerospace Engineering, University of Strathclyde, Glasgow, United Kingdom

This paper presents a novel method of manipulating the spatial pattern of a fractionated micro-satellite constellation in Low Earth Orbit. The method developed allows satellites to manipulate the longitudinal position of their ground-tracks over the Earth's surface, such that they pass over specified targets. This is achieved firstly by pairing satellites on the constellation to the targets on the Earth's surface, and then by developing an artificial potential field controller to define the thrust commands which move the satellites into the appropriate orbital slots to converge upon their targets. The latter is achieved using Coupled Selection Equations – a dynamical systems approach to combinatorial optimisation. [View Full Paper]

IAA-AAS-DyCoSS2-14-01-04

AAS 14 – 503

On Optimization of Earth Coverage Characteristics for Compound Satellite Constellations Based on Orbits With Synchronized Nodal Regression

Yury N. Razoumny, **Pavel G. Kozlov**, **Vladimir Yu. Razoumny** and
Alexander A. Moshnin, Moscow Aviation Institute, Moscow, Russia

The Earth coverage provided by the satellites' swath for the new type of satellite constellations – compound, multi-tiered, constellations with satellites' orbits of different altitude and inclination and synchronized nodal regression – is considered. The method for compound satellite constellation design is described and illustrated. Special attention is given to both continuous and periodic Earth coverage. It is shown that using compound satellite constellations for providing different types of Earth coverage makes it possible to sufficiently improve the Earth coverage, as compared to the traditional constellations based on common altitude and inclination for all the satellites of the constellation, and, as a consequence, to get new opportunities for the satellite constellation design for different types of prospective space systems (remote sensing, communications, etc.) regarding increasing the quality of solving their tasks or/and minimization of the number of the satellites required. At the same time, the condition of synchronized nodal regression of all the satellites in the compound constellations considered provides the delta-V (fuel) budget on-board the satellites, which is necessary for constellation station keeping, being on the same level as for traditional satellite constellations.

[View Full Paper]

IAA-AAS-DyCoSS2-14-01-06
AAS 14 – 504
Network Topologies for Distributed Space Systems With Perturbed Distance-Bounded Relative Motion

Jing Chu, **Jian Guo** and **Eberhard K. A. Gill**, Faculty of Aerospace Engineering, Delft University of Technology, Delft, The Netherlands

Since the network topology of a distributed space system depends on relative distances among satellites, an analysis of the frequency of relative motion and distance variations is crucial to the evaluation of the properties of the network topology. This paper analyses how perturbed distance-bounded relative motion affects the properties of the network topology. For this purpose, the approximated separable Hamiltonian that includes secular terms, short-periodic terms and long-periodic terms caused by the J_2 perturbation is exploited to describe the absolute motion of a satellite, and the action-angle variables are used to derive the nodal period as well as the drift of right ascension of ascending node (RAAN) per nodal period. The distance-bounded relative motion is established once the nodal period and the drift of RAAN per nodal period are matched, respectively. Subsequently, the relative motion model is employed to analyze the characteristics of the distance-bounded relative motion. The properties of the network topology are analyzed by using the graph theory. In such a way, the evolution of the network topology is obtained which includes the adjacency matrix and the Laplacian matrix. In addition, the eigenvalues of the Laplacian matrix are determined, which reveals the properties of the network topology. [View Full Paper]

SESSION 2: SPACECRAFT GUIDANCE, NAVIGATION AND CONTROL I

Chair: Paolo Gasbarri, Sapienza and Università di Roma La Sapienza, Italy

IAA-AAS-DyCoSS2-14-02-01
AAS 14 – 505
Autonomous Guidance and Control in the Proximity of Asteroids Using a Simple Model of the Gravitational Potential

Andrea Turconi and **Phil Palmer**, Surrey Space Centre, University of Surrey, Guildford, England, United Kingdom; **Mark Roberts**, Department of Mathematics, University of Surrey, Guildford, England, United Kingdom

Proximity operations about asteroids are challenging because of the small and non-uniform attraction of those celestial bodies. In addition, the combination of such gravitational potentials with the asteroids' rotation, generates equilibrium points around them. In order to perform autonomous guidance, a spacecraft will need a model of the gravitational potential that can be handled on-board besides the knowledge of the asteroid's rotation and of relative position and velocity. This work describes guidance laws that, thanks to a simplified gravity model, take advantage of the natural dynamics in proximity of asteroids and of the properties of their equilibrium points.
[View Full Paper]

IAA-AAS-DyCoSS2-14-02-02
AAS 14 – 506
Orbit Maintenance Maneuver for Lagrange Point Missions Using DST in Sun-Earth ER3BP

Yoshihide Sugimoto, Japan Aerospace Exploration Agency, Sagamihara, Kanagawa, Japan; **Yasuhiro Kawakatsu** and **Takanao Saiki**, Japan Aerospace Exploration Agency/Institute of Space and Astronautical Science, Sagamihara, Kanagawa, Japan

This study investigates the effective orbit maintenance maneuver for the periodic orbits around collinear equilibrium point (Lagrangian point) in Elliptic Restricted Three-Body Problem (ER3BP) using the Dynamical Systems Theory (DST). The assumed state displacement is stabilized by nullifying the unstable relative motion. The other displacement, which will not be deviated from the reference are permitted in this maneuver plan. The periodic orbits in the ER3BP are considered as multiple revolution orbit and, in total, by choosing the invariant unstable direction to calculate the stabilizing maneuver reduces control budget from choosing the unstable direction of each revolution. Obtained. [View Full Paper]

IAA-AAS-DyCoSS2-14-02-03
AAS 14 – 507
Performance Analysis of Real Time Precise Orbit Determination by Using Adaptive Kalman Filtering on HIL Generated GPS Receiver Data

Giuseppe Catastini and **Francesco Menzione**, Thales Alenia Space Italia S.p.A., Rome, Italy

Currently on-board operating s/c navigation systems use Kalman filtering of GPS data to achieve real-time Precise Orbit Determination (POD). It allows to greatly reducing dependency on ground support, but high accuracy still relies on manual tuning from ground analysts. The suitable solution for this problem is the adaptive filtering approach. This paper presents the performance analysis of one POD adaptive Kalman filtering on Hardware-in-the-Loop (HIL) data generated by a dedicated GNSS facility. The study has demonstrated the capability of the innovation based adaptive filter to perform the self-tuning and improve the performance w.r.t. sub-optimal parameter initialization case. [View Full Paper]

IAA-AAS-DyCoSS2-14-02-04
AAS 14 – 508
Study and Simulation of the Attitude Determination and Control Subsystem of a CubeSat

Luis Olier-Gárate and **Ramón Martínez Rodríguez-Osorio**, Señales Sistemas y Radiocomunicaciones (SSR), Universidad Politécnica de Madrid (UPM), Madrid, Spain

This paper studies the attitude of a CubeSat to optimize its mission life. The paper also presents, discusses and develops a simulator for the Attitude Determination and Control Subsystem (ADCS) of a CubeSat using Simulink. The simulator presented describes the behaviour of a CubeSat during its planned mission, and optimizes the satellite mission lifetime, as well as selects those satellite elements that will allow the best mission results. The simulator includes seven subsystems, each one representing every element of the satellite's ADCS system. Different simulation environments are discussed to demonstrate the actual workability of the simulator. [View Full Paper]

IAA-AAS-DyCoSS2-14-02-05
AAS 14 – 509
Terminal Attitude-Constrained Guidance and Control for Lunar Soft Landing

Zheng-Yu Song, Beijing Aerospace Automatic Control Institute (CASC), Beijing, China; **Dang-Jun Zhao**, School of Aeronautics and Astronautics, Central South University, Changsha, China; **Xin-Guang Lv**, Beijing Aerospace Automatic Control Institute (CASC), Beijing, China

This work concentrates on a 3-dimensional guidance and control (G&C) scheme for the terminal landing phase of a lunar spacecraft. In order to cope with terminal attitude constraints, we take the commanded acceleration as an extended state whose terminal value relates to the terminal attitude constraints. Then in optimal control framework, an optimal terminal attitude-constrained feedback guidance law is derived. In order to accommodate various disturbances, a finite-time convergent extended state observer is utilized to estimate the disturbance. Driven by the disturbance observer, an improved sliding mode controller with a disturbance compensation is proposed. The attitude tracking error signals theoretically prove to be ultimately uniformly bounded. The convincing simulation results reveal the excellent performance is achieved by the proposed method during the terminal landing phase. [View Full Paper]

IAA-AAS-DyCoSS2-14-02-06
AAS 14 – 510

Analysis and Experimentation of an Optical-Flow-Based Navigation Algorithm for a Lander

Claudia Moroni, **Luigi Ansalone** and **Fabio Curti**, ARCA Lab, Department of Astronautical, Electrical and Energy Engineering, Sapienza University of Rome, Rome, Italy

This paper deals with the development and the testing of an algorithm for the landing phase of a space vehicle, based on the optical-flow technique to measure the trajectory's velocity. The Optical-flow sensor is obtained through the processing of 2-D images captured by a camera by knowing the acquisition time for each frame. Image processing techniques have been used for the implementation of an algorithm capable of detecting complex structures. The algorithm can detect craters and the shadows created by the craters themselves. It is possible to obtain the direction of the light by simply connecting the center of the crater with the center of the shadowed zone. The information of the light direction is used to obtain a solar compass. Finally, an extended Kalman filter has been used to estimate the state. The navigation filter is tested on the Lunar Simulator Facility at the Automation, Robotics, and Control for Aerospace Laboratory (ARCAlab) of the Department of Astronautical, Electrical and Energy Engineering of Sapienza University of Rome. [View Full Paper]

SESSION 3: MISSION DESIGN AND OPTIMIZATION I
Chair: Vladislav Solovey

IAA-AAS-DyCoSS2-14-03-01
AAS 14 – 511
End-of-Life Disposal Concepts for Libration Point and Highly Elliptical Orbit Missions

Camilla Colombo, Department of Aerospace Science and Technology, Politecnico di Milano, Italy; **Francesca Letizia**, **Stefania Soldini** and **Hugh Lewis**, Astronautic Research Group, University of Southampton, United Kingdom; **Elisa Maria Alessi** and **Alessandro Rossi**, IFAC-CNR, Sesto Fiorentino, Italy; **Massimo Vetrisano**, **Willem Van der Weg** and **Massimiliano Vasile**, Advanced Space Concepts Laboratory, University of Strathclyde, Glasgow, United Kingdom; **Markus Landgraf**, ESA/ESOC, Darmstadt, Germany

Libration Point Orbits (LPOs) and Highly Elliptical Orbits (HEOs) are often selected for astrophysics and solar terrestrial missions. No guidelines currently exist for their end-of-life; however, it is a critical aspect to other spacecraft and on-ground safety. This paper presents an analysis of possible disposal strategies for LPO and HEO missions as a result of an ESA study. The dynamical models and the design approach are presented. Five missions are selected: Herschel, Gaia, SOHO as LPOs, and INTEGRAL and XMM-Newton as HEOs. A trade-off is made considering technical feasibility, as well as the sustainability context and the collision probability. [View Full Paper]

IAA-AAS-DyCoSS2-14-03-02
AAS 14 – 512
An Earth-Moon System Trajectory Design Reference Catalog

David C. Folta, NASA Goddard Space Flight Center, Greenbelt, Maryland, U.S.A.; **Natasha Bosanac**, **Davide Guzzetti** and **Kathleen C. Howell**, School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana, U.S.A.

As demonstrated by ongoing concept designs and the recent ARTEMIS mission, there is, currently, significant interest in exploiting three-body dynamics in the design of trajectories for both robotic and human missions within the Earth-Moon system. The concept of an interactive and 'dynamic' catalog of potential solutions in the Earth-Moon system is explored within this paper and analyzed as a framework to guide trajectory design. Characterizing and compiling periodic and quasi-periodic solutions that exist in the circular restricted three-body problem may offer faster and more efficient strategies for orbit design, while also delivering innovative mission design parameters for further examination. [View Full Paper]

IAA-AAS-DyCoSS2-14-03-04

AAS 14 – 513

Optimisation of Solar Sail Interplanetary Heteroclinic Connections

Jeannette Heiligers, **Giorgio Mingotti** and **Colin McInnes**, Advanced Space Concepts Laboratory, Department of Mechanical & Aerospace Engineering, University of Strathclyde, Glasgow, United Kingdom

This paper investigates time-optimal solar sail trajectories between displaced Libration Point Orbits (LPOs) of different circular restricted three-body systems. Key in the investigations is the search for transfers that require little steering effort to enable the transfers with low control authority solar sail-like devices such as SpaceChips. Two transfers are considered: 1) from an Earth-L_2 Halo orbit to a Mars-L_1 Halo orbit and 2) from an Earth-L_1 Halo orbit to a Mercury-L_2 Halo orbit. For both transfers the optimal control problem is derived and solved with a direct pseudospectral method. For a sail performance comparable to that of NASA's Sunjammer sail, the results show transfers that require very little steering effort: the sail acceleration vector can be bounded to a cone with a half angle of 5 deg (Earth-Mars) or even 2.5 deg (Earth-Mercury). These transfers can serve a range of novel solar sail applications covering the entire spectrum of sail length-scales: micro-sized SpaceChips could establish a continuous Earth-Mars communication link, a traditional-sized sail provides opportunities for in-situ observations of Mercury and a future kilometer-sized sail could create an Earth-Mars cargo transport gateway for human exploration of Mars. [View Full Paper]

IAA-AAS-DyCoSS2-14-03-06
AAS 14 – 514
Polyhedral Representation of Invariant Manifolds for Earth-Moon Mission Analysis

Mauro Pontani, University "La Sapienza," Rome, Italy

Recently, manifold dynamics has assumed an increasing relevance for analysis and design of low-energy missions, both in the Earth-Moon system and in alternative multibody environments. Several researches have been focused on this topic in the last decades, and some space missions have already taken advantage of the results of these studies. Recent efforts have been devoted to developing a suitable representation for the manifolds, which would be extremely useful for mission analysis and optimization. This work proposes and describes an intuitive polyhedral interpolative approach for each state component associated with manifold trajectories, both in two and in three dimensions. An adequate grid of data, coming from the numerical propagation of a finite number of manifold trajectories, is employed. With regard to the planar manifold associated with the Lyapunov orbit at the interior collinear libration point L_1, accuracy of this representation is evaluated, and is proven to be satisfactory, with the exclusion of limited regions of the manifold. The polyhedral interpolation technique has several applications, outlined in this work, and three of them are illustrated in this paper. First, transit orbits in the phase space are identified at different locations in the synodic reference system. Second, the globally optimal two-impulse transfer between a specified low Earth orbit and a Lyapunov orbit of given energy is determined. Third, six homoclinic trajectories connected with the previously mentioned Lyapunov orbit are detected in a straightforward way. These three applications prove the effectiveness of the polyhedral interpolative technique and represent the premise for its application also to more challenging problems. [View Full Paper]

SESSION 4: ATTITUDE DYNAMICS AND CONTROL I

Chairs: Richard W. Longman, Columbia University, U.S.A.
Arun K. Misra, McGill Universitry, Canada

IAA-AAS-DyCoSS2-14-04-01
AAS 14 – 515
Attitude Dynamics of a Spacecraft With a Solar Stabilizer

Vladislav Sidorenko, Keldysh Institute of Applied Mathematics, Moscow, Russia

A spacecraft can be oriented toward the Sun by means of solar radiation pressure. To provide a restoring torque a spacecraft should be designed in such a way that, under the conditions of solar orientation, the center of the radiation pressure is placed behind the center of mass from the point of view of an observer on the side of the Sun. In particular one can suppose that the spacecraft is equipped with a solar stabilizer of conic or spherical shape. Our aim is to study the dynamics of the spacecraft with the solar stabilizer after its separation from the booster. Usually an active attitude control system is used to slow down initial fast rotation. But there are several ways to control the rotational motion by means of solar rudders – movable plates mounted on the spacecraft in the form of a windmill or propeller. We discuss the outcome if the simplest strategy is chosen: a simultaneous deviation of solar rudders through a given angle to produce a propellor torque. [View Full Paper]

IAA-AAS-DyCoSS2-14-04-03
AAS 14 – 516
Active Magnetic Attitude Control System Providing Three-Axis Inertial Attitude

M. Ovchinnikov, **V. Penkov** and **D. Roldugin**, Keldysh Institute of Applied Mathematics, Moscow, Russia; **A. Guerman**, Department of Electromechanical Engineering, University of Beira Interior, Covilhã, Portugal

Active magnetic attitude control system providing arbitrary inertial attitude of a satellite is considered. Control and gravitational torques are taken into account. Planar motion is considered for the periodical solutions. Stability is assessed using Floquet theory, optimal algorithm parameters are chosen. Overall gravity effect is assessed.
[View Full Paper]

IAA-AAS-DyCoSS2-14-04-04
AAS 14 – 517
Flat-Spin Recovery of Spinning Satellites by an Equatorial Torque

Frank Janssens, Consultant, KA Noordwijk, The Netherlands;
Jozef van der Ha, Consultant, Deming, Washington, U.S.A.

This paper discusses flat-spin recovery maneuvers by means of a body-fixed torque perpendicular to the maximum principal axis of inertia. The conditions for a successful recovery are established. These are quite different from those obtained when the torque is along the minimum axis of inertia where a minimum torque level is required for a successful recovery. If the torque component on the intermediate axis is negative, a recovery from a pure flat spin can be established for any torque magnitude but the time to recovery increases indefinitely. During the recovery maneuver, the angular velocity and angular momentum vectors become aligned with the minimum axis of inertia by turning over about 90° degrees in the body frame. In inertial space, however, the angular momentum stays in the vicinity of its orientation before the start of the recovery.
[View Full Paper]

IAA-AAS-DyCoSS2-14-04-05
AAS 14 – 518

Intermediaries for Gravity-Gradient Attitude Dynamics I. Action-Angle Variables

Sebastián Ferrer and **Francisco J. Molero**, Universidad de Murcia, Espinardo, Spain

Some intermediary models for the study of roto-translatory dynamics of a triaxial rigid body under gravity-gradient torque are considered assuming MacCullagh's approximation. Following Poincaré and Arnold, they are obtained by splitting the Hamiltonian in the form $H = H_0 + H_1$ where each intermediary H_0 defines a non-degenerate integrable 1-DOF Hamiltonian system and includes part of the coupling between the orbital and rotational motions. We focus here on one of them where the body is taken to be in a circular orbit and referred to a rotating frame. For slow rotations we find both relative and absolute equilibria and their bifurcations as functions of the integrals and moments of inertia. Finally, assuming to be in a circulation regimen for rotational motion, the full reduction of the intermediary is constructed giving the action-angle variables defined by the model, which generalize the classic Sadov variables built on the free rigid body model. Studies on the other intermediaries are in progress and will be published elsewhere. [View Full Paper]

IAA-AAS-DyCoSS2-14-04-06
AAS 14 – 519

A Geometric Method for Analyzing the Orthogonal Responses and Eigenfrequencies of Gravity Gradient Stabilized Satellites

A. E. (Arthur) Overlack, Innovative Solutions In Space (ISIS), Delft, The Netherlands; **J. M. (Hans) Kuiper**, Chair, Space Systems Engineering, Delft University of Technology, Delft, The Netherlands

Gravity gradient stabilization as a passive method for spacecraft attitude control can be an attractive and cost effective design option. This method does not require electrical power nor the implementation of mechanical dampers. The geometrical mass distribution of the spacecraft and the orbit will dictate the gravity gradient response and behavior. This response is not necessarily stable for any given orbit and mass distribution. The stability of the gravity gradient response is critical in satellite design. Finding a particular response can be done by linearizing the equations of motion and successively by a transformation to the Laplace domain. However, such a linearization introduces an error in both the amplitude and frequency of the response. It will be shown that these errors are too large for the results to be useful in dedicated satellite design. A geometrical method was found to solve the nonlinear equations of motion and to provide with analytical expressions for the response and eigenfrequency of the spacecraft. These expressions are verified with numerical simulations and can be used directly in spacecraft design. [View Full Paper]

IAA-AAS-DyCoSS2-14-04-07
AAS 14 – 520

Robust Three-Axis Attitude Stabilization for Inertial Pointing Spacecraft Using Magnetorquers

Fabio Celani, Department of Astronautical Electrical and Energy Engineering, Sapienza University of Rome, Rome, Italy

In this work feedback control laws are designed for achieving three-axis attitude stabilization of inertial pointing spacecraft using only magnetic torquers. The designs are based on an almost periodic model of geomagnetic field along the spacecraft's orbit. Both attitude plus attitude rate feedback, and attitude only feedback are proposed. Both feedback laws achieve local exponential stability robustly with respect to large uncertainties in the spacecrafts inertia matrix. The latter properties are proved using general averaging and Lyapunov stability. Simulations are included to validate the effectiveness of the proposed control algorithms. [View Full Paper]

IAA-AAS-DyCoSS2-14-04-08
AAS 14 – 521
B-Dot Moment Offset Control Algorithm for Geo-Magnetic Field Pointing IITMSAT

B. Praneeth Kumar, **B. Sruteesh Kumar**, **C. Sujatha** and **Sandipan Bandyopadhyay**, Indian Institute of Technology Madras, India

The IITMSAT project is a student satellite initiative of Indian Institute of Technology, Madras. It is a nanosatellite with a scientific mission that involves measurement of proton and electron fluxes in the earth's magnetosphere to characterize their interactions with electromagnetic waves. The mission requires that satellite payload axis be autonomously aligned with that of geomagnetic field direction as the measurement happens along the earth's magnetic field. This paper deals with the development of the B-Dot control algorithm coupled with a moment offset that uses only magnetorquers to satisfy the mission requirements. [View Full Paper]

IAA-AAS-DyCoSS2-14-04-09
AAS 14 – 522
Performance Evaluation of the Inverse Dynamics Method for Optimal Spacecraft Reorientation

Jacopo Ventura, Institute of Astronautics, Technische Universität München, Garching, Germany; **Marcello Romano**, Department of Mechanical and Aerospace Engineering, Naval Postgraduate School, Monterey, California, U.S.A.; **Ulrich Walter**, Institute of Astronautics, Technische Universität München, Garching, Germany

In this paper we apply the inverse dynamics in the virtual domain method to Euler angles, quaternion, and modified Rodrigues parameters for rapid optimal attitude trajectory generation for spacecraft reorientation. The impact of the virtual domain and attitude representation is numerically investigated for both minimum-time and minimum-energy problems. Owing to the nature of the inverse dynamics method, it yields sub-optimal solutions for minimum-time problems. The virtual domain improves the solution, but at the cost of more computational time. The attitude representation also affects solution quality and computational speed. For minimum-fuel problems, the optimal solution can be obtained without the virtual domain. [View Full Paper]

IAA-AAS-DyCoSS2-14-04-10
AAS 14 – 523
Low-Orbital Transformable Nanosatellite: Research of the Dynamics and Possibilities of Navigational and Communication Problems Solving for Passive Aerodynamic Stabilization

I. V. Belokonov, **A. V. Kramlikh** and **I. A. Timbai**, Samara State Aerospace University, Samara, Russia

In this paper the uncontrolled motion about the mass center of aerodynamically stabilized nanosatellite with transformable structure moving along the LEO circular orbit was considered. As a result of the construction transformation, static stability is increased. The analytical cumulative distribution function and the probability density function of the maximum nanosatellite angle of attack for Rayleigh and uniform distributions of the initial transverse angular velocity value for the nanosatellite planar motion are obtained. The distribution laws of the maximum of nanosatellite attack angle after transformation are obtained by numerical simulations for the case of spatial motion. Using found distribution laws of the maximum of nanosatellite attack angle it is analyzed the possibility of successful solutions of navigational problems connected with the use of satellite radio navigation systems GLONASS/GPS and low-altitude satellite communication network GlobalStar. The obtained results are used to create nanosatellite SamSat-QB50 as the part of the international project QB50. [View Full Paper]

IAA-AAS-DyCoSS2-14-04-11
AAS 14 – 524
Attitude Stabilization of a Charged Spacecraft Subject to Lorentz Force

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In this paper, the possibility of the use of Lorentz force, which acts on charged spacecraft, is investigated as a means of attitude control. We assume that the spacecraft is moving in the Earth's magnetic field in an elliptical orbit under the effects of the gravitational and Lorentz torques. We derived the equation of the attitude motion of a charged spacecraft in pitch direction. The effect of the orbital elements on the attitude motion is investigated with respect to the magnitude of the Lorentz torque. The oscillation of angular velocity in pitch direction due to Lorentz force is given for various values of charge to mass ratio. The stability of the attitude orientation is analyzed; and regions of stability are provided for various values of charge to mass ratio. Finally, an analytical method is introduced to study the behavior of all the equilibrium positions. The numerical results confirm that the charge to mass ratio can be used as a semi-passive control for Lorentz-Augmented spacecraft. [View Full Paper]

SESSION 5: ORBITAL DYNAMICS AND DETERMINATION I

Chairs: Simei Ji, Beijing Institute of Technology, China
Fabio Curti, Sapienza University of Rome, Italy

IAA-AAS-DyCoSS2-14-05-01
AAS 14 – 525
An Heuristic Approach to the Problem of Initial Orbit Determination: A Test Case With GEO Observations

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The orbit determination of a satellite in a geostationary orbit is usually based on optical observations. Telescopes all around the Earth are observing the geostationary ring to obtain periodically new measurements in order to update the estimation of the objects' orbits. One critical aspect of the orbit determination process is the initial orbit determination because no a priori information are available. This paper proposes a new method based on search algorithms with heuristic principles aiming to find the six independent orbital parameters that best fit the observations. A genetic algorithm makes the candidate solutions moving in a solution space of six dimensions. The problem is reduced into a two dimensional space with a Lambert's solver using the initial and final angular observations. This paper presents the results using a single image acquired by a Earth-based telescope, the acquired streak is correlated to the objects of the NORAD database. [View Full Paper]

IAA-AAS-DyCoSS2-14-05-02
AAS 14 – 526
Natural Intermediaries as Onboard Orbit Propagators

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Short-term satellite onboard orbit propagation is required when GPS position measurements are unavailable due to an obstruction or a malfunction. In this paper, it is shown that natural intermediary orbits of the main problem provide a useful alternative for the implementation of short-term onboard orbit propagators instead of direct numerical integration. Among these intermediaries, Deprit's radial intermediary, obtained by the elimination of the parallax transformation, shows clear merits in terms of computational efficiency and accuracy. Indeed, this proposed analytical solution is free from elliptic integrals, as opposed to other intermediaries, thus speeding the evaluation of corresponding expressions. A comprehensive performance evaluation using Monte-Carlo simulations is performed for various orbital inclinations, showing that the analytical solution based on Deprit's radial intermediary outperforms a Dormand-Prince fixed-step Runge-Kutta integrator as the inclination grows. [View Full Paper]

IAA-AAS-DyCoSS2-14-05-03
AAS 14 – 527
CORAM: ESA's Collision Risk Assessment and Avoidance Manoeuvres Computation Tool

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The protection of active satellites from impacts by space debris objects is a two-stage process which requires, as first step, the identification and assessment of conjunction events and, as second step, the design and execution of avoidance maneuvers. In order to assist ESA's Space Debris Office (SDO) with these tasks, Deimos Space has developed CORAM, a custom-made Collision Risk Assessment and Avoidance Maneuver computation tool fully integrated within the SDO's operational environment. CORAM implements the latest developments in the algorithms for computation of collision risk as well as an avoidance maneuver algorithm for the design of the best suited avoidance strategy. This paper describes CORAM's architecture, algorithms and capabilities that will help ESA's space debris analysts in the collision avoidance problem. It presents also some examples and real collision avoidance scenarios. [View Full Paper]

IAA-AAS-DyCoSS2-14-05-04
AAS 14 – 528
Long Term Nonlinear Propagation of Uncertainties in Perturbed Geocentric Dynamics Using Automatic Domain Splitting

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Current approaches to uncertainty propagation in astrodynamics mainly refer to linearized models or Monte Carlo simulations. Naive linear methods fail in nonlinear dynamics, whereas Monte Carlo simulations tend to be computationally intensive. Differential algebra has already proven to be an efficient compromise by replacing thousands of pointwise integrations of Monte Carlo runs with the fast evaluation of the arbitrary order Taylor expansion of the flow of the dynamics. However, the current implementation of the DA-based high-order uncertainty propagator fails in highly nonlinear dynamics or long term propagation. We solve this issue by introducing automatic domain splitting. During propagation, the polynomial of the current state is split in two polynomials when its accuracy reaches a given threshold. The resulting polynomials accurately track uncertainties, even in highly nonlinear dynamics and long term propagations. Furthermore, valuable additional information about the dynamical system is available from the pattern in which those automatic splits occur. From this pattern it is immediately visible where the system behaves chaotically and where its evolution is smooth. Furthermore, it is possible to deduce the behavior of the system for each region, yielding further insight into the dynamics. In this work, the method is applied to the analysis of an end-of-life disposal trajectory of the INTEGRAL spacecraft.
[View Full Paper]

IAA-AAS-DyCoSS2-14-05-06
AAS 14 – 529
The Role of Dynamical Models in Ballistic Capture: The Perturbed Sun-Planet Case

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Francesco Topputo and **Franco Bernelli**, Politecnico di Milano, Italy;
Guo-Jian Tang, National University of Defense Technology, Changsha, China

The role of the dynamical models plays in the ballistic capture orbits is analyzed. The ballistic capture problem has been studied in the planar restricted three- and four-body problems among the previous works. This paper extends it to the spatial space and the real gravitational field in the solar system. Three dynamical models, including CR3BP, ER3BP, and ephemeris, are introduced to study the influence of these models. The spatial stability is defined by a semi-plane in an inertial frame. The initial conditions are itemized into four types: stable, unstable, crash, and acrobatic. The ballistic capture orbits are generated around the Mercury, Venus, Mars, Jupiter, and Saturn, where the major gravities root from the sun and the planets themselves. The ballistic capture transfers are analyzed in the planar and spatial conditions. [View Full Paper]

IAA-AAS-DyCoSS2-14-05-07
AAS 14 – 530
Performance Characteristics of the UWE-3 Miniature Attitude Determination and Control System

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Modern miniaturization techniques enable the realization of 3-axis attitude determination and control systems (ADCS), appropriate for the 1 kg pico-satellite class. One of the most challenging aspects concerns the support for continuous ADCS operations at reasonable accuracies despite extremely limited resources available on small satellite platforms. The very low power ADCS of the pico-satellite UWE-3 is based on miniature Sun sensors, magnetometers and MEMS sensors for attitude determination to control the satellite using six magnetic torquers and a single reaction wheel. After successful launch in November 2013, the main technical objective of the third UWE satellite is currently the in-orbit demonstration and characterization of its attitude determination and control capabilities. This contribution addresses the system design aspects and provides results obtained during its first months of operation. [View Full Paper]

IAA-AAS-DyCoSS2-14-05-08
AAS 14 – 531
Stability of Orbits Near Large Mass Ratio Binary Systems

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With recent scientific interest into the composition, origin and dynamical environment of small bodies in the solar system, binary asteroids present a potential target for manned and robotic missions. In this investigation, periodic motions near a large mass ratio binary are explored within the context of the circular restricted three-body problem. Specifically, stability analysis is used to evaluate the effect of the mass ratio on the structure of families of periodic orbits. Such analysis is useful in a variety of applications, including trajectory design in a binary asteroid system or determining possible motions for exoplanets in the vicinity of binary star systems. [View Full Paper]

IAA-AAS-DyCoSS2-14-05-09
AAS 14 – 532
An Improved Initial Constraint Among Differential Orbital Elements for the J2 Invariant Relative Motion

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A set of analytic constraints among differential orbital elements for J2 invariant relative motion has been obtained in this paper. These new constraints are deduced by nullifying the rates of mean osculating longitude of ascending node difference and the weighted rates' combination of the mean argument difference of perigee and the mean anomaly difference. Here, the related weight is found by checking the newly developed analytic bounds for satellite relative motion. By carrying on a set of simulations, it has found that the modified J2-invariance conditions can lead to better results for the bounded relative motion than the method presented in the historical reference.
[View Full Paper]

IAA-AAS-DyCoSS2-14-05-10
AAS 14 – 533
A Polar Variables View on the Critical Inclination Problem in Artificial Satellite Theory

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The frozen-perigee behavior of elliptic orbits at the critical inclination is usually displayed after an averaging procedure. However, this singularity in Artificial Satellite Theory manifests also in the presence of short-period effects. Indeed, a closed form expression relating orbital inclination and the ratio anomalistic draconitic frequencies is derived for the main problem, which demonstrates that the critical inclination results from commensurability between the periods with which the radial and polar variables evolve in the instantaneous plane of motion. This relation also shows that the critical inclination value is slightly modified by the degree of oblateness of the attracting body, as well as by the orbit's size and shape. [View Full Paper]

SESSION 6: MISSION DESIGN AND OPTIMIZATION II
Chairs: Mauro Pontani, Sapienza University of Rome, Italy
Michael Ovchinnikov, Keldysh Institute of Applied Mathematics of RAS, Moscow, Russia

IAA-AAS-DyCoSS2-14-06-01
AAS 14 – 534
LARES-Lab: A Facility for Environmental Testing of Satellite Components and Micro Satellites

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In this paper it will be presented a facility that was developed at Sapienza University of Rome for testing the Cube Corner Reflectors and mounting system of LARES satellite. LARES (Laser RElativity Satellite) satellite was launched on February 13th, 2012. It is a passive satellite, with a massive spherical body, carrying 92 Cube Corner Reflectors (CCRs) that allows tracking the satellite using Laser Ranging Technology. One of the reasons for performing the test was the material, never used for the manufacturing a satellite: a tungsten alloy. The LARES-Lab allows to perform tests of small satellite components and small satellites in a simulated space environment.
[View Full Paper]

IAA-AAS-DyCoSS2-14-06-02
AAS 14 – 535
Visual Orbit Design for Next Mars Exploration Mission

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Yasuhiro Kawakatsu, Department of Space Flight Systems, ISAS/JAXA, Sagamihara, Kanagawa, Japan; **Makoto Taguchi**, Department of Physics, Rikkyo University, Tokyo, Japan; **Ayako Matsuoka**, Department of Solar System Sciences, ISAS/JAXA, Sagamihara, Kanagawa, Japan

This study objectives are to devise orbit design methods and propose orbits fulfilling orbit constraints. The orbits were designed as follows: The orbiter's longitude of ascending node and argument of periapsis, in a Mars-Sun fixed coordinate system, are taken as design variables and the orbit constraint, proposed by a science group, is used as an evaluation function. A curved line that expresses a change history of orbiter's elements is draw in the plane. As a result, it is possible to find out rough initial values of longitude of ascending node and argument of periapsis suitable for the mission visually by moving the curved line, and also rough values of periapsis altitude, apoapsis altitude and inclination by choosing a form of orbit profile matching to the evaluation function.
[View Full Paper]

IAA-AAS-DyCoSS2-14-06-03
AAS 14 – 536
Design and Testing of a Thermoacoustic Refrigerator

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During the last decades, pioneering studies on thermoacoustics during the 1980's, have been put into practice with many applications based on the results, in the meanwhile consolidated, of theoretical developments. A new scenario appeared where, together with traditional technology of thermal machines, a new generation of devices based on the principles of thermoacoustics has grown and developed. Their diffusion is due, basically, to: they are intrinsically simple, they are green, they have good efficiency, and they do not need maintenance; all these reasons and others, have imposed this type of devices, as a new technology. Since 2008, the School of Aerospace Engineering is involved in the study of such technology, by investigating the applications to produce power and cooling systems. The submitted work is a report of the design and test activities concerning a steady state wave thermoacoustic refrigerator. The study evidences the numerous correlations between the performances of the device and its geometrical and physical parameters and architecture. Essentially, the system is made of a sealed container, suitably shaped, and filled with helium through which a stationary wave, activated by a loudspeaker, travels. The interaction of the wave with a passive component, called stack, induces a thermal gradient which is used for the cooling. Many configurations have been analyzed, by varying the pressure of the working fluid, the frequency, the materials, and the stack typology. The results of the tests are very interesting and justify the appeal of such a technology. Although the prototype of the study is not appropriate for the current configuration for space application, because of its heavy weight, similar devices have already flown onboard the Space Shuttle as cooling systems as physiological liquids of astronauts. Moreover, the research program HEPS (High Efficiency Power Supply), financed by NASA, is based in the same technology and addressed to power production on board of space vehicles.[View Full Paper]

IAA-AAS-DyCoSS2-14-06-05
AAS 14 – 537
Performance Analysis and Experimental Design for Differential Optical Shadow Sensor

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The Differential Optical Shadow Sensor (DOSS) is one of the sensors to measure the displacement of proof mass in the Modular Gravitational Reference Sensor (MGRS), which is mainly used for the drag-free control loop. In this paper, the measuring principle of DOSS is presented and follows by the performance analysis for the one-dimensional measurement employing one set of DOSS. To evaluate the performance, the signals detected by the DOSS and its sensitivity are modeled mathematically with the assumption of Gaussian beams, and numerical simulation is adopted to reveal the property of the two performance parameters and the applicability of the two types of modeling presented. The experimental setup to validate the function of DOSS is designed. The work can benefit the DOSS optimization design, and offer valuable implications for the payload design applied in space mission. [View Full Paper]

IAA-AAS-DyCoSS2-14-06-06
AAS 14 – 538
Trajectory Options for Low-Cost Missions to Easily Retrievable Objects

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Near-Earth Objects (NEOs) are of contemporary interest, since asteroids and comets hold the key clues to understanding the origin of the solar system and the formation of the planets, and also have a speculated wealth of material resources. The exploitation of these resources has been discussed as a means to lower the cost of future space endeavours. Recently, a new family of so-called Easily Retrievable Objects that can be transported from accessible heliocentric orbits into the Earth's neighbourhood at affordable costs, have been presented. In this paper, the trajectory options for low-cost missions to EROs are explored. We consider a wide variety of multi-impulse transfer and gravity-assist transfer with mid-course maneuvers to obtain low launch energy rendezvous trajectories to EROs. There trajectories are constructed by analytic and numerical search methods, and hybrid optimization algorithms including global search and local search to find the optimal rendezvous opportunities. The best rendezvous opportunities for currently known EROs in the next 20 years are reported. The relevant mission costs are analyzed. A discussion of general characteristics of the various trajectory types is presented. [View Full Paper]

IAA-AAS-DyCoSS2-14-06-08
AAS 14 – 539
Research on Cooperative Motion Planning of Agile and Autonomous On-Orbit Servicing Spacecraft With Complicated Space Environment

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According to the requirements of on-orbit system servicing in the future industrialized and military space, the cooperative motion planning of assembling and servicing of multiple agile autonomous servicing spacecrafts system is studied in this paper. The improved high-dimensional motion planning method considering state of translation, rotation and time, is used for cooperative motion planning of servicing spacecrafts' accurate and agile motion with complicated space environment. This planner satisfies the requirement of agile and autonomous spacecraft maneuvering with complex constraints. The results show that this high-dimensional motion planner can obtain the feasible motion trajectories. [View Full Paper]

IAA-AAS-DyCoSS2-14-06-09
AAS 14 – 540
High Fidelity Direct Transcription Method for Optimization of Many Revolution, Low-Thrust Trajectories

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We investigate new ideas of direct transcription method for modeling low-thrust trajectories as an improvement to the Sims-Flanagan model. First, the sequential impulsive ΔV transcription is replaced by integrated continuous thrust arcs to improve the fidelity of the dynamical model. Next, to enable the simulation of trajectories with multiple revolutions, we adopt a transformation in the independent variable from time to true anomaly. The obtained new algorithm is able to produce an operational trajectory accounting for the real spacecraft dynamics and adapting the segment duration on-line improving the final trajectory optimality. [View Full Paper]

IAA-AAS-DyCoSS2-14-06-10
AAS 14 – 541
Configuration Optimization for Swarm Spacecraft Based on PSO-SQP Algorithm

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Hou Zhendong, Research Center of Satellite Technology, Harbin Institute of Technology, Harbin, China

This paper proposes a method for optimizing the configuration for swarm spacecraft. Based on relative orbital elements, the description parameters of the cluster configuration is presented, and the cluster stability is analyzed in the presence of the J_2 perturbation. Three main constraints are considered for the design of the cluster configuration, including station-keeping ΔV requirements, passive safety requirements and inter-module communication range requirements; we also formulate the constraints in terms of relative orbital elements. Then, the hybrid particle swarm optimization algorithm integrated with sequential quadratic programming is adopted to handle the optimization issue, and a scenario of 8 modules is used as an example. The results show that the proposed approach is valid and the hybrid PSO-SQP algorithm is very effective in optimizing the cluster configuration. [View Full Paper]

SESSION 7: ATTITUDE DYNAMICS AND CONTROL II
Chairs: Richard W. Longman, Columbia University, U.S.A.
Franco Bernelli, Politecnico di Milano, Italy

IAA-AAS-DyCoSS2-14-07-01
AAS 14 – 542
Quasi-Optimal Rotation Deceleration of a Dynamically Asymmetric Body in a Resistive Medium

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The problem of quasi-optimal deceleration of rotations of a rigid body in a resistive medium was studied analytically and numerically. The asymptotic approach made it possible to determine the control, time (Bellman's function), evolutions of the magnitude of the elliptic functions modulus, and dimensionless kinetic energy and kinetic moment. Investigation of quasi-stationary motions of a body was conducted. The qualitative properties of the quasi-optimal motion were found. [View Full Paper]

IAA-AAS-DyCoSS2-14-07-02
AAS 14 – 543
Attitude Control Mechanization to De-Orbit Satellites Using Solar Sails

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Utilization of solar sails for the de-orbiting of satellites is investigated. The proper attitude maneuver mechanization is proposed to harvest highest solar drag for Earth orbiting satellites. The maneuver is realized using a to-go quaternion calculated from body fixed frame measurements. The success of the attitude control during the continuous, as well as abrupt maneuvers is shown through simulations. The reduction in semi major axis due to the solar drag is shown to be similar in orbits with different inclinations. [View Full Paper]

IAA-AAS-DyCoSS2-14-07-03
AAS 14 – 544
Lyapunov Based Attitude Stabilization of an Underactuated Spacecraft With Flexibilities

G. Mattei, **P. Di Giamberardino** and **S. Monaco**, Department of Computer, Control and Management Engineering "Antonio Ruberti," "Sapienza" University of Rome, Italy; **D. Normand-Cyrot**, Laboratoire des Signaux et Systèmes - CNRS, Paris, France

In this work the attitude control problem for an underactuated flexible spacecraft is investigated. Underactuation and the presence of flexibilities are two challenging problems for space applications even considered separately. Underactuation can be overcome using control torques supplied by gas-jet actuators about two of the principal axes of inertia only if the uncontrolled principal axis of the satellite is not a symmetry axis. This ensures, as well known, that the rigid dynamics is small-time locally controllable. However, the spacecraft cannot be globally asymptotically stabilized using a time-invariant continuous feedback. Using Lyapunov direct criterion, we propose a time-varying feedback stabilizing the rigid-body dynamics and adding, if necessary, the appropriate damping to the flexible motions. Moreover, the control law obtained is robust against uncertainties in the coupling matrix. The stabilization property achieved being only local, we propose a digital multirate steering law to bring the system in the neighbourhood of the origin and then apply the Lyapunov-based stabilizer. We compare our controller with a simpler one that does not take into account the flexible dynamics. The results show the effectiveness of the proposed stabilizing control strategy.
[View Full Paper]

IAA-AAS-DyCoSS2-14-07-05
AAS 14 – 545
On Optimization of Parameters for Linear Stabilization Systems

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Ana M. Seabra, Scientific Area of Mathematics, ESTGV, Polytechnic Institute of Viseu, Campus Politécnico, Viseu, Portugal; **Georgi V. Smirnov**, Centre of Physics, Department of Mathematics and Applications, School of Sciences, University of Minho, Campus de Gualtar, Braga, Portugal

This work deals with numerical methods of parameter optimization for linear stabilization systems. We formulate a special mathematical programming problem in terms of matrix inequalities. Solving this problem we get optimal parameters for a stabilizer. The developed methodology is illustrated by an example concerning optimization of parameters for a satellite stabilization system. [View Full Paper]

IAA-AAS-DyCoSS2-14-07-06
AAS 14 – 546
Attitude Control of a Spacecraft With a Double-Gimbal Variable-Speed Control Moment Gyro Via LPV Control Theory

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In this paper, we analyze dynamics of a DGVSCMG (Double-Gimbal Variable-Speed Control Moment Gyro) and develop an easy-to-use LPV (Linear Parameter-Varying) model, in which we deal with 3-axis attitude control of a spacecraft equipped with a DGVSCMG. Although it is hard to consider overall stability and control performance of attitude control at the same time with conventional methods, this paper attains both of them via LPV control theory, while newly introducing an interesting PDCT (Parameter-Dependent Coordinate Transformation) as well as a virtual state variable. Through a numerical example, we demonstrated the efficiency of the proposed method to compare with a conventional method. [View Full Paper]

IAA-AAS-DyCoSS2-14-07-09
AAS 14 – 547
Mixed Control Momentum Gyroscopes and Reactions Wheel Based Attitude Control System

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D. Cascone and **A. Anania**, Thales Alenia Space Italy, Rome, Italy

This paper describes a mixed Control Moment Gyroscope and Reactions Wheels based AOCS developed for COSMO-SkyMed Second Generation. The proposed architecture and control structure permits to optimal coordinate the functioning of the two actuators in order to maximize the exploitation of the CMG performances. The paper results show that the proposed solution permits to dramatically increase the platform's agility capability. [View Full Paper]

IAA-AAS-DyCoSS2-14-07-10
AAS 14 – 548
Attitude Determination and Control in the T-LogoQube Femto-Satellite Mission

Sean McNeil, Department of Earth and Space Sciences, Morehead State University, Morehead, Kentucky, U.S.A.; **Garrett Jernigan**, Little H-bar Ranch, Petaluma, California, U.S.A.; **Benjamin Malphrus**, **Kevin Brown**, **Robert Twiggs** and **William Roach-Barrett**, Department of Earth and Space Sciences, Morehead State University, Morehead, Kentucky, U.S.A.; **Kevin Zack**, Playful Invention Company, Montreal, Quebec, Canada; **Brian Silverman** and **Lynn Cominsky**, Department of Physics and Astronomy, Sonoma State University, Rohnert Park, California, U.S.A.

T-LogoQube is a first generation 3P (size 5 cm x 5 cm x 15 cm) ~500 gram PocketQube femto-satellite currently in low-earth orbit. T-LogoQube includes a payload of magnetic sensors and magnetic torquers. The satellite software collects and analyzes data from the magnetic sensors in the satellite while in orbit. The flight software implements a simple Fourier transform algorithm to determine the spin, precession, and orientation of the satellite from magnetic sensor data. The satellite sends data packets containing the satellite's spin and precession characteristics to ground operations. A payload of magnetic torquers applies a magnetic field to dampen the precession motion and control the orientation of the spacecraft. This paper describes the capabilities of a uniquely small and low-cost femto-satellite platform for attitude determination and control. [View Full Paper]

IAA-AAS-DyCoSS2-14-07-11
AAS 14 – 549
Gyro Misalignment and Scale Factor Error Determination in Mars Orbiter Mission

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This paper deals with the precise estimation of onboard gyros misalignments and scale factor errors using the Star Sensor measurements as exercised in Mars Orbiter Mission. Single axis maneuvers were performed on spacecraft body to get the observability of cross coupling terms as well as asymmetry components independently for each motion. This is a novel approach to determine critical parameters within the accuracy as provided by Star Sensor data for both the selected and non-selected gyro channels. Improvement in attitude accuracy was observed after the obtained results from calibration exercises were translated to spacecraft. [View Full Paper]

SESSION 8: SATELLITE CONSTELLATIONS AND FORMATION FLYING II

Chairs: Simei Ji, Beijing Institute of Technology, China
Pini Gurfil, Technion - Israel Institute of Technology, Haifa, Israel

IAA-AAS-DyCoSS2-14-08-01
AAS 14 – 550
Control Laws for Defective Swarming Systems

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Swarming systems have been considered in the last decades as a promising technique for increasing the robustness, the flexibility and the autonomy of missions envisaging robotic agents. Many researches have been focused on the control laws which enable an accurate mimicking of the natural swarms (or flocks, schools) of animals. Also stability proofs of the proposed control laws have been reported. Starting from this state of the art, this paper will focus on the behavior of these large groups of robotic agents when some reasonable limitations are applied, i.e. a constraint in the sensors range and in the number of neighboring agents that can be sensed. These swarms, here called defective, are shown to be performant in the task of detecting and gathering around a target (even if it is moving and in presence of obstacles) once a proper sensing rule is designed, i.e. a strategy for selecting the neighboring agents that each agent must consider. [View Full Paper]

IAA-AAS-DyCoSS2-14-08-03
AAS 14 – 551
Orbital Elements Feedback for Cluster Keeping Using Differential Drag

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Differential drag (DD) as a means for passive satellite cluster keeping is an old idea, but so far using DD-based cluster keeping while relying on mean orbital elements feedback has not been proposed. This paper develops a DD-based maximum distance keeping method that uses Brouwer-Lyddane differential mean elements feedback for long-term control of the secular drift among satellites. The stability of the maximum distance keeping controller is proven using finite-time stability theory, and high-precision simulation results confirm that the new controller is able to arrest satellite relative drift for mission lifetimes exceeding a year. The maximum distance controller is automatically activated, and does not require a pre-determined activation time. Moreover, as a part of a complete DD-based solution for cluster keeping, a collision-avoidance method based on the same controller structure, albeit with differential osculating elements feedback, is developed and validated. Finally, the possibility to regulate cross-track drift with DD is examined, but it is shown that DD can only provide weak controllability in this case. [View Full Paper]

IAA-AAS-DyCoSS2-14-08-06
AAS 14 – 552
Differential-Drag-Based Roto-Translational Control for Propellant-Less Spacecraft

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This paper introduces a novel concept using atmospheric differential drag to realize the spacecraft rendezvous conditions of a chaser-target system, and to stabilize, at the same time, the chaser's attitude with respect to the local vertical local horizontal frame attached to its body center of mass. The control forces required for relative maneuvers at low Earth orbits can be generated by varying the relative aerodynamic drag via maneuverable sails placed in the back-end of the spacecraft, while, aerodynamic torques, generated by the displacement of the centers of pressure of the sails, can stabilize the orientation of the spacecraft. In this work, the target vehicle is assumed to maneuver an identical sail in cooperative fashion, and to be centered and attitude-stabilized in its local vertical local horizontal frame. This technology enables propellant-free relative maneuvering. The proposed approach is based on the idea of virtual thrusters, emulating the sail's center of pressure's offset in the controller. Several test cases are presented for various existing spacecraft, demonstrating successful roto-translational control of the chaser spacecraft without the use of propellant. [View Full Paper]

IAA-AAS-DyCoSS2-14-08-07
AAS 14 – 553
Charging Strategies for Electrostatic Control of Spacecraft Formations

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Formation control by means of electrostatic forces, generating attractive or repulsive actions by charging the satellites' surfaces, has been recently proposed for high altitude orbits to precisely maintain the configuration without risk of plume impingement. This paper focus on electrostatic control and switching strategies for charge distribution in spacecraft formations, taking into account the limits on the power requirements. Two nonlinear global control approaches are presented and applied to two and three satellites' formations. Then, an optimized charge distribution process among the satellites is discussed and applied to the three spacecraft formation case. Numerical simulations are performed in order to evaluate the advantages and drawbacks of this configuration control technique. [View Full Paper]

IAA-AAS-DyCoSS2-14-08-08
AAS 14 – 554
Improved Design of On-Orbit Separation Schemes for Formation Initialization Based on J_2 Perturbation

Jiang Chao, **Wang Zhaokui** and **Zhang Yulin**, School of Aerospace, Tsinghua University, Beijing, China

Using one Multi-satellite Deployment System to provide each satellite a velocity increment, the initial formation configuration can be formed without any satellite maneuver. To enhance the stability of the formed configurations, relationships between separation parameters and the stability of initial configurations were analyzed at first. Then, new separation schemes were designed to avoid collision for satellites without propulsion systems. And based on J_2 invariant conditions, separation schemes were also improved to minimize the relative drifts for satellites with orbit maneuver capability. Results simulated in the high precision numerical environment, show that the improved design of separation schemes are effective. [View Full Paper]

IAA-AAS-DyCoSS2-14-08-09
AAS 14 – 555

Formation Flying Dynamics of Micro-Satellites Near Equatorial Low Orbits Under the Influence of J_2 and J_3

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The present work assess the effect of the Earth's oblateness parameters, particularly J_2 and J_3, on the formation flight of micro satellites in near equatorial low orbits. The modified Hill-Clohessy-Wiltshire equations are extended to include the J_2 and J_3 effects in the LVLH frame of reference. The primary gravitational perturbation effect is due to the equatorial bulge term, J_2. The J_2 term changes the orbit period, a drift in perigee, a nodal precession rate and periodic variations in all the orbital elements. The J_2 zonal harmonic captures the equatorial bulge of the Earth, and is the largest coefficient describing the Earth's shape. There is about a 21 km difference in equatorial and polar radii due mainly to this bulge. In the Earth orbit about 800 km altitude, the J_2 effect is much larger in comparison with other perturbations such as atmospheric drag, solar radiation pressure and electromagnetic effects. The modified linearized Hill-Clohessy-Wiltshire to take into account the influence of J_2 and J_3 is utilized to determine the orbits of twin spacecraft in formation flight in Near Equatorial orbits, where the variation of J_2 is less apparent. A simplified approach, capitalizing on the balance between linearized approach and expected fidelity of the obtained solution, has been synthesized to arrive at a linearized J_2 and J_3 modified HCW equation. The computational results obtained are assessed by comparison to Schweighart-Sedwick formula. The significance and relevance of the influence of these parameters in the determination and design of formation flying orbits are assessed through parametric study. As a particular example, for low earth orbit (i.e. 847 km), the error is about 0.25 km from the desired relative position in the LVLH or Hill frame after 16.67 hours. Further comparison to similar results in the literature exhibits the plausibility of the work.

Key words: Formation Flying, Gravitational Potential, J_2, J_3, Near-Equatorial Low Orbits, Orbital Mechanics. [View Full Paper]

IAA-AAS-DyCoSS2-14-08-10
AAS 14 – 556
Optimal Selection of Impulse Times for Formation Flying

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In this paper, leader-follower formation flying problems based on the periodic orbits of the Hill-Clohessy-Wiltshire equations and Tschauner-Hempel equations are considered. the control input is assumed to be impulsive. For a given final relative orbit, the admissible controls are feedback controls such that the follower tracks the final orbit asymptotically. The main performance index is the ΔV which is proportional to the fuel consumption. The number of impulses is fixed, but the impulse time is arbitrary and varied. The optimal location of impulse times is sought numerically. Simulation results for a reconfiguration problem are given. [View Full Paper]

SESSION 9: SPACE STRUCTURES AND TETHERS

Chairs: Harijono Djojodihardjo, Universiti Putra Malaysia (UPM), Serdang, Selangor, Malaysia

Paolo Gasbarri, Sapienza and Università di Roma La Sapienza, Italy

IAA-AAS-DyCoSS2-14-09-01

AAS 14 – 557

A Minimum State Multibody/FEM Approach for Modelling Flexible Orbiting Space Systems

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In the past the deployment of space structures has widely been analysed by using multibody formulations. The two leading approaches are usually based on the Newton-Euler (NE) formulation and Euler-Lagrange (EL) formulation. Both of them present advantages and drawbacks. The ideal approach for describing multi-body systems can be represented by a combination between the NE and EL formulations. This can be obtained by considering the NE formulation for assembling the equation of motion and then by defining the ODE governing equations with the use of a minimum set of variables. In this paper the authors present a mixed NE/EL formulation suitable for synthesizing optimal control strategies during the deploying maneuvers of robotic arms or solar arrays. The proposed method has two main characteristics: (i) the reference frame, which all the bodies motions are referred to, is a floating reference frame attached to the orbiting base platform body; (ii) it leads to a more organic formulation which makes a shifting from the NE to the EL formulations possible, through the use of a Jacobian matrix. In the present work this mixed formulation is derived to describe a fully elastic multi-body spacecraft. Furthermore the presented formulation, complemented with gravity, gravity gradient and generalized gravitational modal forces, will be used to study the dynamic behaviour of an orbiting manipulator with flexible appendages. Finally a Reaction Null/Jacobian Transpose control strategy will be applied to control and deploy the robotic arms to grasp an orbiting flexible spacecraft. [View Full Paper]

IAA-AAS-DyCoSS2-14-09-02
AAS 14 – 558
Dynamics Analysis and GNC Design of Flexible Systems for Space Debris Active Removal

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Active Debris Removal is one of current hot spots in space research, necessary for space exploitation durability. Different techniques have been proposed for this challenging task, among them the use of throw-nets and tow-tethers seems promising: that opens new challenges for Guidance Navigation and Control (GNC) design, especially whenever flexible connections are involved. Via numerical simulations using a multi-body dynamics simulation tool developed at Politecnico di Milano – Department of Aerospace Science and Technology, this paper shows that tethered-net systems are a promising technology to capture and remove space debris and discusses the main difficulties that are likely to take place during capture and disposal phases, particularly from a GNC point of view. [View Full Paper]

IAA-AAS-DyCoSS2-14-09-03
AAS 14 – 559
Dynamics of Tethered System Connected to Moon Surface

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We consider the problem of in-plane rotations of a pendulum with variable length attached to the moon surface. We assume that the Earth and the Moon (or a planet and its satellite, or an asteroid and spacecraft) move about their center of mass in unperturbed Keplerian orbits. We discuss the possibilities to cause a prescribed motion of the system by changing the tether's length. We obtain the equation for the tether length control and use the method of small parameter to find periodic solutions of this equation. The stability of these solutions is studied numerically. The analysis shows that there exists a control law that implements tether rotations uniform with respect to true anomaly; one can indicate conditions when the above rotations are stable in the first approximation. These results can be used for development of a lunar elevator or a system for payload transportation to and from asteroid surface. [View Full Paper]

IAA-AAS-DyCoSS2-14-09-04
AAS 14 – 560
Techniques of AOCS Verification and Validation for Uncertain Dynamics Applied to Satellite With Flexible Appendages

Chiara Toglia and **Giovanni Campolo**, Thales Alenia Space Italy, Rome, Italy

Structural characteristics of orbiting flexible structures are subject to large uncertainties. This issue has to be taken into account when designing and evaluating performance of attitude controller. In this paper we define techniques for the AOCS Verification and Validation (V&V) for uncertain dynamics, in order to guarantee the control correct functionality under a large number of different mission scenarios. A gridding approach can be used, and the V&V can be obtained either with a conventional Monte-Carlo analysis or with the Worst-Case Analysis. Results of both techniques will be presented and compared in terms of attitude control performance and computational cost. [View Full Paper]

IAA-AAS-DyCoSS2-14-09-07
AAS 14 – 561

Thermal Properties Characterization of Space Electronic Circuits Via Image-Based Visual Techniques

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One of the main challenges of satellite manufacturers is its fully safety and complete operational functioning and, once a satellite is orbiting, the thermal management of its electronical equipment is one of the most significant issues. In order to verify if all the devices maintain high performances also under the thermal stresses point of view, it is always necessary to perform a detailed thermal analysis of the electronic equipment which of course requires that its thermal properties must be correctly identified. Usually thermal designers consider worst case conditions in order to simplify the numerical simulations and to ensure functionality and safety but when challenging operative conditions, high power consumption is required, or more simply the dimension of the electronic devices are very small, the worst-case approach is not sufficient to take all the aspects of the thermal management under control. In this paper a general purpose in-house numerical code for the thermal characterization of printed circuit board will be proposed. This tool exploits the image-based visual reconnaissance technique to determine the exact distribution in terms of the conductive material mass fraction and in-plane mapping of very complex printed circuits in order to increase the descriptive level for high detailed thermal analyses. By considering the correct thermal conductivity of the circuits a more precise evaluation of the maximum temperatures reached during the operational life and in non-standard operative conditions could be handled reaching an improvement of the confidence with respect the overall equipment design. Different study cases will be proposed and analyzed in the paper in order to underline the effective improvement of the thermal design coming from a more realistic characterization of the electronic devices. [View Full Paper]

IAA-AAS-DyCoSS2-14-09-08
AAS 14 – 562
Low Outgassing Accelerometers and Cables for Thermal Vacuum and Vibration Test Environments

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Exposure to the high vacuum level of a space environment induces material outgassing in ordinary accelerometers and cables. Any substance subjected to a vacuum has the potential to release trapped gasses. Contaminants from outgassing can condense onto nearby surfaces such as photo-optic devices and obscure them, rendering them useless during their intended application.

During random vibration, swept sine or shock testing prior to flight, spacecraft payloads are often fitted with accelerometers in hard to reach mounting locations. As the space structure is built up around them, it can become impossible to remove the accelerometers. Sensors installed for ground vibration testing may therefore remain on the structure even if they are no longer needed for testing purposes.

In any application involving a thermal vacuum environment care must be taken to select the proper accelerometers and cables prior to vibration testing. Accelerometer designs with hermetic housings and connectors can have low outgassing qualities. For all nonmetallic materials outside of a hermetic package, such as cables with polymer strain relief that do not typically have low outgassing qualities, verification is required to ensure that the materials have less than or equal to 1% TML (total mass loss) and a CVCM (collected volatile condensable mass) less than or equal to 0.1%. This is verified either using NASA documentation or test results from an outside laboratory.

Given these design parameters, a series of accelerometer and cable designs for the thermal vacuum environment will be discussed in this paper. They have been specifically designed or tested for low outgassing properties in accordance with the report NASA RP-1124, "Outgassing Data for Selecting Spacecraft Materials."

KEY WORDS: Low Outgassing, Thermal Vacuum Chamber, Vibration, Shock, Acceleration, Accelerometer, Total Mass Loss, Collected Volatile Condensable Materials. [View Full Paper]

IAA-AAS-DyCoSS2-14-09-09
AAS 14 – 563
Modelling, Identification and Control of a Flexible Lightweight Robot for Space Applications

Luca Bascetta, **Gianni Ferretti**, **Federico Fossati** and **Gianantonio Magnani**, Dipartimento di Elettronica, Informazione e Bioingegneria, Politecnico Di Milano, Milano, Italy; **Andrea Rusconi**, Selex ES, Nerviano (Milano), Italy; **Bruno Scaglioni**, MUSP Lab, Piacenza, Italy

This paper presents a preliminary analysis of a flexible link, flexible joint lightweight robot for space applications, aimed at evaluating the effectiveness and performance of the position control loop which is limited by flexibility of the joints and the limbs, and its robustness with respect to disturbances like, for example, gravity and friction. A model and an experimental characterization of the transmission chain is presented, together with a model of the distributed flexibility of the links based on the floating frame of reference technique. A simulation analysis of the behaviour and performance of the position control loop completes the paper. [View Full Paper]

IAA-AAS-DyCoSS2-14-09-10
AAS 14 – 564
3D Printed Parts for CubeSats; Experiences From KySat-2 and PrintSat Using Windform XT 2.0

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The recent predominance of consumer level 3D printers has brought much attention towards the additive manufacturing process. On November 19th 2013 29 small satellites were launched from NASA's Wallops Flight Facility including KySat-2, a 1U CubeSat. KySat-2 was built with 10 additively manufactured, also called 3D printed, parts made from Windform XT 2.0, a material whose previous uses were mainly for automotive racing. Another 1U CubeSat, PrintSat, will be launched in 2014 and whose entire structure is built from the same material. This paper will discuss how each satellite used 3D printing, an overview of Windform XT 2.0, pros, cons and design considerations of 3D printing, and its future potential uses in the design and construction of spacecraft. [View Full Paper]

IAA-AAS-DyCoSS2-14-09-11
AAS 14 – 565
A Concept of Modular Mechanics for Small Satellites as a Key Driver in Modern Satellite Mechanics Development

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The modern approach to mechanics design assumes constructing optimized structures and mechanisms which fulfil the given requirements concerning the overall development cost and product lifetime. Optimization is driven by economical rationales which usually imply diversity of products from a single product line. This approach allows to reduce a development cost if proper assumptions are applied, based on unification, flexibility and rationalistic design of technical requirements. [View Full Paper]

SESSION 10: ATTITUDE DYNAMICS AND CONTROL III
Chairs: Arun K. Misra, McGill University, Canada,
Paolo Teofilatto, University "La Sapienza," Rome, Italy

IAA-AAS-DyCoSS2-14-10-01
AAS 14 – 566
Kinematic Equations of Nonnominal Euler Axis/Angle Rotation

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Euler axis/angle is a useful representation in many attitude control problems, being related to the single rotation that takes an "initial" reference frame to a "target" reference frame. As a matter of fact, there are some cases in which the nominal rotation cannot be performed. It is the case of spacecraft in underactuated conditions, where attitude effectors can deliver a control torque with two components only.

In a recent work an admissible rotation was proposed in order to minimize the alignment error between the target and the attainable attitude. In this paper, the kinematic equations of the nonnominal Euler axis/angle rotation are presented.
[View full Paper]

IAA-AAS-DyCoSS2-14-10-02
AAS 14 – 567
An Application of Adaptive Fault-Tolerant Control to Nano-Spacecraft

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Since nano-spacecraft are small, low cost and do not undergo the same rigor of testing as conventional spacecraft, they have a greater risk of failure. In this paper we address the problem of attitude control of a nano-spacecraft that experiences different types of faults. Based on the traditional quaternion feedback control method, an adaptive fault-tolerant control method is developed, which can ensure that the control system still operates when the actuator fault happens. This paper derives the fault-tolerant control logic under both actuator gain fault mode and actuator deviation fault mode. Taking the parameters of the UKube-1 in the simulation model, a comparison between a traditional spacecraft control method and the adaptive fault-tolerant control method in the presence of a fault is undertaken. It is shown that the proposed controller copes with faults and is able to complete an effective attitude control maneuver in the presence of a fault. [View full Paper]

IAA-AAS-DyCoSS2-14-10-03
AAS 14 – 568
Sun-Heading Estimation Using a Partially Underdetermined Set of Coarse Sun Sensors

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A comparison of several different methods to estimate the sun direction vector using a partially underdetermined set of cosine-type coarse sun sensors is presented. These methods are used in conjunction with a control law to reorient a spacecraft to a power positive orientation. Coarse sun sensors are commonly used to perform coarse attitude determination and accurately point a spacecraft's solar arrays at the Sun. These sensors are attractive due to their relative inexpensiveness, small size, and reduced power consumption. This paper presents four methods for accurately solving for the sun direction vector with decreased sensor requirements, the first is a simple weighted average method, the second and third are variations on a combination of least squares and minimum norm criteria, and the final leverages an extended Kalman filter approach. All four methods are combined with a control law and shown through numerical simulation to be capable of reorienting the spacecraft from any initially unknown attitude to a power positive state in a matter of minutes. The extended Kalman filter method is shown to provide the most accurate estimate of the sun heading direction, but the weighted least squares minimum norm solution provides the fastest convergence when no angular velocity measurements are available. [View full Paper]

IAA-AAS-DyCoSS2-14-10-04
AAS 14 – 569

Backstepping Attitude Coordination Control for Spacecraft Formation With Multiple Delays

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This paper addresses attitude coordination control for spacecraft formation with multiple delays. A distributed angular velocity input law is firstly constructed for attitude synchronization and tracking under multiple communication delays. Introducing virtual auxiliary systems makes it possible to integrate the angular velocity input law with the true control torque, and asymptotic stability of the system is guaranteed by Lyapunov theory. Moreover, by modifying the angular velocity input law, attitude coordination among spacecrafts can be guaranteed even under control input saturation constraints. Finally, effectiveness of the proposed methodology is illustrated by concrete simulations. [View full Paper]

IAA-AAS-DyCoSS2-14-10-05
AAS 14 – 570

Advanced Technique for Kalman Filter Adjustment and its Implementation Onboard of "TabletSat" Microsatellite Series

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In the paper we introduce the analytical approach that allows us to study the filter performance and it can be applied for quasi-stationary motion determination. The approach based on a computation of filter covariance matrix after convergence, and it allows us to estimate the influence of unaccounted perturbations on motion determination accuracy. Accuracy dependence on filter parameters and perturbation is analytically derived. The proposed advanced method for Kalman filter performance adjustment and study is applied for a set of the algorithms of "TabletSat" microsatellites series.
[View full Paper]

IAA-AAS-DyCoSS2-14-10-07
AAS 14 – 571
Adaptive Robust Redesign of Feedback Linearization for a Satellite With Flexible Appendages

G. Mattei, **A. Carletti**, **P. Di Giamberardino** and **S. Monaco**, Department of Computer, Control and Management Engineering "Antonio Ruberti," Sapienza – University of Rome, Italy;
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The paper deals with the attitude control problem for a satellite with flexible appendages in the presence of perturbations. Satellite dynamics is nonlinear and depends on poorly known parameters and environmental disturbances; flexible appendages increase complexity. In this work an adaptive robust Lyapunov redesign of feedback linearization is applied to the uncertain nonlinear system to achieve large-angle manoeuvres. While gravity-gradient and aerodynamic drag are considered partially structured uncertain terms and are counteracted with the robust part of the control law, the structured unknown parameters characterizing the flexible dynamics become naturally part of the adaptation laws. Not relying completely on a worst-case design has the affect of reducing conservatism and enhancing performance. Simulation results show the superiority of the robust adaptive approach compared to all-robust and nominal versions.
[View full Paper]

IAA-AAS-DyCoSS2-14-10-08
AAS 14 – 572

Examining the Properties of the Waterbed Effect in Spacecraft Disturbance Rejection Control Systems

Edwin S. Ahn, Air Force Research Laboratories, Kirtland AFB, Albuquerque, New Mexico, U.S.A.; **Richard W. Longman**, Departments of Mechanical Engineering and Civil Engineering, Columbia University, New York, New York, U.S.A.;
Richard Carreras, Air Force Research Laboratories, Kirtland AFB, Albuquerque, New Mexico, U.S.A.

Spacecraft have mechanical rotating devices onboard such as CMG's, reaction wheels, cryo pumps, etc. Slight imbalances within these rotating devices cause structural vibrations or jitter, affecting fine pointing equipment. Examples include use of laser communication between spacecraft over a long distance. Repetitive control and various adaptive algorithms can address periodic disturbance with a fundamental and harmonics. Linear feedback control systems are subject to the waterbed effect that says if disturbances are attenuated in some frequency range, they must be amplified in some other range. This paper seeks methods of avoiding substantial amplification between addressed frequencies, while keeping the notch width relatively wide for robustness to period uncertainty. And in addition, we seeks to find ways that can push the amplification to high frequencies where disturbances are small, as is done in routine feedback control systems. Within repetitive control (RC), no method was found to achieve this last objective, but a zero-phase frequency-dependent RC gain was developed that can assist in performing the compromise between the other two objectives. It can produce local modifications of the waterbed behavior. Nonlinear adaptive algorithms are also studied. Although the waterbed theory does not consider nonlinear systems, it is observed that they too are subject to the same kind of limitation. It is also observed that for a complex disturbance environment, adaptive control can shift amplification to high frequencies. Furthermore, the benefits of this shift can be increased by using a faster sample rate.
[View full Paper]

IAA-AAS-DyCoSS2-14-10-09
AAS 14 – 573

CubeSat Orientation Control and Matching to Communications System Requirements

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CubeSat class spacecraft development presents challenges to match communications systems to pointing capabilities. Mission operations, developer capabilities, and resource constraints dominate the decision when implementing ADCS and defining the communications link. An in depth look at the development of an S-Band solution for a CubeSat mission will be presented and how the ADCS solution is predicted to affect the operations. This will provide insight into this second generation level CubeSat program which uses a high performance ground station to compensate for limited aperture on the CubeSat platform. [View full Paper]

SESSION 11: ORBITAL DYNAMICS AND DETERMINATION II

Chairs: Pini Gurfil, Technion - Israel Institute of Technology, Haifa, Israel
Fabio Curti, Sapienza University of Rome, Italy

IAA-AAS-DyCoSS2-14-11-01
AAS 14 – 574

Libration-Point Orbit Missions Disposal at the End-of-Life Through Solar Radiation Pressure

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Markus Landgraf, ESA/ESOC, Darmstadt, Germany

This paper investigates an end-of-life propellant-free disposal strategy for Libration-point orbits that allows the zero-velocity curves to be closed by exploiting solar radiation pressure. The spacecraft is initially disposed into the unstable manifold leaving the Libration-point orbit, before a reflective sun-pointing surface is deployed to enhance the effect of solar radiation pressure. Therefore, the consequent increase in energy prevents the spacecraft's return to Earth. An energetic approach is used to compute the required area for the Hill's curve closure at the pseudo Libration-point SL2, via numerical optimisation. Three European Space Agency missions are selected as test case scenarios: Herschel, SOHO and Gaia. Finally, guidelines for the end-of-life disposal of future Libration-point orbit missions are proposed. [View full Paper]

IAA-AAS-DyCoSS2-14-11-02
AAS 14 – 575
A Method to Evaluate the Perturbation of Nonspherical Bodies

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The purpose of this work is to show an analysis made using a method to measure the amount of perturbation in a trajectory of a spacecraft using the integral of the acceleration over the time. This integral gives the change in the velocity, meaning that the smaller the change is, the reduced will be the effect of the perturbation. The results are generated for trajectories around oblate and prolate spheroids, representing an irregular body. Because of the non-spherical shape, the trajectory around these bodies will not be like a keplerian orbit. Knowing the change of velocity, it is possible to search for the least perturbed orbits and, consequently, the more stable orbits, which can be very helpful for space missions. [View full Paper]

IAA-AAS-DyCoSS2-14-11-03
AAS 14 – 576
Comparative Study of FSS and SPT for Interplanetary Solar Sail Propulsion

Harijono Djojodihardjo and **Ali Yousefian**, Universiti Putra Malaysia (UPM), Serdang, Selangor, Malaysia

With the progress of solar sail interplanetary travel in the last two decades, various alternative concepts and technologies have been developed. Two of the solar sail technologies gaining more popularity are the Flat Solar Sail and Solar Photonic Thruster. Along this frame of thought, the present work is aimed to compare a conventional Flat Solar Sail (FSS) to a modified Solar Photon Thruster (SPT) in order to demonstrate their potentials. To that end, an interplanetary mission is analyzed for a specific trajectory to Mars as an example. The advantages and disadvantages of a SPT are discussed in comparison to a conventional FSS. **Keywords**: Interplanetary Travel, Flat Solar Sail, Solar Photonic Thruster, Solar Radiation Pressure, Solar Sail. [View full Paper]

IAA-AAS-DyCoSS2-14-11-05
AAS 14 – 577
Analytic Model for the Motion About an Oblate Planet in the Presence Atmospheric Drag

Vladimir Martinusi, **Lamberto Dell'Elce** and **Gaëtan Kerschen**, Department of Aerospace and Mechanical Engineering, University of Liège, Belgium

The paper introduces a new model for the motion about an oblate planet under the influence of the atmospheric drag. Both qualitative and quantitative insights are revealed, as well as closed-form equations of motion. The main tool consists in averaging the effects of both perturbations (oblateness and drag), and deriving the variational equations for the vectorial orbital elements. The model is singularity-free and may serve as an initial guess for control problems, as well as an analytic propagator.
[View full Paper]

IAA-AAS-DyCoSS2-14-11-06
AAS 14 – 578
Bounded Trajectories of a Spacecraft Near an Equilibrium Point of a Binary Asteroid System

Pamela Woo and **Arun K. Misra**, Department of Mechanical Engineering, McGill University, Montreal, QC, Canada

With a growing interest in asteroid exploration, combined with the fact that numerous asteroids in nature occur in pairs, it is likely that future missions will include the exploration of binary asteroid systems. Thus, it is useful to study the motion of a spacecraft in the vicinity of such systems, modelled as the three-body problem. In this paper, the circular restricted full three-body problem is considered. The zeroth order equations of motion near an equilibrium point are similar in form to those in the classical case with point-masses or spherical primaries. For most asteroid pairs found in practice, all five equilibrium points are unstable. However, with selection of appropriate initial conditions, it is possible to obtain bounded solutions to the zeroth order equations, corresponding to the Lissajous trajectories near collinear points, and bounded trajectories near noncollinear points. Numerical simulations confirm that when including the additional perturbations due to the asphericity of the asteroid pair, the motion of the spacecraft is unbounded. Thus, control laws are developed by utilizing an appropriate Lyapunov function, with the solutions to the zeroth order equations as reference trajectories. These were found to be sufficient to maintain the spacecraft in bounded trajectories. [View full Paper]

IAA-AAS-DyCoSS2-14-11-07
AAS 14 – 579
Automated Flight Dynamics System for Thaichote Satellite

Manop Aorpimai, Thai-Paht Satellite Research Centre, Mahanakorn University of Technology, Nongchok, Bangkok, Thailand; **Pornthep Navakitkanok**, Orbit and Space Object Analysis Division, Geo-Informatics and Space Technology Development Agency (GISTDA), Ministry of Science and Technology, Bangkok, Thailand;
Sujate Jantarang, President, Mahanakorn University of Technology, Nongchok, Bangkok, Thailand

In this paper, we present the development of the flight dynamics system used for the operations of the Thaichote satellite. The system comprises the orbit determination, orbit propagation, event prediction and orbit control maneouvre modules. The ground-based orbit determination employs the spacecraft's navigation data retrieved from the onboard GPS receiver on a daily basis. Using the estimated orbital state vector from the orbit determination module, the equations of motion are integrated forward in time to predict the satellite states. The higher geopotential harmonics as well as other disturbing forces are taken into account to resemble the environment in low-earth orbit where the satellite is operating. Using a highly accurate numerical integrator based on the Burlish-Stoer algorithm, the satellite's ephemeris can be generated accurately even for long-term predictions. Events occurring during the prediction course that relates the mission operations are detected and reported. They include the drift of groundtrack and local solar time of the orbital nodes, which are vital for orbit control maneouvre planning. We also propose the automation system to handle all the flight dynamics routines, where the spacecraft operations require only initial parameter setup via the user-friendly graphical user interface. [View full Paper]

IAA-AAS-DyCoSS2-14-11-08
AAS 14 – 580
Orbital Evolution of Planet Around a Binary Star

R. Vilhena de Moraes and **J. P. S. Carvalho**, UNIFESP – Instituto de Ciência e Tecnologia, Universidade Federal de São Paulo, São José dos Campos, SP, Brazil; **A. F. B. A. Prado**, Division of Space Mechanics and Control – INPE, São José dos Campos SP, Brazil; **O. C. Winter** and **D. C. Mourão**, UNESP – Univ Estadual Paulista, Guaratinguetá, SP, Brazil.

We study the secular dynamics of hierarchical (if there is a clearly defined binary and a third body which stays separate from the binary) triple systems composed by a Sun-like central star and a Jupiter-like planet, which are under the gravitational influence of a further perturbing star (brown dwarf). The main goal is to study the orbital evolution of the planet. In special, we investigate the orientation (inclination) and the shape (eccentricity) of its orbit. One key feature explored is the time needed for the first flip in its orientation (prograde to retrograde). The gravitational potential is developed in closed form up to the third order. We have compared the secular evolution of systems with and without the third order term of the disturbing potential. The R_2 (quadrupole) and R_3 (octupole) terms of the disturbing potential are developed without using the elimination of nodes. Numerical simulations were also performed to compare with the analytical model using the N-body simulations with the Mercury code. The results show that the analytical model are in agreement with the numeric simulations.
[View full Paper]

IAA-AAS-DyCoSS2-14-11-09
AAS 14 – 581
Orbital Dynamics for a Non-Perfectly Reflecting Solar Sail Close to an Asteroid

Ariadna Farrés and **Àngel Jorba**, Departament de Matemàtica Aplicada i Anàlisi, Universitat de Barcelona, Barcelona, Spain; **Josep-Maria Mondelo**, Departament de Matemàtiques, Universitat Autónoma de Barcelona, Bellaterra (Barcelona), Spain

In this paper we focus on a mission scenario of a solar sail close to an asteroid. We consider the Augmented Hill Three Body problem as a model, where the asteroid is considered as a point mass and both the effect of solar tides and the solar radiation pressure due to the solar sail are included. We will give a complete description of the most relevant dynamics properties of the system. We will compute families of periodic and quasi-periodic orbits for different fixed sail orientations. [View full Paper]

IAA-AAS-DyCoSS2-14-11-10
AAS 14 – 582
Design of a 3U Satellite: Barqna 786 on CubeSat Design Specifications

Shoaib Mansoor, **S. M. Shehzeb Abbas** and **Zainab Saleem**, Department of Aeronautics and Astronautics, Institute of Space Technology, Islamabad, Pakistan

Barqna 786 is the Spacecraft Dynamics and Control project at Institute of Space Technology, Islamabad. Pakistan. The aim of the satellite is to give a chance to the graduating students of Department of Aeronautics & Astronautics to get familiar with the workings of satellites and therefore on the design specifications of CubeSat program, small satellites have been being designed. Barqna 786 is unique in the aspects of having military and research benefits to Pakistan along with equipping students of insight into the satellite designing. This paper highlights the features and capabilities of Barqna 786, including experiments related to gathering of ocean and land data near Pakistan's coast, GPS-based position determination and, reaction wheel and mini-ion thrusters for attitude control. [View full Paper]

SESSION 12: SPACECRAFT GUIDANCE, NAVIGATION AND CONTROL II

Chairs: Jean Mignot, France
Antonio Prado, National Institute for Space Research (INPE), Brazil

IAA-AAS-DyCoSS2-14-12-01
AAS 14 – 583
Multi-Purpose Experimental Test-Bed for Space and Planetary Exploration

F. Curti, **M. Parisse**, **L. Ansalone**, **E. Nardi**, **P. Cassiano**, **M. Moriani**, **F. M. Testi** and **S. Paiano**, Department of Astronautical, Electrical and Energy Engineering, Sapienza University of Rome, Italy

The paper presents an experimental facility built through the collaboration among professors and students of Sapienza for experimental activities concerning the space and planetary exploration and On-Orbit Servicing. The work describes some characteristics of the test-bed and gives a brief description of experimental results for the navigation landing and the lunar rover navigation. [View full Paper]

IAA-AAS-DyCoSS2-14-12-02
AAS 14 – 584
Analysis and Simulation of Attitude Determination and Control for the SERPENS Nanosatellite

Gabriel Figueiró de Oliveira, Satellite Application and Development Division, Brazilian Space Agency, Brasília, Brazil; **Pedro Henrique Dória Nehme**, Electrical Engineering Department, University of Brasília, Brasília, Brazil; **Chantal Cappelletti**, Aerospace Engineering Department, University of Brasília, Gama, Brazil

This paper considers the analysis and simulation of the attitude determination and control system of the SERPENS nanosatellite. The Space System for Research and Experiments with Nanosatellites (SERPENS, from Portuguese: Sistema Espacial para Realização de Pesquisas e Experimentos com Nanossatélites) is part of an initiative of the Brazilian Space Agency to enrich the Brazilian aerospace engineering courses. The main goal of the project is to provide hands-on experience to students. In this sense, different control algorithms developed by the students are to be tested in SERPENS. In this paper, a first analysis of the determination and control system is performed, to serve also as a guideline for future developments. [View full Paper]

IAA-AAS-DyCoSS2-14-12-03
AAS 14 – 585
Neighboring Optimal Guidance for Soft Lunar Landing

Giampaolo Cecchetti and **Mauro Pontani**, Department of Aerospace Engineering, University “La Sapienza,” Rome, Italy; and **Paolo Teofilatto**, Department of Flight Mechanics, University “La Sapienza,” Rome, Italy

This paper presents a general-purpose neighboring optimal guidance algorithm that is capable of driving a space vehicle along a specified nominal, optimal path. This goal is achieved by minimizing the second differential of the objective function along the perturbed trajectory. This minimization principle leads to deriving all the corrective maneuvers, in the context of a closed-loop guidance scheme. Original analytical developments, based on optimal control theory, constitute the theoretical foundation for two relevant features: (i) a new, efficient law for the real-time update of the time of flight (the so called time-to-go), and (ii) a new formulation of the sweep method. Some challenging but nevertheless promising projects have the purpose of building a stable lunar base for future interplanetary missions. For soft lunar landing, the nominal trajectory is represented by the minimum-time path departing from the periselenium of a given elliptic orbit and arriving at the Moon surface. Perturbations arising from the imperfect knowledge of the propulsive parameters and from errors in the initial conditions are considered. Extensive Monte Carlo tests are performed and definitely prove the effectiveness, robustness, and accuracy of the neighboring optimal guidance, also in comparison with the well-established linear tangent steering law. [View full Paper]

IAA-AAS-DyCoSS2-14-12-04
AAS 14 – 586
Mission Analysis and Trajectory GNC for Phobos Proximity Phase of PHOOTPRINT Mission

Francesco Cacciatore and **Javier Martín**, Mission Analysis and Navigation, Deimos-Space, Tres Cantos (Madrid, Spain).

The main characteristic of the Phobos-Mars dynamic environment, key in the design of the proximity operations around the Martian moon, is that it is not possible to consider classical Keplerian motion about such body due to the mass-distance relation between Phobos and Mars. The direct consequence of this fact is that the Lagrange points of the Phobos-Mars system are very close to the surface of Phobos, and the region of influence of Phobos is included below its surface. In the frame of the analyses carried out to design the proximity operations at Phobos for the ESA PHOOTPRINT mission study the main focus was on the so-called Quasi Satellite Orbits (QSO). Such kind of orbits are located beyond the Lagrange points, as seen from the rotating synodic reference frame usually used in three-body problems. As seen from an areocentric inertial reference frame such orbits will appear very close to Phobos' orbit itself; in a Phobos-centered synodic frame the motion of the S/C on a QSO will in turn result similar to a retrograde ellipse, with semi-major axis in the direction of Phobos' areocentric velocity. A detailed investigation was carried out to assess the coverage performances that QSOs allowed for the observation of Phobos' surface. Different QSOs sizes were analyzed, with different inclinations with respect to Phobos' equatorial plane (lying on average in the plane of the satellite orbit around Mars). High latitude areas coverage was achieved introducing specifically targeted polar fly-bys. For close observation of specific areas of Phobos' surface low altitude fly-bys were designed. Operational feasibility and delta-V cost for QSOs, fly-bys, transfers amongst QSOs and Phobos proximity re-acquisition were assessed. Alongside with trajectory design, navigation and guidance performances were analyzed. Estimation accuracy and impact on dispersion evolution were assessed, taking into account the navigation architecture selected and operational safety. Low altitude hovering option was taken into account as intermediate step in descent sequence; the guidance logic was designed, and simulated initially assuming perfect navigation. A more detailed assessment of the hovering GNC performances was carried out including of navigation and control in the loop by making use of adequate performance models for altimetry and optical measurements and for impulsive controls.
[View full Paper]

IAA-AAS-DyCoSS2-14-12-05
AAS 14 – 587
Closed-Form Analytical Solution Based Feasible Trajectory Generation for Hypersonic Re-Entry Guidance

Weiwei Cai, **Leping Yang**, **Yanwei Zhu** and **Yuanwen Zhang**, National University of Defense Technology, Changsha 410073, China

The hypersonic re-entry guidance problem is investigated in this paper with the focus on the feasible trajectory generation using path constraints control strategy. Based on the analysis of the mathematic properties of path constraints, a unified formulation describing the corresponding altitude-velocity relationship for constant path constraints is derived. Also the closed-form analytical bank angle solution is developed and compared with the one obtained from the well-known quasi-equilibrium gliding condition. Dividing the trajectory into several phases of constant path constraints, the longitudinal trajectory is rapidly planned by a search of fewer parameters. The re-entry guidance scheme is then developed using feedback linearization tracking and bank reversal strategy. Numerical simulations show that the approach proposed here steers a typical vehicle along a feasible re-entry trajectory, which satisfies both terminal and path constraints. [View full Paper]

IAA-AAS-DyCoSS2-14-12-06
AAS 14 – 588
Accuracy of Determining the Aberrated Coordinates of a Relativistic Interstellar Spacecraft Using Quasars' Reference Frame

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Previous studies showed that the position and velocity of a relativistic interstellar spacecraft can be determined by means of automatic measurements on-board the spaceship of the aberrated angular distances between three quasars, at least. In this paper we report the results of a simulation finalized to optimize the determination of the aberrated coordinates of a relativistic spacecraft during an interstellar space mission. Indeed, it has been shown that the uncertainties of measurements in navigation control can be minimized selecting the set of quasars, suggesting that the quasars used as an inertial reference frame could be changed during an interstellar voyage to maintain the spaceship's trajectory towards its target. In particular, the algorithm used in this study has shown that the accuracy of determining the aberrated apical coordinates of a spacecraft increases significantly ($p < 0.01$) using quasars as an inertial reference frame with aberrated apical latitudes lower than 50°. This result suggests that one or more normal-sized telescopes aboard the spacecraft can carry out feasible maneuvers along the direction of motion to measure velocity and aberrated coordinates of the spacecraft using quasars within a cone with the axis in the direction of motion of the spaceship and an angular aperture of 50°. In addition, it has been demonstrated that assuming that quasars' angular distances can be measured onboard the spacecraft with reasonable accuracies close to 1 mAs, the aberrated apical latitudes of the spacecraft can be determined with relative errors ranging from 10^{-7} to 10^{-9} using quasars' aberrated apical latitude $\theta \leq 50°$. [View full Paper]

IAA-AAS-DyCoSS2-14-12-07
AAS 14 – 589
Thruster Failure Recovery Strategies or Libration Point Missions

Maksim Shirobokov and **Sergey Trofimov**, Moscow Institute of Physics and Technology, Dolgoprudny, Moscow Region, Russia

Recovery strategies in case of possible thruster failure are proposed for collinear libration point missions. It is implied that, instead of a failed main thruster, a redundant set of thrusters is used to transfer a spacecraft to periodic orbits close to the nominal one or to associated stable manifolds. The basic idea behind this approach consists in the fact that making a spacecraft to follow a reference periodic orbit is often not critical while it is much more important to save enough fuel for station-keeping during the planned mission term. In the paper, a family of planar Lyapunov orbits around the Sun-Earth L2 point is considered though similar results can be obtained in the same way for halo orbits. Transfers to the "cheapest-to-get" periodic orbit and to the reference one are compared for different correction maneuver delay values.
[View full Paper]

IAA-AAS-DyCoSS2-14-12-08
AAS 14 – 590
Active Vision-Based Pose Estimation of an Uncooperative Target

Roberto Opromolla, **Giancarmine Fasano**, **Giancarlo Rufino** and **Michele Grassi**, Department of Industrial Engineering, University of Naples "Federico II," Naples, Italy

This paper aims at investigating the performance of a LIDAR-based system for pose determination of a known debris. A customized template matching technique is implemented for pose initial acquisition, while pose tracking is carried out by Iterative Closest Point algorithms based on different matching approaches. In order to evaluate the achievable accuracy in pose estimation, a numerical simulator is developed implementing realistic debris geometry, target/removal-system relative dynamics, and sensor operation. Results relevant to a large debris in Low Earth Orbit show that even relatively sparse point clouds allow the pose to be computed with sub-degree accuracy in attitude and sub-centimeter accuracy in the relative position. [View full Paper]

IAA-AAS-DyCoSS2-14-12-10
AAS 14 – 591
A Global Sliding Mode Control With Pre-Determined Convergence Time Design for Reusable Launch Vehicles in Reentry Phase

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This paper addresses the robust attitude control problem of reusable launch vehicles (RLV) with parametric uncertainties and external disturbances in reentry phase. Based on the feedback-linearized RLV rotational equations of motion, a global sliding mode control (SMC) strategy with a priori stated convergence time is first proposed, which ensures the global robustness of the controlled system. As compared with the existing sliding mode attitude control method, an improved system performance can be obtained in terms of convergence time and robustness. Then, the steady-state error problem caused by the continuous approximation techniques such as the boundary layer method (which is used to alleviate the control chattering) is considered. A disturbance observer (DO) based global SMC strategy is presented to improve the control accuracy. Finally, the validity of the proposed strategies is verified by both theoretical analysis and simulation results for the attitude control problem of X-33 RLV in reentry phase.
[View full Paper]

SESSION 13: ATTITUDE SENSORS AND ACTUATORS

Chairs: Franco Bernelli, Politecnico di Milano, Italy
Michael Ovchinnikov, Keldysh Institute of Applied Mathematics of RAS, Moscow, Russia

IAA-AAS-DyCoSS2-14-13-01
AAS 14 – 592
MHD Reaction Wheel for Spacecraft Attitude Control: Configuration and Lumped Parameter Model

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A novel actuator for spacecraft attitude control with liquid flywheel is presented. The main characteristic of this new concept of a reaction wheel is that a conductive liquid rather than a solid mass is accelerated to change the angular momentum of the equipment and, as a consequence, to provide the torque to the spacecraft. The conductive liquid inside an annulus with rectangular cross section is accelerated using the Lorentz force originates from the interaction between an electric current flowing through the fluid and a magnetic field. This paper proposes two suitable configurations of the device and a lumped parameter model based on Magneto-Fluid Dynamics set of equations under the hypothesis of low Magnetic Reynolds. The lumped parameter model is addressed to one of the two configurations considered more suitable for space application. [View full Paper]

IAA-AAS-DyCoSS2-14-13-02
AAS 14 – 593
MicroSat Biomagnetic Control System

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Antonella De Ninno, Department UTAPRAD-DIM, ENEA Frascati, Frascati, Italy;
Giuseppe Rondinelli, Chief Technical Officer Dept, Telespazio S.p.A. Rome, Italy

One of the frontier of the spaceflight to be overcome in the next years is the use of organic elements to integrate the on board automated or robotic systems. The adoption of these technologies on board requires their space qualification that is the possibility of testing and experimenting their behavior at low cost in space. So that, the opportunity offered by CubeSat or Microsatellite missions, able to assure the test on field of fundamental parts of the basic elements of such systems, has a crucial role.

The ambitious target from now on is the creation of an autonomous system where satellite position determination and magnetic attitude control might be performed by bio-sensors and bio-actuators capable autonomously and promptly to react to the environment variations.

The present paper shows a proof-of-concept study of the innovative design for magnetic attitude control system based on biosensors able to detect variations of the Earth's magnetic field in LEO satellite mission and bio-elements capable to provide appropriate feedbacks to steer the activation by pulses of attitude control system. It has been proven through in vitro experiments that suitable organic compounds or aqueous solutions of biomolecules undergo to changes in the acid-base equilibrium when exposed to variations of magnetic field, even at low intensities. Using this concept it can be derived that measurable variations of the pH of the compound might be determined by magnetic field variations: thus, it might be possible to design a new class of magnetic biosensors based on special hydrogels. [View full Paper]

IAA-AAS-DyCoSS2-14-13-04
AAS 14 – 594
GNSS Based Attitude Determination Systems for Nanosatellites

Vincenzo Capuano, **Cyril Botteron** and **Pierre-André Farine**, ESPLAB, École Polytechnique Fédérale de Lausanne (EPFL), Switzerland

Attitude determination systems based on Global Navigation Satellite Systems (GNSSs) present several advantages, most of all for very small satellites. Indeed, GNSS receivers have low power consumption, limited mass, small volume, and are relatively inexpensive. However, if the attitude information is extracted from the relative position between two or more GNSS antennas placed on the nanosatellite, due to the small baseline between them, the achievable accuracy will not be as good as the one obtained with other high performance attitude sensors. In order to circumvent this accuracy limitation, an alternative single-antenna GNSS-based method is presented, which estimates attitude information through the use of the GNSS-derived accelerations. [View full Paper]

IAA-AAS-DyCoSS2-14-13-05
AAS 14 – 595
The Detection and Identification of Control Moment Gyro Faults

Hwa-Suk Oh and **Ji-Chul Kim**, Department of Aerospace and Mechanical Engineering, Korea Aerospace University, Goyang, Korea

When control moment gyros (CMGs) are employed as satellite actuators, they generate a large amount of torque through the steering of their gimbals. Each gimbal holds a high speed rotating wheel. Wheel speed error and imbalances induce disturbances and degrade satellite control quality. Disturbances thus need to be detected and identified as a precaution against actuator faults. State observers have been used as one method of detecting disturbances. A continuous second order sliding mode observer is suggested and applied for the detection of single disturbances/faults on CMGs. A frequency compensation algorithm is also suggested for the improvement of magnitude identification on the existence of highly oscillating disturbances. Highly oscillating disturbances induced by wheel speed errors and imbalance faults are thus satisfactorily detected and identified even in the high frequency domain. [View full Paper]

IAA-AAS-DyCoSS2-14-13-06
AAS 14 – 596
Power Consumption Based on a Four Reaction Wheels in a Pyramidal Configuration

Ronald Hurtado and **Jesús González–Llorente**, Escuela de Ciencias Exactas e Ingeniería, Universidad Sergio Arboleda, Bogotá, Colombia; **Yesid Villota**, Departamento de Ciencias Básicas, Universidad Santo Tomas, Bogotá, Colombia

A cluster of four reaction wheels, used for attitude control in a 3U CubeSat, has been chosen for a power consumption analysis. The reaction wheels cluster is arranged in a pyramidal configuration. The reaction wheels were modeled as a dc motor. It's shown how the power consumption for this configuration is affected according to the pyramid angle. The power consumption was evaluated while the orientation process occurred. The simulation was made for a particular desired attitude, varying the pyramid angle each time. The results show the power consumption considering the voltage and current in each wheel and the entire cluster. [View full Paper]

IAA-AAS-DyCoSS2-14-13-07
AAS 14 – 597
CubETH Sensor Characterization:
Sensor Analysis Required for a CubeSat Mission

Stefano Rossi, **Anton Ivanov**, **Gaëtan Burri** and **Volker Gass**, École Polytechnique Fédérale de Lausanne (EPFL), Switzerland;
Christine Hollenstein and **Markus Rothacher**, ETHZ, Zürich, Switzerland

Swiss Federal Universities of Lausanne and Zurich have initiated a new 1U CubeSat project. The main objective of the CubETH is to demonstrate use of commercial GNSS receivers in space and test Precision Orbit Determination algorithms. One of the key driving requirements is to provide zenith pointing with a 20 degrees of precision and rotation rate less than 2 degree / second, in order to track GNSS constellation satellites. This paper will describe details of Attitude Determination and Control Subsystem (ADCS) based on magnetotorquers, sun sensors, gyros and magnetometers in order to satisfy the science requirements. We will discuss the lessons learned from the ADCS implementation on the first Swiss nanosatellite SwissCube (in operation since 2009) and we present the characterization of the selected sensors in the laboratories of the Ecole Polytechinque Federale de Lausanne (EPFL) in Switzerland. The main lesson learned from SwissCube is to establish vigorous testing procedures for all sensors. This paper will present tests set-up and procedures used for the present and the future tests in the laboratories of the Swiss Space Center that take experience from that heritage. We describe the main issues encountered in the preparation of tests set-up, interfaces and procedures to establish the trade-off study for the sensors: static and dynamic characterizations, temperature behaviors and others. We address, as conclusions, the main performances obtained after the three test campaigns done. The paper gives to the CubeSat community a validated and simple process to characterize the sensors for the attitude determination. [View full Paper]

IAA-AAS-DyCoSS2-14-13-08
AAS 14 – 598
CubETH Magnetotorquers: Design and Tests for a CubeSat Mission

Stefano Rossi, Anton Ivanov, Gael Soudan and Volker Gass, École Polytechnique Fédérale de Lausanne (EPFL), Switzerland;
Christine Hollenstein and **Markus Rothacher**, ETHZ, Zürich, Switzerland

Swiss Federal Universities of Lausanne and Zurich have initiated a new 1U CubeSat project. The main objective of the CubETH is to demonstrate use of commercial GNSS receivers in space and test Precision Orbit Determination algorithms. One of the key driving requirements is to provide zenith pointing with a 20 degrees of precision and rotation rate less than 2 degree / second, in order to track GNSS constellation satellites. This paper will describe details of Attitude Determination and Control Subsystem (ADCS) based on magnetotorquers in order to satisfy the science requirements. We will discuss lessons learned from the ADCS implementation on the first Swiss nanosatellite SwissCube (in operation since 2009) and we present the flat shaped magnetotorquers (MTQs) designed in the laboratories of the École Polytechnique Fédérale de Lausanne (EPFL) in Switzerland, detailing design, the test setup and the procedures performed. We present theoretical calculations for the magnetotorquer parameters, simulations, details of manufacturing and results of testing done in the shielded room of the École Polytechnique Fédérale de Lausanne. Testing shows a 93% of match between the 3D model and tests done with the magnetic probe on the new design prepared for CubETH, where the design slightly changed from the previous shape of SwissCube. The paper presents the description of the manufacturing and the process followed in order to highlight the encountered issues on the magnetotorquers fabrication. We address the process to select the proper materials and quantities for the manufacturing of flight and engineering models, addressing the required characteristics for the material selected. [View full Paper]

SESSION 14: OPTIMAL CONTROL IN SPACE FLIGHT DYNAMICS

Chairs: Georgi Smirnov, Centre of Physics, Department of Mathematics and Applications, School of Sciences, University of Minho, Campus de Gualtar, Braga, Portugal
Mauro Pontani, Sapienza University of Rome, Italy

IAA-AAS-DyCoSS2-14-14-01
AAS 14 – 599
Optimal Control on Gauss' Equations

Stefano Campagnola, Department of Space Flight Systems, ISAS, JAXA, Sagamihara-shi, Kanagawa-ken, Japan;
Ryan P. Russell, Department of Aerospace Engineering and Engineering Mechanics, W.R.Woolrich Laboratories, University of Texas at Austin, Texas, U.S.A.

This paper presents some theoretical developments on optimal control applied to Gauss' equations, when only control perturbations are considered. For a large family of problems, it is shown that the optimal control points toward a primer vector (equivalent to Lawden's primer vector in cartesian coordinates). The primer vector is a compromise between feedback laws (named here *control primitives*), with the costates acting as time-varying weights. The general state and costate equations are provided together with the linearized equations needed for the propagation of the partials. The first and second derivatives of Gauss equations in Keplerian and equinoctial elements are presented in a compact form, which is easy to derive and to code using cartesian tensor notation and logarithmic differentiation. Finally it is analytically proven that the optimal control maximizing the final semi-major axis is not always tangent; although it is it confirmed that a constant, tangential thrust (which is the control primitive associated to the semi-major axis) represent a good approximation. [View full Paper]

IAA-AAS-DyCoSS2-14-14-03
AAS 14 – 600
Symmetry Properties of Optimal Space Trajectories

Mauro Pontani, Department of Aerospace Engineering, University "La Sapienza," Rome, Italy

The determination of minimum-fuel or minimum-time space trajectories has been pursued for decades, using different methods of solution. This work illustrates some symmetry properties that hold for optimal space trajectories and can considerably simplify their determination. The existence of symmetry properties is demonstrated in the presence of certain boundary conditions for the problem of interest. If the linear Euler-Hill equations of motion are used, a pair of properties are proven to hold for minimum-time and minimum-fuel rendezvous trajectories, both in two and in three dimensions. With regard to minimum-fuel paths, the primer vector theory predicts the existence of several powered phases, divided by coast arcs. In general, the optimal thrust sequence and duration depend on the time evolution of the switching function, and can be proven to satisfy interesting symmetry properties, provided that a pair of elementary boundary conditions holds. In the context of the circular restricted three-body problem, the theorem of image trajectories, proven about 50 years ago, establishes the symmetry properties of feasible trajectories. In this work this theorem is extended to optimal trajectories, thus substantiating a conjecture that dates back to the 60's. [View full Paper]

IAA-AAS-DyCoSS2-14-14-04
AAS 14 – 601
Robust Rendez-vous Planning Using the Scenario Approach and Differential Flatness

Lamberto Dell'Elce and **Gaëtan Kerschen**, Department of Aerospace and Mechanical Engineering, University of Liège, Belgium

There is a growing interest in uncertainty handling in the spacecraft dynamics community. In particular, robust optimization of spacecraft maneuvers is regarded as an important challenge. This paper proposes an optimal control approach for orbital rendez-vous planning under stochastic dynamics and constraints. The method combines differential flatness theory with the scenario approach for optimization under uncertainties. By mapping state and control variables into a set of flat outputs, the enforcement of dynamics equations and boundary conditions is automatically satisfied. The rigorous foundations of the scenario approach lead to a finite-dimensional formulation of the problem which guarantees the feasibility of the solution within an arbitrary portion of the stochastic domain. The methodology is illustrated by means of two case studies involving a rendez-vous in elliptic orbit and a propellantless maneuver using differential drag, respectively. [View full Paper]

IAA-AAS-DyCoSS2-14-14-07
AAS 14 – 602
Embedded MPC for Space Applications

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Autonomy is being defined as the capability of a vehicle by means of its on board systems to perform functions without external support. Focusing on stabilization and guidance, in this paper we investigate the use of the Model Predictive Control (MPC) technique as a candidate technology to help bringing more autonomy to future space systems. By means of a multi-rotor Unmanned Aerial Vehicle (UAV) case study we detail the software and the hardware aspects concerning a fast real time MPC implementation for low level GNC functions on a low power embedded computing platform. Our control scheme performances are assessed through simulations, on-board testing and comparisons with other techniques. [View full Paper]

IAA-AAS-DyCoSS2-14-14-09
AAS 14 – 603
Low Thrust Minimum Fuel Optimization in the Circular Restricted Three Body Model

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In this paper, low-thrust fuel-optimal transfer trajectories are studied in the Earth-Moon restricted three-body model with constant specific impulse engines. In order to cope with high computational burden and convergence problems caused by multi spirals and large number of bang-bang control structures, homotopy method is implemented by starting from the related and easier energy-optimal problem, for which, the analytical Jacobian is derived, and a combination of Newton and bisection methods is proposed to accurately detect the switching points together with a variable step 7th/8th-order Runge-Kutta integrator. The case study is a low-thrust transfer from the GTO to a periodic three-dimensional halo orbit around the Earth-Moon L_1 point. Initial costates are first achieved by solving the problem with a high thrust level, which is then reduced through discrete homotopy. The final orbit has about 150 revolutions and the control profile is characterized by about 150 bang-bang structures. The techniques presented in the paper are useful in practical cases where very low-thrust accelerations is used in high nonlinear vector fields. [View full Paper]

IAA-AAS-DyCoSS2-14-14-10
AAS 14 – 604
ALSAT-2A Mission: Experience of Three Years of Station Keeping Orbit Maintenance

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On 12th July 2010 at 03h52’ UT, ALSAT-2A has been launched by PSLV-C15 from Sriharikota, Chennaï (India). Nine days after, the satellite has been placed on its mission orbit. This paper describes the in-orbit results of the orbit maintenance maneuvers performed by using a new version of flight dynamics software. The obtained results on the ground track corrections demonstrate that with the new version, the realization of small maneuvers become as accurate as for strong ones. [View full Paper]

SESSION 15: MISSION DESIGN AND OPTIMIZATION III

Chair: Antonio Prado, National Institute for Space Research (INPE), Brazil

IAA-AAS-DyCoSS2-14-15-01
AAS 14 – 605
First-Guess Generation of Solar Sail Interplanetary Heteroclinic Connections

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This work deals with the generation of first-guess interplanetary trajectories connecting Libration Point Orbits (LPOs) belonging to different restricted three-body problems. With the Sun always as first primary, the Earth, Mars and Mercury are assumed as second primary, and their relative models are coupled together with the view of defining heteroclinic connections. On suitable Poincaré sections, solar sail sets are constructed to obtain transit conditions from LPOs of the departure dynamical system to LPOs of the arrival one. Constant attitude solar sails are investigated, assuming spacecraft with limited control capabilities. The preliminary propellant-free transfer trajectories are considered for a range of novel solar sail applications, including a continuous Earth–Mars communication link, an Earth–Mars cargo transport gateway and an opportunity for in-situ observations of Mercury. [View Full Paper]

IAA-AAS-DyCoSS2-14-15-02
AAS 14 – 606

Optimal Spacecraft Trajectories for Flight to Asteroid Apophis With Return to Earth Using Chemical High Thrust Engines

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Energy optimal trajectories for the flight to asteroid Apophis, staying there during some time and following return to the Earth are determined and investigated in the paper. The Rocket "Soyuz" is proposed to be used for the spacecraft launch onto an initial LEO orbit. The upper stage "Fregat" is used for the escape. A special chemical engine is used for the following heliocentric corrections, and maneuvers, including the deceleration as well as the acceleration near the Apophis. On the first stage of the analysis, the impulse approximation is performed for the trajectories determination. Then the trajectories are varied with taking into account the thrust values of the chemical engines used. There are determined optimal trajectories and their characteristics for the expedition from Earth to Apophis and back for the flights during 2019-2022 years, with the flight duration up to two years. Comparison with the flight using the low thrust electric-jet engines is performed. The flight of the asteroid's satellite near Apophis is analyzed at the last part of the paper. [View Full Paper]

IAA-AAS-DyCoSS2-14-15-03
AAS 14 – 607

Impact on Mission Design Due to Collision Avoidance Operations Based on TLE or CSM Information

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Collision avoidance manoeuvres are considered for mission design and fuel budget allocation, and may have a relevant impact in particular orbital regimes. Current operations for collision avoidance are based on Two-Line-Elements (TLE) orbital data or the Conjunction Summary Message (CSM) data. This paper presents the most suitable approach for collision avoidance for several mission types when operations are based on TLE or CSM data, with a detailed analysis of the impact of the orbital accuracy of catalogue data and warning time–to–event on mission design in terms of fuel budget for collision avoidance activities and operational constraints imposed by the avoidance manoeuvres. [View Full Paper]

IAA-AAS-DyCoSS2-14-15-04
AAS 14 – 608
Terminal Attitude-Constrained Optimal Feedback Guidance for Pinpoint Planetary Landing

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The pinpoint landing problem of planetary exploration is considered in this paper. The terminal position and velocity as well as the terminal attitude are dealt with by taking the derivative signals of commanded acceleration as a virtual input vector, thus the commanded acceleration relating with attitude becomes an extended state vector. The indirect optimization method is used to derive an analytical optimal solution, which is a function of the time-to-go. The explicit formulation of the proposed feedback optimal guidance law extremely minimize the computational burden. Further, the closed-loop nature brought the capacity of accommodating external disturbances. The whole powered decent phase of the lunar mission is used to validate the proposed method. The convincing simulation results reveal that accurately pinpoint landing and terminal attitude constraints are satisfied. [View Full Paper]

SESSION 16: SPACECRAFT GUIDANCE, NAVIGATION AND CONTROL III
Chair: Vladislav Solovey

IAA-AAS-DyCoSS2-14-16-03
AAS 14 – 609
Evaluating Orbits With Potential to Use Solar Sail for Station-Keeping Maneuvers

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The purpose of this paper is to find the necessary and the sufficient conditions to use solar sails in order to compensate or to reduce the perturbation effects due to external forces received by a satellite. The study considers a satellite with the following disturbing forces: the solar radiation pressure, the zonal harmonic perturbation J_2 to J_4 and the third body perturbation due to the Sun and the Moon. The necessary and the sufficient conditions are, for a given orbit, the area and the attitude that the solar sail must have in order to compensate or to reduce the effects of the other perturbation forces. In this way, the cost of the station keeping maneuver can be reduced in terms of the fuel consumption, since there is less perturbation acting on the satellite. Consequently, the lifetime of the satellite can be extended, since it is dependent from the fuel left to perform orbital maneuvers. The use of the integrals over the time is a new approach that provides the accumulated effects of the perturbation forces. In this way, it is also possible to evaluate the magnitude of each perturbation force acting separately or all added together and also the evaluation of the magnitude of the reduction of the disturbing forces with the solar sail usage. The result of this integral is also the total velocity variation that the satellite suffers from the perturbation forces. In addition, the evaluation of the direction of the perturbation forces can guarantee the use of the solar sail to reduce the shifts caused by the external forces acting on the satellite by applying a disturbing force from the solar sail in the opposite direction of the other perturbations.
[View Full Paper]

IAA-AAS-DyCoSS2-14-16-04
AAS 14 – 610
A Low Earth Orbit Agile Satellite Mission Plan Guidance Checking Software Tool

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In this work, a software tool for guidance checking of a mission plan of an agile low earth orbit satellite is presented. Indeed, the agility feature will increase the satellite maneuverability, but leading to some guidance discontinuities that sometimes bring the satellite to important pointing errors. To overcome this problem, an on-ground guidance checking software tool based on an attitude propagator to ensure a correct mission plan execution is developed. As an application, we consider the second Algerian satellite ALSAT-2A characterized by a high resolution, and a three axis stabilized with an off nadir pointing capability in pitch and roll axis. [View Full Paper]

IAA-AAS-DyCoSS2-14-16-05
AAS 14 – 611
More Sustainability and Profits With Deorbiting Systems

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Thousands of satellites have been launched in the space era: it is difficult not to think about their possible impacts with other future satellites, or with some place in the Earth when falling down. Concerns are about loss of image, interruption of services, loss of money, damages to goods or even injury to persons. From a different perspective, however, actions for debris prevention and removal could be seen not only as means for avoiding negative situations, but as means to implement positive actions as to implement "space sustainability" and profits. [View Full Paper]