SPACEFLIGHT MECHANICS 2016

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Front Cover Illustration:

NASA's New Horizons spacecraft captured this high-resolution enhanced color view of Pluto on July 14, 2015. The image combines blue, red and infrared images taken by the Ralph/ Multispectral Visual Imaging Camera (MVIC). Pluto's surface sports a remarkable range of subtle colors, enhanced in this view to a rainbow of pale blues, yellows, oranges, and deep reds. Many landforms have their own distinct colors, telling a complex geological and climatological story that scientists have only just begun to decode. The image resolves details and colors on scales as small as 0.8 miles (1.3 kilometers). Credit: NASA/JHUAPL/SwRI.

SPACEFLIGHT MECHANICS 2016

Volume 158

ADVANCES IN THE ASTRONAUTICAL SCIENCES

Edited by
Renato Zanetti
Ryan P. Russell
Martin T. Ozimek
Angela L. Bowes

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FOREWORD

This volume is the twenty-sixth of a sequence of Spaceflight Mechanics volumes which are published as a part of *Advances in the Astronautical Sciences*. Several other sequences or subseries have been established in this series. Among them are: Astrodynamics (published for the AAS every second year), Guidance and Control (annual), International Space Conferences of Pacific-basin Societies (ISCOPS, formerly PISSTA), and AAS Annual Conference proceedings. Proceedings volumes for earlier conferences are still available either in hard copy, CD ROM, or in microfiche form. The appendix of the volume lists proceedings available through the American Astronautical Society.

Spaceflight Mechanics 2016, Volume 158, Advances in the Astronautical Sciences, consists of four parts totaling about 4,800 pages, plus a CD ROM/digital format version which also contains all the available papers. Papers which were not available for publication are listed on the divider pages of each section in the hard copy volume. A chronological index and an author index appear at the end of the main linking file, and are appended to the third part of the volume.

In our proceedings volumes the technical accuracy and editorial quality are essentially the responsibility of the authors. The session chairs and our editors do not review all papers in detail; however, format and layout are improved when necessary by the publisher.

We commend the general chairs, technical chairs, session chairs and the other participants for their role in making the conference such a success. We would also like to thank those who assisted in organizational planning, registration and numerous other functions required for a successful conference.

The current proceedings are valuable to keep specialists abreast of the state of the art; however, even older volumes contain some articles that have become classics and all volumes have archival value. This current material should be a boon to aerospace specialists.

AAS/AIAA SPACEFLIGHT MECHANICS VOLUMES

Spaceflight Mechanics 2016 appears as Volume 158, *Advances in the Astronautical Sciences*. This publication presents the complete proceedings of the 26th AAS/AIAA Space Flight Mechanics Meeting 2016.

Spaceflight Mechanics 2015, Volume 155, *Advances in the Astronautical Sciences*, Eds. R. Furfaro et al., 3626p., three parts, plus a CD ROM supplement.

Spaceflight Mechanics 2014, Volume 152, *Advances in the Astronautical Sciences*, Eds. R.S. Wilson et al., 3848p., four parts, plus a CD ROM supplement.

Spaceflight Mechanics 2013, Volume 148, *Advances in the Astronautical Sciences*, Eds. S. Tanygin et al., 4176p., four parts, plus a CD ROM supplement.

Spaceflight Mechanics 2012, Volume 143, *Advances in the Astronautical Sciences*, Eds. J.V. McAdams et al., 2612p., three parts, plus a CD ROM supplement.

Spaceflight Mechanics 2011, Volume 140, *Advances in the Astronautical Sciences*, Eds. M.K. Jah et al., 2622p., three parts, plus a CD ROM supplement.

Spaceflight Mechanics 2010, Volume 136, *Advances in the Astronautical Sciences*, Eds. D. Mortari et al., 2652p., three parts, plus a CD ROM supplement.

Spaceflight Mechanics 2009, Volume 134, *Advances in the Astronautical Sciences*, Eds. A.M. Segerman et al., 2496p., three parts, plus a CD ROM supplement.

Spaceflight Mechanics 2008, Volume 130, *Advances in the Astronautical Sciences*, Eds. J.H. Seago et al., 2190p., two parts, plus a CD ROM supplement.

Spaceflight Mechanics 2007, Volume 127, *Advances in the Astronautical Sciences*, Eds. M.R. Akella et al., 2230p., two parts, plus a CD ROM supplement.

Spaceflight Mechanics 2006, Volume 124, *Advances in the Astronautical Sciences*, Eds. S.R. Vadali et al., 2282p., two parts, plus a CD ROM supplement.

Spaceflight Mechanics 2005, Volume 120, *Advances in the Astronautical Sciences*, Eds. D.A. Vallado et al., 2152p., two parts, plus a CD ROM supplement.

Spaceflight Mechanics 2004, Volume 119, *Advances in the Astronautical Sciences*, Eds. S.L. Coffey et al., 3318p., three parts, plus a CD ROM supplement.

Spaceflight Mechanics 2003, Volume 114, *Advances in the Astronautical Sciences*, Eds. D.J. Scheeres et al., 2294p, three parts, plus a CD ROM supplement.

Spaceflight Mechanics 2002, Volume 112, *Advances in the Astronautical Sciences*, Eds. K.T. Alfriend et al., 1570p, two parts.

Spaceflight Mechanics 2001, Volume 108, *Advances in the Astronautical Sciences*, Eds. L.A. D'Amario et al., 2174p, two parts.

Spaceflight Mechanics 2000, Volume 105, *Advances in the Astronautical Sciences*, Eds. C.A. Kluever et al., 1704p, two parts.

Spaceflight Mechanics 1999, Volume 102, *Advances in the Astronautical Sciences*, Eds. R.H. Bishop et al., 1600p, two parts.

Spaceflight Mechanics 1998, Volume 99, *Advances in the Astronautical Sciences*, Eds. J.W. Middour et al., 1638p, two parts; Microfiche Suppl., 2 papers (Vol. 78 *AAS Microfiche Series*).

Spaceflight Mechanics 1997, Volume 95, *Advances in the Astronautical Sciences*, Eds. K.C. Howell et al., 1178p, two parts.

Spaceflight Mechanics 1996, Volume 93, *Advances in the Astronautical Sciences*, Eds. G.E. Powell et al., 1776p, two parts; Microfiche Suppl., 3 papers (Vol. 73 *AAS Microfiche Series*).

Spaceflight Mechanics 1995, Volume 89, *Advances in the Astronautical Sciences*, Eds. R.J. Proulx et al., 1774p, two parts; Microfiche Suppl., 5 papers (Vol. 71 *AAS Microfiche Series*).

Spaceflight Mechanics 1994, Volume 87, *Advances in the Astronautical Sciences*, Eds. J.E. Cochran, Jr. et al., 1272p, two parts.

Spaceflight Mechanics 1993, Volume 82, *Advances in the Astronautical Sciences*, Eds. R.G. Melton et al., 1454p, two parts; Microfiche Suppl., 2 papers (Vol. 68 *AAS Microfiche Series*).

Spaceflight Mechanics 1992, Volume 79, *Advances in the Astronautical Sciences*, Eds. R.E. Diehl et al., 1312p, two parts; Microfiche Suppl., 11 papers (Vol. 65 *AAS Microfiche Series*).

Spaceflight Mechanics 1991, Volume 75, *Advances in the Astronautical Sciences*, Eds. J.K. Soldner et al., 1353p, two parts; Microfiche Suppl., 15 papers (Vol. 62 *AAS Microfiche Series*).

AAS/AIAA ASTRODYNAMICS VOLUMES

Astrodynamics 2015, Volume 156, Advances in the Astronautical Sciences, Eds. M. Majji et al., 4512p, three parts plus a CD ROM Supplement.

Astrodynamics 2013, Volume 150, Advances in the Astronautical Sciences, Eds. S.B. Broschart et al., 3532p, three parts plus a CD ROM Supplement.

Astrodynamics 2011, Volume 142, Advances in the Astronautical Sciences, Eds. H. Schaub et al., 3916p, four parts plus a CD ROM Supplement.

Astrodynamics 2009, Volume 135, Advances in the Astronautical Sciences, Eds. A.V. Rao et al., 2446p, three parts plus a CD ROM Supplement.

Astrodynamics 2007, Volume 129, *Advances in the Astronautical Sciences*, Eds. R.J. Proulx et al., 2892p, three parts plus a CD ROM Supplement.

Astrodynamics 2005, Volume 123, *Advances in the Astronautical Sciences*, Eds. B.G. Williams et al., 2878p, three parts plus a CD ROM Supplement.

Astrodynamics 2003, Volume 116, *Advances in the Astronautical Sciences*, Eds. J. de Lafontaine et al., 2746p, three parts plus a CD ROM Supplement.

Astrodynamics 2001, Volume 109, *Advances in the Astronautical Sciences*, Eds. D.B. Spencer et al., 2592p, three parts.

Astrodynamics 1999, Volume 103, *Advances in the Astronautical Sciences*, Eds. K.C. Howell et al., 2724p, three parts.

Astrodynamics 1997, Volume 97, *Advances in the Astronautical Sciences*, Eds. F.R. Hoots et al., 2190p, two parts.

Astrodynamics 1995, Volume 90, *Advances in the Astronautical Sciences*, Eds. K.T. Alfriend et al., 2270p, two parts; Microfiche Suppl., 6 papers (Vol. 72 *AAS Microfiche Series*).

Astrodynamics 1993, Volume 85, *Advances in the Astronautical Sciences*, Eds. A.K. Misra et al., 2750p, three parts; Microfiche Suppl., 9 papers (Vol. 70 *AAS Microfiche Series*)

Astrodynamics 1991, Volume 76, *Advances in the Astronautical Sciences*, Eds. B. Kaufman et al., 2590p, three parts; Microfiche Suppl., 29 papers (Vol. 63 *AAS Microfiche Series*)

Astrodynamics 1989, Volume 71, *Advances in the Astronautical Sciences*, Eds. C.L. Thornton et al., 1462p, two parts; Microfiche Suppl., 25 papers (Vol. 59 *AAS Microfiche Series*)

Astrodynamics 1987, Volume 65, *Advances in the Astronautical Sciences*, Eds. J.K. Soldner et al., 1774p, two parts; Microfiche Suppl., 48 papers (Vol. 55 *AAS Microfiche Series*)

Astrodynamics 1985, Volume 58, *Advances in the Astronautical Sciences*, Eds. B. Kaufman et al., 1556p, two parts; Microfiche Suppl. 55 papers (Vol. 51 *AAS Microfiche Series*)

Astrodynamics 1983, Volume 54, *Advances in the Astronautical Sciences*, Eds. G.T. Tseng et al., 1370p, two parts; Microfiche Suppl., 41 papers (Vol. 45 *AAS Microfiche Series*)

Astrodynamics 1981, Volume 46, *Advances in the Astronautical Sciences*, Eds. A.L. Friedlander et al., 1124p, two parts; Microfiche Suppl., 41 papers (Vol. 37 *AAS Microfiche Series*)

Astrodynamics 1979, Volume 40, *Advances in the Astronautical Sciences*, Eds. P.A. Penzo et al., 996p, two parts; Microfiche Suppl., 27 papers (Vol. 32 *AAS Microfiche Series*)

Astrodynamics 1977, Volume 27, *AAS Microfiche Series*, 73 papers

Astrodynamics 1975, Volume 33, *Advances in the Astronautical Sciences*, Eds., W.F. Powers et al., 390p; Microfiche Suppl., 59 papers (Vol. 26 *AAS Microfiche Series*)

Astrodynamics 1973, Volume 21, *AAS Microfiche Series*, 44 papers

Astrodynamics 1971, Volume 20, *AAS Microfiche Series*, 91 papers

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Robert H. Jacobs, Series Editor

PREFACE

The 26th Spaceflight Mechanics Meeting was held in Napa, California, February 14-18, 2016. The meeting was sponsored by the American Astronautical Society (AAS) Space Flight Mechanics Committee and co-sponsored by the American Institute of Aeronautics and Astronautics (AIAA) Astrodynamics Technical Committee. Approximately 304 people registered for the meeting; attendees included engineers, scientists, and mathematicians representing government agencies, the military services, industry, and academia from the United States and abroad.

There were 276 technical papers presented in 28 sessions on topics related to spaceflight mechanics and astrodynamics. The special session on the 8th Global Trajectory Optimization Competition was well received and strongly attended.

Dr. Daniele Mortari was the recipient of the 2015 AAS Dirk Brouwer award. As part of the awards ceremony on Tuesday evening, Dr. Mortari gave a lecture titled "Flower Constallations and k-vector Applications."

The editors extend their gratitude to the Session Chairs who made this meeting successful: Maruthi Akella, Morgan Baldwin, Stefano Campagnola, Stefano Casotto, Diane Davis, Kyle DeMars, Christopher D'Souza, Roberto Furfaro, Michael Gabor, Marcus Holzinger, Felix Hoots, Brandon Jones, Alan Lovell, Ryan Park, Jeff Parker, Anastassios Petropoulos, Jill Seubert, Jon Sims, Andrew Sinclair, David Spencer, Thomas Starchville, Sergei Tanygin, Paul Thompson, Francesco Topputo, Sean Wagner, Ryan Weisman, Matthew Wilkins, and Roby Wilson.

Renato Zanetti
NASA Johnson Space Center
AAS Technical Chair

Martin Ozimek
Applied Physics Laboratory
AAS General Chair

Ryan Russell
The University of Texas at Austin
AIAA Technical Chair

Angela Bowes
NASA Langley Research Center
AIAA General Chair

CONTENTS

Page

TRAJECTORY OPTIMIZATION 145

Part II

Part III

Part IV

ATTITUDE DETERMINATION

Session Chair:

Session 1: Sergei Tanygin

The following paper was not available for publication:

AAS 16-392 Paper Withdrawn

AAS 16-225

OPTIMIZATION OF A 3D PRINTED CUBESAT BAFFLE USING RAY TRACING

Tjorven Delabie,[*] Diego Gómez Ramírez,[†] Matt Boucher,[*] Gert Raskin[‡] and Dirk Vandepitte[§]

This paper presents a project that aims to improve the baffle of a star tracker by stepping towards novel vane designs. The stray light reduction performance of a baffle is greatly influenced by the shape, dimensions and placement of the vanes at the inside. Using the relaxed manufacturing constraints of 3D printing, we can step away from the typical concentric cylindrical baffles and experiment with more complex baffle shapes. A simulation environment is set up using simplified ray tracing software and an iterative approach is used to simulate and assess the performance of different vane designs. A state-of-the-art and novel design was 3D printed and tested on an optical bench. Results indicate that the novel baffle reduces the influence of stray light better at low angles of incidence and performs slightly worse at higher angles of incident stray light. The results of the optical bench tests correspond well with the simulation results.

[View Full Paper]

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AAS 16-287

STAR CENTROID ON THE F-RADIUS SPHERE USING VON MISES-FISHER PROBABILITY DISTRIBUTION

Daniele Mortari,[*] Márcio A. A. Fialho[†] and Steven A. Lockhart[‡]

This paper proposes two methods to perform star centroid particularly suitable when using wide field-of-view star trackers with small focal lengths, such as micro and nano star trackers. These sensor cameras are those where the physical dimensions of the imager (CCD or CMOS) and PSF (point spread function) are large in comparison to the system focal length. The proposed methods avoid the gnomonic distortion affecting projections of observed data into a planar imager by working on a fictitious spherical imager, the f-radius sphere. The gray tones and areas mapping between imager pixels and f-radius sphere pixels are derived for both, continuous and discrete (real) imagers. The first method is an extension of the center of mass method to the f-radius sphere, whereas the second method performs an iterative nonlinear least-squares best fit to the observed data, by considering the von Mises-Fisher probability distribution from directional dispersion statistics. Methodologies to perform Montecarlo numerical tests are proposed to validate these methods and compare them to the classical 2D center of mass method.

[View Full Paper]

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IDEAS FOR MULTISPECTRAL CAMERAS WITH STACKED PIXELS FOR STAR TRACKING AND OPTICAL NAVIGATION

Marcio A. A. Fialho,* Daniele Mortari† and Leonel F. Perondi‡

This paper presents a new concept for multispectral (color sensitive) cameras with important additional features with respect to traditional star trackers and optical navigation cameras. The main concept is to use an image sensor with stacked pixels, where each pixel layer constitutes a spectral filter for the layers below. The paper describes the limitations of commonly used technologies for color discrimination and shows how they can be solved by using an image sensor with stacked pixels.

[View Full Paper]

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AAS 16-322

THE BRAZILIAN AUTONOMOUS STAR TRACKER DEVELOPMENT

Marcio A. A. Fialho,[*] Leonel F. Perondi[†] and Daniele Mortari[‡]

This paper presents the development effort of a Brazilian autonomous star tracker, a brief history and design decisions taken in order to increase star tracker survivability and flexibility to space environment, operation errors and changing mission requirements. The design is flexible enough to allow the use of the same hardware for different purposes, like a navigation camera or as a horizon sensor. An overview of the test and calibration setup is also presented.

[View Full Paper]

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AAS 16-348

ATTITUDE DETERMINATION AND CONTROL OF ITASAT CUBESAT

Valdemir Carrara*

The ITASAT CubeSat is a satellite being developed at Aeronautic Technological Institute in Brazil, to be launched in mid-2016. This work addresses the ADCS (Attitude Determination and Control Subsystem) of ITASAT, and the computer simulation done so far to assure that the mission requirements were accomplished. The formulation of a Kalman filter will be presented to estimate the attitude quaternion along with the gyro bias, having as inputs the raw measurements of the magnetometer and gyroscopes, and a preprocessed vector of coarse cosine sun sensors. The formulation shown here was taken from an algorithm of a similar Kalman filter, but adapted for employment on on-board computers in which unnecessary computations were eliminated. Attitude is estimated during the illuminated part of the orbit, based on measurements of the angular sensors. During eclipse attitude estimation procedure relies only on the magnetometer and gyros measurements, but the estimation error increases with the time the satellite remains in the shadow due to the lack of sun sensor readings necessary for full attitude estimation. Preliminary results indicate that the Kalman filter can track the bias of the gyroscope and its drift, significantly decreasing the noise level present in the angular sensors. However, the angular velocity remains with high noise levels, which restricts the use of the gyroscope to drive the control signal without previous filtering. The ITASAT should be stabilized and controlled in three-axis, with geocentric pointing. A set of three reaction wheels and three magnetorquers provide torques for attitude control. Simulations indicated that the pointing accuracy is particularly affected by the Kalman filter estimation error, when the reaction wheels are used as main actuators. However, due to the high power consumption of the wheels they can not be used during the whole orbit, and therefore a purely three-axis magnetic stabilization and control will also be required. The magnetorquer's inability to generate torques in all directions limits the attitude stabilization of this control. Coupled to the poor resolution of the angular velocity from gyros, pointing errors bellow 20 degrees are difficult to achieve, except when the angular velocity is estimated by other means such as, for example, by gyro filtering, or by numeric attitude derivative. The ITASAT attitude control modes will be presented, together with some simulation results.

[View Full Paper]

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AAS 16-374

DISCRETE ADAPTIVE ANGULAR VELOCITY ESTIMATION – AN EXPERIMENTAL ANALYSIS

Marcelino M. de Almeida[*] and Maruthi Akella[†]

This paper presents hardware experimental results for the use of a recently formulated angular velocity estimation algorithm. The main motivation for the use of this algorithm comes from the possibility of estimating angular velocity with use of estimated quaternions for a system whose attitude is progressively changing with time. The innovation on the estimation algorithm resides on the fact that it tries to be adaptive when determining the direction of the axis of rotation. It uses a sliding window whose size changes with time so as to use more or fewer past measurements when estimating the unknown angular rate. In order to test the effectiveness of the algorithm, an experimental setup was prepared in the Autonomous GN&C research laboratory of The University of Texas at Austin. The experimental setup used equipment to be able to accurately measure the real angular velocity of a rotating system, so that noisy attitude measurements could be used as input to the algorithm and the results would be consistently compared to some "credible truth". For the sake of algorithm comparison, this paper compares the results of the estimation algorithm with a simpler solution obtained through Pure Derivative altogether with the Quaternion Kinematics Equation (PDQKE). The final results suggest that the studied algorithm is mostly beneficial compared to the PDQKE when higher-variance noise is present in the quaternion measurement vector.

[View Full Paper]

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AAS 16-397

SPACECRAFT DYNAMICS SHOULD BE CONSIDERED IN KALMAN FILTER ATTITUDE ESTIMATION

Yaguang Yang[*] and Zhiqiang Zhou[†]

Kalman filter based spacecraft attitude estimation has been used in some high-profile missions and has been widely discussed in literature. While some models in spacecraft attitude estimation include spacecraft dynamics, most do not. To our best knowledge, there is no comparison on which model is a better choice. In this paper, we discuss the reasons why spacecraft dynamics should be considered in the Kalman filter based spacecraft attitude estimation problem. We also propose a reduced quaternion spacecraft dynamics model which admits additive noise. Geometry of the reduced quaternion model and the additive noise are discussed. This treatment is more elegant in mathematics and easier in computation. We use some simulation example to verify our claims.

[View Full Paper]

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AAS 16-413

DISTORTION CORRECTION OF THE ICESAT STAR TRACKER DATA

Sungkoo Bae[*] and Natalie Wolfenbarger[†]

Attitude independent and dependent methods are presented for distortion correction of the star tracker camera data. Without proper correction of measurement distortion, caused by an imperfect star tracker lens and detector, it would be difficult to achieve the attitude determination goal of sub-arc-second accuracy required in many modern spacecraft missions. While the impact of random noise can be effectively reduced by a filtering technique that combines star tracker and gyro data in processing, systematic errors, like focal plane distortion, persistently degrade attitude determination performance if no calibration is performed. This paper describes distortion correction methods that use star tracker data obtained in-flight. These methods are tested using both simulated and flight star tracker data. The results of the distortion correction are evaluated by analyzing the distortion map and attitude determination solutions.

[View Full Paper]

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AAS 16-534

CHARACTERIZATION OF THE EFFECTIVE OUTPUT MAGNETIC FIELD OF A TRI-AXIAL SQUARE HELMHOLTZ CAGE

Ankit Jain,[*] Erik Kroeker,[†] Vedant,[‡] Alexander Ghosh[§] and Patrick Haddox[†]

The accuracy of the Attitude Determination and Controls System (ADCS) for CubeSat-class satellites is crucial to their required space-flight functionality. For such satellites, with a magnetic-based attitude system (i.e. involving magnetometers and torque coils); a Tri-Axial Square Helmholtz Cage serves as a ground-based simulation and testing platform to both verify and validate the desired pointing accuracy of the satellite. The University of Illinois' Tri-Axial Square Helmholtz Cage is known as the HC3. The calibration of such a system is critical to validating the magnetic-based ADCS of a small satellite. The calibration and characterization process of the effective output magnetic field generated by the HC3 is discussed in this paper. For the validation of magnetic-based attitude systems, the center of the HC3 was required to be calibrated to within 0.5% error in the magnitude of the magnetic field and to within 0.5° of angular error in the magnetic field, both with respect to the commanded value. Results demonstrated that at the center of the HC3, the calibrated model produced within 0.3% error in magnitude of the magnetic field and within 0.4° of angular error in the magnetic field, again both with respect to the commanded value; therefore, satisfying the requirements at the center of the HC3. The calibrated model, at the center of the HC3, performed about an order of magnitude better than the un-calibrated model for most test cases.

[View Full Paper]

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SPACE BASED IR SENSOR MANAGEMENT FOR SITUATIONAL AWARENESS

John E. Freeze,[*] Ajay Verma[†] and Maruthi Akella[‡]

A LEO cluster of IR sensors are dynamically scheduled to observe various target sites on earth associated with range of events posing varying degree of threat levels. The overall threat uncertainty is minimized by determining a near optimal solution for fixed time horizon non-myopic scheduling while considering target visibility based on relative sensor-target geometry resulting from sensor orbital dynamics.

[View Full Paper]

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TRAJECTORY OPTIMIZATION

Session Chairs:

Session 2: Stefano Campagnola

Session 20: Jon Sims

Session 26: Roby Wilson

The following papers were not available for publication:

AAS 16-206 Paper Withdrawn

AAS 16-226 Paper Withdrawn

AAS 16-247 Paper Withdrawn

AAS 16-417 Paper Withdrawn

AAS 16-487 Paper Withdrawn

AAS 16-516 Paper Withdrawn

AAS 16-212

APPROXIMATE ANALYTICAL SOLUTION OF THE MULTIPLE REVOLUTION LAMBERT'S TARGETING PROBLEM

Claudio Bombardelli,[*] Javier Roa[†] and Juan Luis Gonzalo[†]

An approximate analytical solution of the multiple revolution Lambert's targeting problem is presented. The solution is obtained starting from Battin's optimum single-impulse transfer with a linear phasing correction and offers remarkable accuracy near minimum delta-V transfer conditions. Consequently, the method is useful for rapidly obtaining low delta-V solutions for interplanetary trajectory optimization. The solution is easy to program and non-iterative, which makes it ideal for GPU implementation. In addition, the method can be employed to provide a fast first guess solution for enhancing the convergence speed of an accurate numerical multi-revolution Lambert solver.

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AAS 16-227

BROAD SEARCH FOR DIRECT TRAJECTORIES FROM EARTH TO DOUBLE-SATELLITE-AIDED CAPTURE AT JUPITER WITH DEEP SPACE MANEUVERS

Alfred E. Lynam*

Double-satellite-aided capture involves gravity assists of two of Jupiter's Galilean moons while a spacecraft is capturing into Jupiter orbit. In this paper, both gravity assists occur before a Jupiter Orbit Insertion (JOI) maneuver that completes the capture. This particular scheme is easier to navigate than other double-satellite-aided captures because there are no flybys after the JOI maneuver that would be adversely affected by the JOI maneuver's stochastic errors. We also find direct interplanetary trajectories from Earth to Jupiter that include a deep space maneuver (DSM). In each double-satellite-aided capture "window", we use an optimizer to find the solution that captures the most mass into Jupiter orbit. The best solutions that launch in either 2022 or 2023 were numerically integrated in GMAT to provide practical double-satellite-aided captures for the Europa Mission's nominal and backup launch windows.

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AAS 16-239

GLOBAL OPTIMIZATION OF LOW-THRUST INTERPLANETARY TRAJECTORIES SUBJECT TO OPERATIONAL CONSTRAINTS

Jacob A. Englander,[*] Matthew A. Vavrina[†] and David W. Hinckley, Jr.[‡]

Low-thrust interplanetary space missions are highly complex and there can be many locally optimal solutions. While several techniques exist to search for globally optimal solutions to low-thrust trajectory design problems, they are typically limited to unconstrained trajectories. The operational design community in turn has largely avoided using such techniques and has primarily focused on accurate constrained local optimization combined with grid searches and intuitive design processes at the expense of efficient exploration of the global design space. This work is an attempt to bridge the gap between the global optimization and operational design communities by presenting a mathematical framework for global optimization of low-thrust trajectories subject to complex constraints including the targeting of planetary landing sites, a solar range constraint to simplify the thermal design of the spacecraft, and a real-world multi-thruster electric propulsion system that must switch thrusters on and off as available power changes over the course of a mission.

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DYNAMIC OPTIMIZATION FOR SATELLITE IMAGE COLLECTION

I. M. Ross,* R. J. Proulx,† J. M. Greenslade‡ and M. Karpenko§

The full satellite image collection planning and scheduling problem can be framed as a constrained hybrid dynamic optimization problem. That is, the variables are discrete, continuous, dynamic and constrained. It is well-established that even a simplified version of this problem is NP-hard. Consequently, proprietary methods are used in the industry to address this problem. Regardless, these methods can be broadly classified as solving the problem in two hierarchical iterative steps: an operational graph problem in the first step and an engineering feasibility problem in the second step. In this paper, we suggest that doing the opposite of the hierarchical approach may indeed be simpler. This new approach is based on using an indicator function to represent the vertices of the graph. This concept transforms the full hybrid problem to a nonsmooth dynamic optimization problem. By using a smooth approximation for the indicator function, the nonsmooth problem is transformed to a smooth approximate problem. The smooth problem is solved using well-established pseudospectral techniques. Numerical results over random graphs demonstrate the viability and scalability of this simpler approach.

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AAS 16-272

GLOBAL OPTIMIZATION OF *N*-MANEUVER, HIGH-THRUST TRAJECTORIES USING DIRECT MULTIPLE SHOOTING

Matthew A. Vavrina,* Jacob A. Englander† and Donald H. Ellison‡

The performance of impulsive, gravity-assist trajectories often improves with the inclusion of one or more maneuvers between flybys. However, grid-based scans over the entire design space can become computationally intractable for even one deep-space maneuver, and few global search routines are capable of an arbitrary number of maneuvers. To address this difficulty a trajectory transcription allowing for any number of maneuvers is developed within a multi-objective, global-optimization framework for constrained, multiple gravity-assist trajectories. The formulation exploits a robust shooting scheme and analytic derivatives for computational efficiency. The approach is applied to several complex, interplanetary problems, achieving notable performance without a user-supplied initial guess.

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AAS 16-300

STOCHASTIC DIFFERENTIAL DYNAMIC PROGRAMMING FOR LOW-THRUST TRAJECTORY DESIGN WITH STATE UNCERTAINTY

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This paper proposes a robust-optimal trajectory design method for uncertain system to minimize the expected value of cost-to-go function in Dynamic Programming. The fundamental idea is introducing Stochastic Differential Dynamic Programming (SDDP), which solves stochastic-optimal control problem by the second-order expansion of Bellman's equation around reference trajectory. Most recent studies have focused on trajectory optimization assuming that the spacecraft can control the trajectory perfectly as planed; however, the assumption is violated in realistic operations where uncertain events, such as navigation error or uncertainty on dynamical system, perturb the predetermined trajectory. Conventionally, experienced specialists empirically determine "margin" on optimal low-thrust trajectory by duty cycle or forced coast period. A proposed SDDP autonomously provides "margin" in optimization for future feedback as well. Numerical results by V-infinity leveraging problem show that SDDP has "margin" without duty cycle or coast period. Monte-Carlo simulation shows the SDDP solution has better performance than DDP considering uncertainty.

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AAS 16-304

AN ACCELERATED TRAJECTORY OPTIMIZATION TECHNIQUE BASED ON PSEUDOSPECTRAL METHODS

Qi Gong* and I. Michael Ross†

Motivated by the needs of unscented trajectory optimization and rapid mission analysis, we present a propagator-agnostic trajectory optimization method. The fundamentals are based on accelerating a standard pseudospectral method. The acceleration is achieved by discretizing the state trajectory at a significantly lower rate than the control program. In turn, the discretization of the control program is chosen such that any propagator applied to the dynamics generates feasible solutions. This advancement supports the growing need from the industry for "good" feasible solutions. The goodness of the solution can be quantified in terms of optimality by a new covector mapping theorem developed in this paper. This new theorem provides computational tests for checking the optimality of the feasible solution. Numerical tests show that computational accelerations of up to 100 times are quite possible by simply changing the discretization grid; however, the efficiencies gained are problem specific.

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AAS 16-316

SPIRAL LAMBERT'S PROBLEM WITH GENERALIZED LOGARITHMIC SPIRALS

Javier Roa* **and Jesús Peláez†**

Lambert's problem subject to a continuous acceleration is solved using the family of generalized logarithmic spirals. Thanks to the existence of two first integrals related to the energy and angular momentum surprising analogies with the Keplerian case are found. A minimum-energy spiral transfer exists. Increasing the value of the constant of the generalized energy yields pairs of conjugate spiral trajectories. The properties of such spirals are strongly connected with the properties of conjugate Keplerian orbits. When the generalized constant of the energy reaches a critical value the two solutions degenerate into a pair of parabolic spirals, one of which connects the two vectors through infinity. From that point the spiral transfers become hyperbolic. Generalized logarithmic spirals admit closed-form solutions to all the required magnitudes including the time of flight, providing a deep insight into the dynamics of the problem. In addition, the maximum acceleration along the transfer is found analytically so the solutions that violate the design constraints on the maximum thrust acceleration can be rejected without any further computations. When the time of flight is fixed there is still a degree of freedom in the solution, related to a control parameter. Resonant transfers appear naturally thanks to the symmetry properties of the generalized logarithmic spirals. The problem of designing a low-thrust transfer between two bodies can be reduced to solving the corresponding spiral Lambert's problem. In order to show the versatility of the method it is applied to the design of an asteroid tour and to explore launch opportunities to Mars.

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AAS 16-317

INTRODUCING A DEGREE OF FREEDOM IN THE FAMILY OF GENERALIZED LOGARITHMIC SPIRALS

Javier Roa* **and Jesús Peláez†**

The versatility of the family of generalized logarithmic spirals is improved by introducing a degree of freedom in the solution. The low-thrust acceleration profile now includes a control term that affects both the magnitude and the direction of the thrust. Exact and fully analytic solutions to the trajectory, the velocity, the time of flight, etc. are made available. Two integrals of motion are preserved. The first one is a generalization of the equation of the energy and depends on the values of the control parameter. The second one relates to the equation of the angular momentum. The problem of finding spiral transfers between two arbitrary state vectors reduces to solving one algebraic equation with one unknown. The degree of freedom allows fixing the time of flight of the transfer. If the time of flight is fixed, then there are two equations with two unknowns. No other iterative procedures are required. Coast arcs can be introduced in the solution naturally. An explicit expression for the maximum acceleration reached along the transfer is provided. Thanks to the symmetry properties of the solution a simple algorithm for generating periodic orbits is presented. An arbitrary number of intermediate nodes can be introduced to improve the flexibility of the solution when facing optimization problems. An example of a low-thrust gravity-assist Earth-Mars-Ceres trajectory shows that the solution is comparable to that obtained with other preliminary design techniques.

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THREE-DIMENSIONAL GENERALIZED LOGARITHMIC SPIRALS

Javier Roa[*] and Jesús Peláez[†]

The family of generalized logarithmic spirals including a control parameter is extended to the three-dimensional case. The in-plane motion is decoupled from the out-of-plane motion in such a way that the integrals of motion found in the planar problem are still preserved in the three-dimensional case. Designing a low-thrust orbit transfer decomposes in two stages: first, orbits are projected on a reference plane and the planar transfer is solved with a generalized logarithmic spiral. Second, the out-of-plane component of the motion is included in order to target the final orbit. The projection of the three-dimensional transfer orbit on the reference plane is a generalized logarithmic spiral. Arbitrary shape-based laws for the 3D motion can be considered. This paper explores a polynomial and a Fourier series shaping method, together with a polynomial steering law. A fictitious low-thrust sample return mission to Ceres is designed to show the versatility of the method.

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AAS 16-367

PARALLEL GENETIC ALGORITHMS FOR OPTIMAL CONTROL

Christopher B. McGrath,[*] Ronald J. Proulx[†] and Mark Karpenko[‡]

This paper investigates the application of parallel genetic algorithms in finding solutions to optimal control problems using a direct shooting method. An example lunar lander problem is solved with parallel island genetic algorithms to demonstrate the effectiveness of different encoding types, crossover operators, and constraint-handling techniques. The incorporation of parallel processing is shown to improve robustness and accuracy in all algorithms considered in this study.

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AAS 16-368

UNSCENTED EVOLUTION STRATEGIES FOR SOLVING TRAJECTORY OPTIMIZATION PROBLEMS

Christopher B. McGrath,* Mark Karpenko,† Ronald J. Proulx‡ and I. Michael Ross§

This paper incorporates the unscented transform as part of an efficient evolution strategy for solving optimal control problems. The use of sigma points is shown to achieve superior performance when compared to an evolution strategy that uses classical random sampling as the basis for search. A suite of highly multimodal benchmark test problems is used to illustrate the performance of this new scheme which incorporates an annealing concept to further enhance performance. The new evolution strategy is then used to solve an optimal control problem from astrodynamics. The results of this paper illustrate a promising new concept in evolutionary computation that may be advantageous for astrodynamics problems.

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AAS 16-385

INTERPLANETARY PARKING METHOD AND ITS APPLICATION TO DUAL LAUNCH TRAJECTORY DESIGN OF MULTIPLE EXPLORERS

Toshinori Ikenaga,[*] Masayoshi Utashima,[†] Nobuaki Ishii,[‡] Yasuhiro Kawakatsu,[§] Makoto Yoshikawa,[§] Ikkoh Funaki[§] and Takahiro Iwata[§]

After the successful launch on the world first spacecraft, Sputnik 1 by the former Soviet Union in 1957, 58 years has passed. In 1960, Pioneer 5 of the United States escaped the Earth's gravity at the first time, and since then many interplanetary explorers had set to sail interplanetary. However, even in the present day, interplanetary voyages are not still easy. First, interplanetary missions require large amounts of delta-V, and second, the opportunity to get to the destination opens only every synodic period with the destination celestial body. For example, the synodic period with Mars is about 2 years, which means the opportunity to get to Mars opens every 2 years. For such circumstances, this paper proposes a new type of low-thrust orbit design method, "Interplanetary Parking Method" that realizes "anytime" launch of deep-space explorers. The proposed interplanetary parking method enables to make an Earth return orbit with an arbitrary time-of-flight connecting to the minimum energy transfer orbit to a destination. While the time-of-flight of the transfer orbit is fixed, the Earth return orbit with the arbitrary time-of-flight virtually eliminates the severe launch window constraint in interplanetary missions. As application of the proposed method, the paper demonstrates dual launch trajectory design of explorers to different destinations i.e., Mars and Venus. The proposed method will widen the scope of opportunity for interplanetary missions.

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AAS 16-408

OPTIMAL 3D ORBIT CORRECTIONS IN CURVILINEAR COORDINATES

Juan L. Gonzalo[*] and Claudio Bombardelli[†]

The minimum-time, constant-thrust orbit correction between two close non-coplanar circular orbits is studied using a relative motion formulation in curvilinear coordinates. The associated optimal control problem in the thrust orientation is tackled using the direct method to numerically solve a diverse set of problems for varying orbital radius and inclination. Additionally, an analytical estimate for the minimum-time inclination change maneuver is obtained. Fundamental changes in the structure of the solution and objective function are highlighted depending on the relation between the required radial displacement, inclination change and available thrust.

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AAS 16-422

GLOBAL SEARCH FOR LOW-THRUST TRANSFERS TO THE MOON IN THE PLANAR CIRCULAR RESTRICTED THREE-BODY PROBLEM

Kenta Oshima,* Stefano Campagnola† and Tomohiro Yanao‡

The present study globally searches for low-thrust transfers to the Moon in the planar, circular, restricted, three-body problem. To reduce the dimensionality of parameters for determining initial costates, we narrow down candidates of solutions to those satisfying the necessary conditions for optimality based on the indirect method and use an analogy with the two-body dynamics for the initial periodic orbit around the Earth. We obtain a wide range of Pareto solutions in terms of time of flight and mass consumption. Several solutions exploit resonant lunar gravity assists to reduce fuel consumption.

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AAS 16-426

FROM LOW THRUST TO SOLAR SAILING: A HOMOTOPIC APPROACH

N. Sullo,[*] A. Peloni[*] and M. Ceriotti[†]

This paper describes a novel method to solve solar-sail minimum-time-of-flight optimal control problems starting from a low-thrust solution. The method is based on a homotopic continuation. This technique allows to link the low-thrust with the solar-sail acceleration, so that the solar-sail solution can be computed starting from the usually easier low-thrust one by means of a numerical iterative approach. Earth-to-Mars transfers have been studied in order to validate the proposed method. A comparison is presented with a conventional solution approach, based on the use of a genetic algorithm. The results show that the novel technique has advantages, in terms of accuracy of the solution and computational time.

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AAS 16-427

AN ADAPTIVE APPROACH FOR MODIFIED CHEBYSHEV PICARD ITERATION

Ahmad Bani Younes* **and John L. Junkins†**

The demand of having fast and efficient numerical propagators to solve engineering problems has become essential. The level of system complexity increases the cost of obtaining the solution. Many real world problems require developing efficient, precise and fast solutions. For example, efficient, high precision orbit propagation has gained renewed impetus due to the rapidly escalating demands for improved Space Situational Awareness (SSA) and the challenges posed by the Kessler Syndrome, which hypothesizes that every collision of two space objects drastically increases the probability of subsequent collisions. The recent development Junkins et al. of Modified Chebyshev Picard Iteration (MCPI) has shown efficient solution for many engineering problems that require precise and fast solutions. This paper is an extension to various developments on MCPI by introducing an adaptive technique that enables the flexibility in the choice of the degree to approximate the trajectory and the force function. The proposed approach avoids the need to use the same number of nodes to approximate, both, the trajectory and the force function. This reduces the computation cost. In addition, the different choices of the approximation degree can be utilized to adapt the iteration process by tuning the approximation degree. The cost benefit of this approach depends strongly on the problem of interest. Some examples showed that a speed up of greater than 1.5X is achieved compared with the original MCPI approach.

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AAS 16-440

ATTRACTIVE SET OF OPTIMAL FEEDBACK CONTROL FOR THE HILL THREE-BODY PROBLEM

Mai Bando[*] and Daniel J. Scheeres[†]

This paper investigates the combination of optimal feedback control with the dynamical structure of the three-body problem. The results provide new insights for the design of continuous low-thrust spacecraft trajectories. Specifically, we solve for the attracting set of an equilibrium point under optimal control with quadratic cost. The analysis reveals the relation between the attractive set and original dynamics. In particular, we find that the asymptotic form of the attractive set to an equilibrium point or a fixed point under optimal control is completely defined by its left unstable eigenvectors and a term inversely proportional to its unstable eigenvalue.

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AAS 16-446

A NONLINEAR CONTROLLER FOR LOW THRUST STABILIZATION OF SPACECRAFT ON CRTBP ORBITS

Dimitrios Pylorof,* Efstathios Bakolas† and Ryan P. Russell‡

The problem of stabilizing a spacecraft on Circular Restricted Three Body Problem orbits with a nonlinear, feedback controller subject to input constraints is studied in this paper. The proposed solutions are based on Lyapunov methods, which are fused with results from convex optimization. The control inputs are calculated online, through a pointwise Quadratic Programming optimization problem, while the neighborhood around the orbit where stabilization is possible is calculated offline, using Semidefinite Programming techniques with sum of squares constraints. The results can be used for the design and execution of low thrust spacecraft missions in multi-body environments.

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AAS 16-448

TWO-IMPULSE EVOLUTIONARY OPTIMIZATION OF SATELLITE FORMATIONS WITH TOPOLOGICAL CONSTRAINTS

David W. Hinckley, Jr.* and Darren L. Hitt†

In this work we apply the evolutionary technique of Differential Evolution (DE) to topologically constrained trajectory optimization of a satellite formation limited to two-impulsive maneuvers. The motivation and constraints for the problem are drawn from NASA's Magnetospheric Multi-Scale Mission (MMS). In a previous work a DE-based optimization framework was developed for a single impulsive maneuver. This work aims to improve upon that work by expanding the search-space to include the additional degree of freedom allowed by a second maneuver. With this addition, greater adherence to the topological constraints as demanded by the scientific goals of the mission will be demonstrated.

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AAS 16-471

TRAJECTORY OPTIMIZATION UNDER UNCERTAINTY FOR RENDEZVOUS IN THE CRTBP

Juliana D. Feldhacker,[*] Brandon A. Jones[†] and Alireza Doostan[‡]

Polynomial regression models and polynomial chaos expansions (PCEs) are useful in the mapping of deterministic and stochastic system inputs, respectively, through complex dynamics such as nonlinear astrodynamic systems. By combining the two techniques, a single model can be developed to enable a method for trajectory optimization under uncertainty (OUU) that requires orders of magnitude fewer realizations of the full system dynamics than a Monte Carlo approach to the same problem. This paper considers OUU for the robust design of spacecraft rendezvous maneuvers in the Earth-Moon circular restricted three-body problem (CRTBP). Additional savings in the computational expense of generating the model are demonstrated through the use of compressive sampling.

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AAS 16-476

APPLICATION OF MODIFIED CHEBYSHEV PICARD ITERATION TO DIFFERENTIAL CORRECTION FOR IMPROVED ROBUSTNESS AND COMPUTATION TIME*

Travis Swenson,† Robyn Woollands,‡ John Junkins§ and Martin Lo**

A novel application of Modified Chebyshev Picard Iteration (MCPI) to differential correction is presented. By leveraging the Chebyshev basis functions of MCPI, interpolation in 1 dimension may be used to target plane crossing events, instead of integrating the 42 dimensional variational equation required for standard step integrators. This results in dramatically improved performance over traditional differential correctors. MCPI was tested against the Runge-Kutta 7/8 integrator on over 45,000 halo orbits in three different three-body problems, and was found to be an order of magnitude faster, while simultaneously increasing robustness.

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AAS 16-479

ON THE APPLICATION OF EXTENDED LOGARITHMIC SMOOTHING TECHNIQUE FOR INDIRECT OPTIMIZATION OF MINIMUM-FUEL TRAJECTORIES

Ehsan Taheri,* Ilya Kolmanovsky† and Ella Atkins‡

In this paper, the extended logarithmic smoothing technique is integrated into the indirect optimal control formulation to numerically generate minimum-fuel low-thrust trajectories. This approach is considered for three cases in which equations of motion are specified in terms of Cartesian coordinates, spherical coordinates and modified equinoctial orbital elements. It is shown that by combining logarithmic smoothing with formulating equations of motion in an appropriate coordinate system, which can be problem dependent, the optimal control problem is more amenable to numerical treatment with better solutions generated after a fewer number of iterations even if a single shooting technique is applied with a poor initial guess. In addition, the paper addresses the calculation of the Jacobian matrix of the constraints via a new implementation of the State Transition Matrix approach that circumvents the discontinuities of the control along the trajectory. The results of applying this technique to two interplanetary rendezvous missions from Earth to Mars and Earth to asteroid Dionysus are reported and compared in terms of the number of iterations, accuracy in satisfying the constraints, and computational time. We demonstrate that bang-off-bang type solutions can be generated efficiently using general purpose solvers that benefit from accurate sensitivity information and provide a distinct advantage.

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AAS 16-481

PARAMETRIC ANALYSIS OF LOW-THRUST LUNAR TRANSFERS WITH RESONANT ENCOUNTERS

Maksim Shirobokov* **and Sergey Trofimov†**

In this work, low-thrust transfers to a halo orbit around the Earth–Moon L_1 point using the resonant encounters are considered. The goal is to examine the relationship between different transfer variables and parameters: the injection point in the halo orbit, the sequence of resonances, the date and time of launch etc. For that purpose, the calculated trajectories are grouped in correspondence with chosen values of variables and parameters forming tables that contain the numerical description of the best trajectories. The tables constructed for all possible values of the parameters, provide a global picture of solutions and can help mission designers to conduct mission feasibility analysis.

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AAS 16-519

FEASIBILITY REGIONS OF BOUNDARY VALUE PROBLEMS OF LOW-THRUST TRAJECTORIES

Chit Hong Yam,[*] Stefano Campagnola,[†]
Yasuhiro Kawakatsu[‡] and Ming Tony Shing[§]

Two types of boundary values problems of low-thrust trajectories are considered: the position matching problem and the reachability problem. We perform experiments on three approaches to solve and to analyze such boundary value problems, particularly the feasible regions of the solutions. A linear approximation method is applied which can compute the attainable sets of solutions efficiently and accurately for short transfer arcs as compared with the nonlinear constraint satisfaction method. An optimization approach that can map out the feasible set of solutions for long transfer arcs is also examined. Our method can provide an initial estimate for broad searches of multi-leg low-thrust trajectories.

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AAS 16-523

THE SHADOW TRAJECTORY MODEL FOR FAST LOW-THRUST INDIRECT OPTIMIZATION

Ricardo L. Restrepo[*] and Ryan P. Russell[†]

Preliminary design of low-thrust trajectories generally benefits from broad searches over the feasible space. Despite convergence issues, indirect methods are generally faster than direct methods, and therefore well-suited for such searches. Nonetheless, indirect solutions typically require expensive numerical integration of at least the state and costate equations. Here, based on the physical interpretation of the primer vector, a fast model that approximates solutions to all the dynamics is introduced. If the ballistic dynamics have a closed form solution, then the costate equations can be approximated without resorting to numerical integration. Analogous to the Sims-Flanagan model for direct optimization, the new model approximates thrust arcs with a series of ballistic arcs and impulsive maneuvers. The closed form solution is obtained using a Sundman-transformed independent variable, which also provides an efficient discretization. Furthermore, a low order series solution is used for the ballistic propagation. The model is introduced and evaluated for speed and accuracy using examples with Keplerian dynamics. Speedups vary according to thrust and discretization levels. For accuracies relevant to preliminary design, order of magnitude speedups are achieved.

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AAS 16-526

HYBRID DIFFERENTIAL DYNAMIC PROGRAMMING WITH STOCHASTIC SEARCH

Jonathan D. Aziz,[*] Jeffrey S. Parker[†] and Jacob A. Englander[‡]

Differential dynamic programming (DDP) has been demonstrated as a viable approach to low-thrust trajectory optimization, namely with the recent success of NASA's Dawn mission. The Dawn trajectory was designed with the DDP-based Static/Dynamic Optimal Control algorithm used in the Mystic software. Another recently developed method, Hybrid Differential Dynamic Programming (HDDP), is a variant of the standard DDP formulation that leverages both first-order and second-order state transition matrices in addition to nonlinear programming (NLP) techniques. Areas of improvement over standard DDP include constraint handling, convergence properties, continuous dynamics, and multi-phase capability. DDP is a gradient based method and will converge to a solution nearby an initial guess. In this study, monotonic basin hopping (MBH) is employed as a stochastic search method to broaden the search space beyond local optimization.

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SPACECRAFT DYNAMICS

Session Chair:

Session 3: Francesco Topputo

AAS 16-299

TRANSFERS TO A SUN-EARTH SADDLE POINT: AN EXTENDED MISSION DESIGN OPTION FOR LISA PATHFINDER

Andrew Cox* and Kathleen C. Howell†

The LISA Pathfinder extended mission may immediately follow the primary mission to a Sun-Earth L_1 libration point orbit. One extended mission concept with scientific appeal is a spacecraft path that includes multiple passes within 100 km of a gravitational equilibrium point. To explore this option, two methodologies are investigated: linking arcs from the circular restricted three-body problem, and propagating natural motion in a four-body model that leverages lunar gravity to complete multiple Earth passes or capture in the system. Potential trajectories are detailed and compared to the mission requirements.

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AAS 16-310

ALGEBRAIC MANIPULATORS: NEW PERSPECTIVES IN ANALYTICAL OR SEMI-ANALYTICAL SOLUTIONS TO ASTRODYNAMICS PROBLEMS

Juan Félix San-Juan,[*] Rosario López[†] and Roberto Armellin[‡]

The evolution of the hardware and the capabilities of the general computer algebra system have supplied us with the possibility of developing an environment called MathATESAT embedding in Mathematica, which is not linked to a Poisson series processor. MathATESAT implements all the necessary tools to carry out high accuracy analytical or semi-analytical theories in order to analyze the quantitative and qualitative behavior of a dynamic system.

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AAS 16-311

APPLICATION OF THE HYBRID METHODOLOGY TO SGP4

Juan Félix San-Juan,[*] Montserrat San-Martín[†] and Iván Pérez[‡]

The current source of publicly distributed observations for propagations, Two-Line Elements (TLEs), is gradually becoming insufficient for the growing demands of Space Situational Awareness (SSA). New approaches are needed in order to extend the validity of TLEs in a near-future scenario in which the amount of cataloged orbiters can impede the regular observation and processing of every object. We propose applying the hybrid methodology to the TLE propagator, Simplified General Perturbations-4 (SGP4), through the modeling and correction of its error in a non-intrusive manner. This strategy implies the broadcast of hybrid TLEs, HTLEs, which include a few additional parameters resulting from the error modeling process. Coherently, propagation needs to be performed through the hybrid propagator HSGP4, which comprises both the standard SGP4 and an error corrector able to compute the necessary correction from the HTLE additional parameters. Both the error modeling, in the distributor side, and the error correction, in the end user side, imply a few basic operations, and thus a very reduced computational overhead.

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AAS 16-312

MANEUVER AND VIBRATION SUPPRESSION OF FLEXIBLE MANIPULATORS FOR CAPTURING UNKNOWN OBJECTS USING VARIABLE-SPEED CONTROL MOMENT GYROS

Shiyuan Jia,[*] Yinghong Jia[†] and Shijie Xu[‡]

This paper addresses the problem of trajectory control and vibration suppression of space manipulators with unknown objects. The variable-speed control moment gyros (VSCMGs) are considered as actuators for vibration suppression. The dynamics model containing the influence of VSCMGs is adopted. A singular perturbation approach is used to transform the dynamics model into a two timescale subsystem. A slow subsystem is associated with rigid motion dynamics and a fast subsystem is associated with flexible dynamics. An adaptive sliding-mode controller is designed to realize trajectory tracking. An adaptive controller is designed for vibration suppression. Based on the composite control, the steering law is designed. According to the numerical simulation it can be concluded that the proposed composite controller has an efficient performance for maneuver and vibration suppression.

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AAS 16-332

SURVEY OF NUMERICAL METHODS FOR COMPUTING QUASI-PERIODIC INVARIANT TORI IN ASTRODYNAMICS

Nicola Baresi,[*] Zubin Olikara[†] and Daniel J. Scheeres[‡]

Quasi-periodic invariant tori are of great interest in astrodynamics because of their capability to further expand the design space of satellite missions. This paper compares the performance of three different approaches available in the literature. The first method computes invariant tori of flows using central differences, whereas the other two strategies calculate invariant curves of maps via shooting algorithms (one using surfaces of section and one using a stroboscopic map). All the algorithms are used for studying quasi-periodic motion in the Hill Problem, although only the last approach succeeds in generating three-dimensional tori while investigating their stability.

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AAS 16-334

ACTIVE VIBRATION SUPPRESSION IN FLEXIBLE SPACECRAFT DURING ATTITUDE MANEUVER

Zhaohui Wang,[*] Ming Xu,[†] Shijie Xu,[‡] Shiyuan Jia[§] and Guoqi Zhang[**]

A novel method using the optical measurement to measure the dynamic behaviors of the spacecraft flexible appendages such as solar panels and solar arrays which are not allowed to be settled with piezoelectric actuators and sensors is proposed. Active vibrations suppression for these spacecraft flexible appendages during spacecraft large-angle maneuvers is discussed. The vibration information of the flexible appendages is obtained by the measured displacement; a finite convergence observer is designed to estimate the vibration velocity. The active vibration suppression algorithm is designed, based on the back-stepping control and Lyapunov method. The stabilization of the controller and the observer is proved. The actuator that used to the complete the active vibration control is collocating at the spacecraft body.

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AAS 16-378

MEDIUM-ENERGY, RETROGRADE, BALLISTIC TRANSFER TO THE MOON

Kenta Oshima,[*] Francesco Topputo,[†] Stefano Campagnola[‡] and Tomohiro Yanao[§]

This study analyzes a recently discovered new class of exterior transfers to the Moon under the perspective of lunar collision orbit dynamics. These transfers typically end with a retrograde ballistic capture, i.e., with negative Keplerian energy and angular momentum with respect to the Moon. Yet their Jacobi constant is relatively low, at which no forbidden regions exist, and the transfers do not appear to mimic the dynamics of the invariant manifolds of the Lagrange points. This paper shows that these orbits shadow instead lunar collision orbits. We investigate the dynamics of singular, lunar collision orbits in the Earth–Moon planar circular restricted three-body problem, and reveal their rich phase space structure in the medium-energy regime, for which invariant manifolds of the Lagrange point orbits break up. We show that lunar retrograde ballistic capture trajectories lie inside the tube structure of collision orbits. We also develop a method to compute medium-energy transfers by patching together the orbits inside the collision tube and those whose apogees are located in the appropriate quadrant in the Sun–Earth system. The method is used to systematically reproduce the novel retrograde ballistic capture.

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AAS 16-379

DESIGN AND OPTIMIZATION OF TENSION DISTRIBUTION FOR SPACE DEPLOYABLE MESH REFLECTORS

Sichen Yuan[*] and Bingen Yang[†]

A new method for determination of tension distribution of space deployable mesh reflectors is developed. In this method, a two-step numerical optimization process is used to minimize the band-width of tension distribution of a mesh reflector structure. In the first step, the nodal coordinates of a mesh reflector are devised from a geometry design, yielding a set of nonlinear equilibrium equations of the reflector. In the second step, an optimization algorithm is implemented to obtain a good tension distribution among all possible solutions from the equilibrium equations of the reflector. Numerical simulation shows that the proposed method is able to significantly narrow down the band-width of tension distribution of deployable mesh reflectors.

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AAS 16-484

DYNAMICS OF ASTEROID 2006 RH120: PRE-CAPTURE AND ESCAPE PHASES

Brian D. Anderson* **and Martin W. Lo†**

Asteroid 2006 RH120 was the first natural object captured by the Earth to be observed called a Minimoon. In this work, we show that the invariant manifolds of the orbits around the L_1 and L_2 Lagrange points play a significant role in the capture of the asteroid around Earth and its eventual escape from the Earth approximately 1 year later. This is similar to the Temporary Capture of comets around Jupiter. We determined that the asteroid was in a 27:29 mean motion resonance with the Earth and approached the Earth through the stable manifold of an L_1 Northern Halo Orbit. After the Temporary Capture, the asteroid escaped the Earth through the unstable manifold of an L_2 southern halo orbit and into a 21:20 resonant orbit with the Earth. The asteroid travelled through a series of resonant orbits before and after the capture. These resonant transitions are similar to the orbits of Galileo and Cassini during their touring phase, using resonant orbits to reduce mission ΔV requirements.

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AAS 16-499

DYNAMICS AND CONTROL OF THE FLEXIBLE ELECTROSTATIC SAIL DEPLOYMENT

JoAnna Fulton* and Hanspeter Schaub†

The deployment dynamics of a radially configured, spin stabilized, electrostatic sail (E-sail) are modeled for a hub-mounted control actuator. Spacecraft hub control torque requirements for obtaining desired system spin rate trajectories are investigated. The dynamics are treated as a planar deployment and feedback control is applied with a PID controller. The sail is modeled for two different deployment strategies and tether stowage configurations, a tether spool wound up on a cylindrical hub which deploys the tether end masses tangentially, and a radially deployed configuration where each tether is stowed on an individual hub and actuated by a spool motor. The advantages and challenges of each deployment strategy are discussed. Additionally, deployment durations and torque capability requirements are determined for several tangentially deployed E-sails with varying characteristics.

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AAS 16-547

MECHANICS OF BOUNDED INEXTENSIBLE MEMBRANES SUBJECT TO SOLAR RADIATION PRESSURE

Bo Fu,[*] Rida T. Farouki[†] and Fidelis O. Eke[†]

The equilibrium shape of a thin inextensible membrane subject to solar radiation pressure under given boundary constraints is studied. The membrane is assumed to be insusceptible to elastic deformation and to have negligible bending resistance, and its steady–state shape is therefore described by a developable surface (i.e., a surface of zero Gaussian curvature), resulting from equilibrium between external radiation pressure and membrane tension forces. A quantitative understanding of the mechanics of such membranes is essential to analyzing the dynamics of solar sail spacecraft that employ sail wing tip displacement as an attitude control mode. The key result is that, under reasonable simplifying assumptions, solar radiation pressure and a prescribed wing tip displacement yield a billowed solar sail wing shape that is a generalized cylinder (i.e., a developable ruled surface whose rulings are all parallel), rather than a general developable with variable ruling directions.

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SPACECRAFT AUTONOMY

Session Chair:

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AAS 16-217

SUPERSONIC FLIGHT DYNAMICS TEST 2: TRAJECTORY, ATMOSPHERE, AND AERODYNAMICS RECONSTRUCTION

Christopher D. Karlgaard,[*] Clara O'Farrell,[†]
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The Supersonic Flight Dynamics Test is a full-scale flight test of aerodynamic decelerator technologies developed by the Low Density Supersonic Decelerator technology demonstration project. The purpose of the project is to develop and mature aerodynamic decelerator technologies for landing large-mass payloads on the surface of Mars. The technologies include a Supersonic Inflatable Aerodynamic Decelerator and supersonic parachutes. The first Supersonic Flight Dynamics Test occurred on June 28th, 2014 at the Pacific Missile Range Facility. The purpose of this test was to validate the test architecture for future tests. The flight was a success and, in addition, was able to acquire data on the aerodynamic performance of the supersonic inflatable decelerator. The Supersonic Disksail parachute developed a tear during deployment. The second flight test occurred on June 8th, 2015, and incorporated a Supersonic Ringsail parachute which was redesigned based on data from the first flight. Again, the inflatable decelerator functioned as predicted but the parachute was damaged during deployment. This paper describes the instrumentation, analysis techniques, and acquired flight test data utilized to reconstruct the vehicle trajectory, main motor thrust, atmosphere, and aerodynamics.

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AAS 16-221

LDSD POST2 MODELING ENHANCEMENTS IN SUPPORT OF SFDT-2 FLIGHT OPERATIONS

Joseph White,[*] Angela L. Bowes,[†] Soumyo Dutta,[‡] Mark C. Ivanov[§] and Eric M. Queen[**]

Program to Optimize Simulated Trajectories II (POST2) was utilized to develop trajectory simulations characterizing all flight phases from drop to splashdown for the Low-Density Supersonic Decelerator (LDSD) project's first and second Supersonic Flight Dynamics Tests (SFDT-1 and SFDT-2) which took place June 28, 2014 and June 8, 2015, respectively. This paper describes the modeling improvements incorporated into the LDSD POST2 simulations since SFDT-1 and presents how these modeling updates affected the predicted SFDT-2 performance and sensitivity to the mission design. The POST2 simulation flight dynamics support during the SFDT-2 launch, operations, and recovery is also provided.

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AAS 16-222

POST-FLIGHT ASSESSMENT OF LOW DENSITY SUPERSONIC DECELERATOR FLIGHT DYNAMICS TEST 2 SIMULATION

Soumyo Dutta,[*] Angela L. Bowes,[†] Joseph P. White,[‡] Scott A. Striepe,[§] Eric M. Queen,[**] Clara O'Farrell[††] and Mark C. Ivanov[‡‡]

NASA's Low Density Supersonic Decelerator (LDSD) project conducted its second Supersonic Flight Dynamics Test (SFDT-2) on June 8, 2015. The Program to Optimize Simulated Trajectories II (POST2) was one of the flight dynamics tools used to simulate and predict the flight performance, and was a major tool used in the post-flight assessment of the flight trajectory. This paper compares the simulation predictions with the reconstructed trajectory. Additionally, off-nominal conditions seen during flight are modeled in the simulation to reconcile the predictions with flight data. These analyses are beneficial for characterizing the results of the flight test and to improve the simulation and targeting of the subsequent LDSD flights.

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AAS 16-243

CASSINI MANEUVER EXPERIENCE THROUGH THE LAST ICY SATELLITE TARGETED FLYBYS OF THE MISSION

Sonia Hernandez,[*] Sean V. Wagner, Mar Vaquero, Yungsun Hahn, Powtawche N. Valerino, Frank E. Laipert, Mau C. Wong and Paul W. Stumpf[†]

The Cassini spacecraft will reach its spectacular end-of-mission in September 2017, after having spent a successful twenty years in space gathering invaluable scientific data about Saturn, its rings, and moons. Cassini has flown the most complex gravity-assist trajectory ever designed, which requires frequent maneuvering to achieve the desired targets. After so many years in operation the propellant is starting to dwindle, making it of paramount importance that the maneuvers be designed to prioritize preserving propellant. This paper highlights the strategies for 50 planned maneuvers during twelve Titan flybys and the last Dione and Enceladus flybys of the mission.

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AAS 16-305

CASSINI MANEUVER PERFORMANCE ASSESSMENT AND EXECUTION-ERROR MODELING THROUGH 2015

Sean V. Wagner*

Launched on October 15, 1997 and inserted into Saturn orbit on July 1, 2004, the Cassini spacecraft continues to gather valuable data as it tours Saturn and its moons. Cassini has executed a total of 336 propulsive maneuvers through February 2016. With more than 30 maneuvers planned through the end of mission in September 2017, a dwindling propellant supply has become a chief concern. Efforts to improve Cassini's maneuver performance have led to several execution-error model updates and calibrations of on-board flight parameters throughout the years. This paper reports on a recent analysis of Cassini maneuvers executed through December 30, 2015 and validates the current execution-error models in use since August 2012. Execution-error model updates based on recent maneuver performance, as well as a new execution-error model for a mixed-thruster mode, are discussed. Finally, this paper will examine the evolution of the execution-error model parameters as maneuver data is added.

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AAS 16-309

MAINTAIN A LIBRATION POINT ORBIT IN THE SUN-MERCURY ELLIPTIC RESTRICTED SYSTEM

Hao Peng,* Yuxin Liao,† Shijie Xu‡ and Shiyuan Jia§

In the Sun-Mercury Elliptic Restricted Three-Body Problem (ERTBP), there exist special kinds of libration point orbit resonant with the period of the motion of the two primaries, the Sun and the Mercury. These orbits can be generated through a continuation method, starting from a traditional halo orbit in the Circular Restricted Three-Body Problem (CRTBP). In this paper, such an orbit is chosen as the nominal orbit, and a Receding Horizon Control strategy, solved by an Indirect Radau Pseudospectral Method, is utilized to maintain a hypothetical spacecraft around the nominal orbit. Many series of Monte Carlo stochastic simulations are carried out to test the controllability of the periodic orbit, and also test the robustness of the controller. The special libration point orbit is shown to be easily controlled, and the controller shows sufficient robustness with respect to initial deviations around the nominal orbit. Some discussions and conclusions are given at the end of the paper.

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AAS 16-329

TIME-OPTIMAL ATTITUDE CONTROL LAW WITH A STRATEGY OF APPLYING TO ORBITAL CONTROL FOR SPINNING SOLAR SAIL DRIVEN BY REFLECTIVITY CONTROL

Kenshiro Oguri* and Ryu Funase†

This paper presents the time-optimal attitude control for spinning solar sail utilizing the controllability of the membrane reflectivity. Although solar sail is an ideal spacecraft due to its propellant-free acceleration by solar radiation pressure, conventional solar sails require fuel for its attitude control, which prevents completely propellant-free space exploration. It was demonstrated that fuel-free attitude control can be achieved by reflectivity control; however, no effective control strategy has been proposed. The time-optimal control law proposed in this paper gives a solution for the problem. Besides, the time-optimal control law enables us to solve the orbital and attitude control simultaneously. As an example of orbital control, V-infinity leveraging problem is numerically solved, where fast calculation was realized by analytical formulations derived from the proposed control law. The result indicates the importance of incorporating transient thrust generated during attitude maneuvers into orbital design of reflectivity-controlled solar sail.

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AAS 16-412

REACTIVE AND ROBUST PARADIGMS FOR AUTONOMOUS MISSION DESIGN AT SMALL BODIES

David A. Surovik* and Daniel J. Scheeres†

The complexity and sensitivity of strongly non-Keplerian orbital motion near asteroids and comets motivates an autonomous on-board approach to mission design. By applying heuristic-guided numerical reachability analyses in a receding horizon scheme, impulsive orbit control maneuvers are successively designed to fulfill sets of abstractly-specified science objectives. Building upon prior work, this solution technique is extended to mitigate state and model uncertainty through the use of robust planning and reaction to excessive deviations, a low-frequency form of feedback. Planning policy effectiveness is verified by conducting Monte Carlo analysis of mission planning trials at the highly irregularly shaped comet 67/P Churyumov-Gerasimenko. Comparisons of different planner parameterizations are drawn based upon control behavior and mission profile characteristics, ultimately indicating that a balance of the two mitigation paradigms is the most practical and effective.

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OPTIMAL SLIDING GUIDANCE FOR EARTH-MOON HALO ORBIT STATION-KEEPING AND TRANSFER

Joel Mueting,[*] Roberto Furfaro,[†] Francesco Topputo[‡] and Jules Simo[§]

An Optimal Sliding Guidance (OSG) is implemented in the Circular Restricted Three-Body Problem and Restricted Four-Body Problem for spacecraft near libration points of the Earth-Moon system. Based on a combination of generalized Zero-Effort-Miss/Zero-Effort-Velocity and time-dependent sliding control theory, OSG is capable of generating closed-loop guided trajectories that are demonstrated to be globally finite-time stable against uncertain perturbing accelerations with known upper bound. The application of the OSG for Halo orbit station-keeping and orbital transfer are studied in a perturbed four body dynamical model in order to evaluate response and effectiveness of the proposed guidance approach.

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AAS 16-517

GEOSTATIONARY SATELLITE STATION KEEPING USING DRIFT COUNTERACTION OPTIMAL CONTROL

Robert A. E. Zidek[*] and Ilya V. Kolmanovsky[†]

The framework of Drift Counteraction Optimal Control (DCOC) is used to generate a feedback control policy that maximizes the time until a geostationary satellite violates prescribed position, velocity, and fuel constraints. For this problem, we modify a recently developed DCOC algorithm to provide higher accuracy when large time horizons are considered. The nonlinear satellite model accounts for perturbations due to luni-solar gravity, solar radiation pressure, and J_2. The example satellite is equipped with six on-off thrusters. Simulation results are presented.

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AAS 16-551

MAGNETIC ATTITUDE CONTROL WITH AERODYNAMIC STABILIZATION FOR THE LAICE SATELLITE

Erik Kroeker,[*] Craig Babiarz[†] and Alexander Ghosh[‡]

The LAICE satellite will make use of magnetic torqueing coils augmented with aerodynamic stabilization to accomplish the mission attitude control requirements. The proposed control method relies on aerodynamic stabilization of the spacecraft to maintain pointing in the satellite normal frame. The aerodynamic stabilization reduces the dimensionality of the magnetic attitude control to a one-dimensional problem. As a result, it is possible to design a controller for the magnetic torqueing coils based upon models of the orbital trajectory and the Earth's magnetic field. The design of the controller along with the results of a hardware-in-the-loop attitude control simulation is presented.

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ESTIMATION

Session Chair:

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AAS 16-336

RELATIVE MOTION ESTIMATION USING RECTILINEAR AND CURVILINEAR LINEARIZED RELATIVE ORBIT ELEMENTS

Trevor Bennett[*] and Hanspeter Schaub[†]

Relative motion estimation finds application in space-based space situational awareness and proximity operations. Prior work demonstrates the control capability and insight provided by a relative motion state vector chosen to be the Clohessy-Wiltshire integration constants, referred to as Linearized Relative Orbit Elements (LROEs). This study compliments the LROE control with a navigation study using a curvilinear coordinate state vector. Estimation performance and applicability is considered for curvilinear and both dimensional and non-dimensional rectilinear state estimation approaches. An Extended Kalman Filter (EKF) is developed to estimate the rectilinear and curvilinear LROE state and tested in an inertial simulation with bearings-only measurements and compared to bearings-plus-range filters. The curvilinear formulation demonstrates observability and improved estimation performance for the presented relative orbits. All LROE estimation approaches preserve much of the geometrical insight of the relative orbit while accommodating large initial condition errors.

[View Full Paper]

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AAS 16-341

MOON AND EARTH IMAGE PROCESSING USING ASYMMETRIC 2-DIMENSIONAL FUNCTIONS ON IMAGE GRADIENT

Daniele Mortari[*] and Stoian Borissov[†]

Asymmetric Gaussian-type data distribution is found in the image processing at the edge of an observed illuminated body (Moon, Earth, planet) using the image gradient. The reason is, one side of this Gaussian behavior is associated with the dark background (pretty uniform) while the other side is associated with the illuminated part, which is perturbed by different reflecting areas: craters for Moon and high clouds for Earth. This variation is here implemented by modeling the standard deviation as a sigmoid function. Nonlinear least squares estimate is then applied for OpNav problem using synthetic Moon and Earth images.

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AAS 16-399

DEVELOPMENT OF A SATELLITE GROUP TRACKING METHOD

Christopher R. Binz* and Liam M. Healy*

When multiple objects are orbiting in close proximity to one another, as in the early stages of a breakup or a deployment, conventional tracking is difficult because of the observation association problem. However, the ability to characterize and track these objects quickly is important for spaceflight safety. This paper explores the concept of group tracking for space surveillance. Explicit observation association is not required, as the "cloud" of objects is tracked as a parameterized collective. A scheme for tracking the centroid and extent parameters of the collection separately is presented, along with preliminary results.

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AAS 16-402

THE GAUSSIAN MIXTURE CONSIDER KALMAN FILTER

James S. McCabe[*] and Kyle J. DeMars[†]

The consider Kalman filter, or Schmidt-Kalman filter, is a tool developed by S.F. Schmidt at NASA Ames in the 1960s to account for uncertain parameters or biases within the system and observational models of a tracking algorithm. Its novelty is in that it “considers” the effects of the uncertain parameters rather than other Kalman-filter-based approaches, which instead estimate these parameters directly. Avoiding this online estimation of parameters allows, in many cases, for a more computationally feasible algorithm to be acquired, making it amenable to real-time applications. The consider Kalman filter, however, is an approach that works solely with the mean and covariance of the posterior distribution. In many problems, mean and covariance are often insufficient statistical descriptions of the filtering state. This work presents a consider formulation that works with a Gaussian sum approximation of the true distribution, permitting the Gaussian mixture consider Kalman filter and enabling an operator to maintain a more complete description of the true posterior state density while still working within a consider framework.

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AAS 16-414

ANALYTIC UNCERTAINTY PROPAGATION IN SATELLITE RELATIVE MOTION ALONG ELLIPTIC ORBITS

Sangjin Lee,[*] Hao Lyu[†] and Inseok Hwang[‡]

For satellites flying in close proximity, monitoring the uncertainties of neighboring satellites' states is a crucial task since the uncertainty information is used to compute the collision probability between satellites with the objective of collision avoidance. In this study, an analytical closed-form solution is developed for uncertainty propagation in satellite relative motion near general elliptic orbits. The Tschauner-Hempel equations are used to describe the linearized relative motion of the deputy satellite where the chief orbit is eccentric. Under the assumption of the linearized relative motion and white Gaussian process noise, the uncertainty propagation problem is defined to compute the mean and covariance matrix of the states of the deputy satellite. The evolutions of the mean and covariance matrix are governed by a linear time-varying differential equation, whose solution requires the integration of the quadratic function of the inverse of the fundamental matrix associated to the Tschauner-Hempel equations. The difficulties in evaluating the integration are alleviated by the introduction of an adjoint system to the Tschauner-Hempel equations and the binomial series expansion. The accuracy of the developed analytical solution is demonstrated in a couple of numerical examples through the comparison with Monte-Carlo analysis.

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AAS 16-423

STATE ESTIMATION AND MANEUVER RECONSTRUCTION WITH THE NONLINEAR ADAPTIVE OPTIMAL CONTROL BASED ESTIMATOR

Daniel P. Lubey[*] and Daniel J. Scheeres[†]

This paper derives, develops, and demonstrates a nonlinear sequential state estimation algorithm known as the Nonlinear Adaptive Optimal Control Based Estimator. This algorithm combines optimal estimation and optimal control into a state tracking method that is robust to dynamic mismodeling and is able to reconstruct dynamic mismodeling via estimated optimal control policy. The method is also made adaptive by including an automated maneuver detection and compensation method so that mismodeled dynamics are addressed as they are encountered in the measurement arc. After a full derivation of this algorithm, we then demonstrate the algorithm via numerical simulations that replicate spacecraft tracking scenarios in the presence on mismodeled dynamics. The results clearly indicate that the algorithm is able to automatically maintain track of a maneuvering vehicle while also obtaining information on how it is maneuvering.

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AAS 16-489

AN UPDATE TO THE THEMIS THERMAL GAUGING FUEL ESTIMATION PROCESS AND ITS USE IN A FUEL IMBALANCE ANOMALY

Aaron J. Burgart,* Daniel Cosgrove,† Jeffrey Marchese* and Manfred Bester‡

Accurate knowledge of propellant mass is crucial to a spacecraft mission's success, especially as the propellant mass decreases as the mission progresses. When the fuel loads are imbalanced between multiple tanks, as has been discovered on the THEMIS spacecraft, this knowledge becomes even more crucial. A thermal gauging fuel estimation process was initially developed at the beginning of the extended missions to validate the bookkeeping fuel levels, and was later improved upon as the fuel imbalance was discovered. This paper discusses these improvements and how the thermal gauging process has been utilized to quantify and monitor the fuel imbalances between tanks. This has allowed the operations team to make informed decisions to draw from individual tanks for maneuvers to progress towards leveling the fuel load.

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AAS 16-512

ANGLES-ONLY INITIAL RELATIVE-ORBIT DETERMINATION VIA SUCCESSIVE MANEUVERS

Laura M. Hebert,* Andrew J. Sinclair† and T. Alan Lovell‡

For relative-orbit determination using linear, Cartesian dynamics, angles-only measurements are not sufficient. A known maneuver performed by either the chief or resident space object can provide observability. However, some maneuvers result in singular measurement equations and therefore do not provide full-state observability. These singular maneuvers can be avoided, but no further information can be provided about desirable maneuvers. The goal of this paper is to provide an iterative method by which to improve observability and the accuracy of the solution. Successive maneuvers planned from covariance predictions using previous state estimates give increasingly good estimates.

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IMPROVED MANEUVER-FREE APPROACH TO ANGLES-ONLY NAVIGATION FOR SPACE RENDEZVOUS

Joshua Sullivan,* Adam W. Koenig* and Simone D'Amico†

This work introduces a novel strategy for improving angles-only relative navigation for distributed space systems. Instead of relying on orbit or attitude maneuvers to reconcile the known observability issues, a rigorous state comparison and observability assessment is conducted to provide new insight into the benefits gained from improved dynamic and measurement modeling. First of all, a new method is described to derive a J_2-perturbed state transition matrix in mean quasi-nonsingular relative orbit elements. In particular, Floquet theory is used to solve the resulting set of time-varying, periodic differential equations under the assumption of small state components. The presented formulation enables the seamless derivation of computationally efficient state transition matrices valid for different regimes of orbit eccentricity (from near-circular to arbitrary). Second, this research shows how the inclusion of nonlinearities in the measurement model vastly improves the condition number of the system's observability Gramian by increasing the accuracy of modeled bearing measurements. The results of this assessment lead to the design of a novel architecture for angles-only relative navigation which is comprised of an initial batch relative orbit determination algorithm used to initialize a sequential extended Kalman filter. The initialization method leverages the relative orbital element description to decouple the range uncertainty from the observable relative geometry, and a series of navigation filters are built using different combinations of the derived dynamics and measurement models. The prototype navigation algorithms are tested and validated in high-fidelity simulations which show that improved dynamics modeling has little effect on observability, whereas preserving nonlinearities in the measurement model reconciles the range ambiguity issues without necessarily requiring maneuvers.

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MISSION DESIGN

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Session 22: David Spencer

AAS 16-208

NEW HORIZONS TRAJECTORY CORRECTION MANEUVER FLIGHT IMPLEMENTATION AND PERFORMANCE

Gabe D. Rogers,[*] Sarah H. Flanigan[†] and Madeline Kirk[‡]

To meet key science observations during its flyby of the Pluto/Charon system in July 2015 the New Horizons spacecraft has conducted trajectory correction maneuvers (TCMs) throughout the mission. This paper will discuss the design of New Horizons Guidance and Control (G&C) system, including details of the propulsion system and how TCMs are conducted onboard the spacecraft. It will present TCM requirements, the flight software and hardware, and the algorithms used during 3-axis and spin mode TCM maneuvers. It will present the historical performance of the TCMs conducted to date and lessons learned during flight operations.

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AAS 16-231

INTERPLANETARY NANOSPACECRAFT TRAVEL CAPABILITIES

Simon Tardivel,[*] Stefano Campagnola[†] and Andrew T. Klesh[‡]

This paper investigates the solar system travel capabilities of nanospacecraft, which have already proven their worth in Earth orbit and can reach for further goals. Recent developments in nanopropulsion now theoretically enable high ΔV budgets for nanospacecraft, but mission, system and operations constraints limit these optimistic capabilities. Unfortunately, interplanetary nanospacecraft, as hitchhikers of larger spacecraft launches, have only a select number of rideshare opportunities. Nevertheless, appropriate initial orbit injections coupled with new propulsion technologies allows them to timely reach and effectively explore a vast range of targets.

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AAS 16-234

BEPICOLOMBO TRAJECTORY OPTIONS TO MERCURY IN 2018 AND 2019

Rüdiger Jehn* **and Yves Langevin†**

Low-thrust transfer options to Mercury in the years 2018 and 2019 are investigated. Both direct launches to Venus as well as transfers with an Earth-to-Earth leg are considered. Only options with two Venus flybys are studied. To keep the total delta-V below 5 km/s and to guarantee a weak stability capture at Mercury, 4 to 5 Mercury flybys are required. The most promising option is a direct launch in April 2018 towards Venus with an arrival at Mercury on 18 December 2024. Reasonable backup launch options exist in October 2018 and March 2019 with arrival on 5 December 2025. Both back-up options have an Earth flyby in April 2020 with an identical trajectory from the Earth flyby until Mercury orbit insertion. In October 2018 there is a 1.5-year Earth-to-Earth leg whereas in March 2019 there is a one year Earth-to-Earth leg.

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AAS 16-237

MAVEN NAVIGATION OVERVIEW*

**Mark Jesick,† Stuart Demcak,‡ Brian Young,† Drew Jones,†
Sarah Elizabeth McCandless,† Maximilian Schadegg,† Eric Graat,†
Mark Ryne,† Hui Ying Wen,† Paul Stumpf,† Min-Kun Chung,†
Andrew Vaughan,† Eric Gustafson,† Try Lam† and David Folta§**

The Mars Atmosphere and Volatile Evolution mission (Maven) is the first mission devoted primarily to the study of the Martian atmosphere. The Maven orbiter launched on November 18, 2013, entered Mars orbit on September 22, 2014, and continues to acquire measurements of Mars' upper atmosphere in an effort to understand the loss of Martian volatiles to space. The navigation team is responsible for estimating and predicting Maven's position and velocity, and designing and reconstructing propulsive maneuvers. After Mars orbit insertion, the team faced additional challenges unique to Maven's orbit and tracking data schedule, including the determination of the atmospheric density at each periapsis, which is necessary to keep the spacecraft within a predefined density corridor. This paper briefly describes the Maven mission and overviews the operations of the Maven navigation team from launch through the nominal science phase.

[View Full Paper]

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AAS 16-244

LUNAR NEAR RECTILINEAR ORBITS AND CIS-LUNAR TRANSFER TRAJECTORIES IN SUPPORT OF THE DEEP SPACE PROVING GROUND

Michel Loucks,[*] Kevin Post[†] and John Carrico[‡]

The NASA Evolvable Mars Campaign (EMC) contains the Deep Space Proving Ground (DSPG) in the near-Lunar vicinity as one of the major increments along the path to a sustainable human spaceflight architecture. The DSPG development path includes several key hardware architectural elements including the Space Launch System (SLS), the Orion crew vehicle, and an extended stay capability provided by an Exploration Augmentation Module (EAM). Recent NASA studies have indicated that a class of cislunar Halo orbits known as Near Rectilinear Orbits or NROs, could be a useful staging location for human-tended cislunar operations in the DSPG away from the Lunar Distant Retrograde Orbit (LDRO). In this paper, we describe a method for the simple creation and analysis of these orbits and provide and describe their fundamental characteristics.

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AAS 16-251

MULTIPLE DESIGN OPTIONS FOR INTERPLANETARY ORBITER MISSIONS USING PSEUDOSTATE TECHNIQUE

S. P. Parvathi[*] and R. V. Ramanan[†]

An iterative analytical method based on pseudostate technique to generate the transfer trajectory design for interplanetary orbiter missions is developed. This method identifies the four distinct transfer trajectory design options for a given departure date and a flight duration. The proposed method includes the Sun's gravity within the pseudosphere of the planets and iterates upon the pseudostates to generate the excess velocity vectors. An analytical tuning strategy is used to obtain the departure hyperbolic characteristic that achieves the departure excess velocity vector at the Earth pseudosphere. The design obtained from this method reduces the deviations in the target parameters. The deviation in closest approach altitude is reduced by more than 98% and the time of closest approach altitude by 95% upon numerical propagation, as compared to the V-infinity tuned patched conic design. This method is useful for quick mission design and analysis of orbiter missions. Also, it provides a better initial guess for numerical refinements under extended force models that include other perturbations. For illustration, a typical 2018 Type I minimum energy opportunity is analyzed using the V-infinity tuned patched conic and the proposed iterative methods.

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AAS 16-255

END-TO-END TRAJECTORY FOR CONJUNCTION CLASS MARS MISSIONS USING HYBRID SOLAR-ELECTRIC/CHEMICAL TRANSPORTATION SYSTEM

Patrick R. Chai,[*] Raymond G. Merrill[*] and Min Qu[†]

NASA's Human Spaceflight Architecture Team is developing a reusable hybrid transportation architecture in which both chemical and solar-electric propulsion systems are used to deliver crew and cargo to exploration destinations. By combining chemical and solar-electric propulsion into a single spacecraft and applying each where it is most effective, the hybrid architecture enables a series of Mars trajectories that are more fuel efficient than an all chemical propulsion architecture without significant increases to trip time. The architecture calls for the aggregation of exploration assets in cis-lunar space prior to departure for Mars and utilizes high energy lunar-distant high Earth orbits for the final staging prior to departure. This paper presents the detailed analysis of various cis-lunar operations for the EMC Hybrid architecture as well as the result of the higher fidelity end-to-end trajectory analysis to understand the implications of the design choices on the Mars exploration campaign.

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AAS 16-257

FINAL MISSION AND NAVIGATION DESIGN FOR THE 2016 MARS INSIGHT MISSION

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NASA's Interior Exploration using Seismic Investigations, Geodesy, and Heat Transport (InSight) mission was scheduled to launch the next lander to Mars in March 2016 arriving to the Red Planet in the fall. Derived from the Phoenix mission which successfully landed on Mars in May 2008, the InSight Entry, Descent, and Landing system will place a lander in the Elysium Planitia region. This paper specifies the mission and navigation requirements set by the Project and how the final mission and navigation design satisfies those requirements. Background information affecting navigation including spacecraft modeling and the physical environment which influences the spacecraft motion are included. (Note from the author: The InSight launch in 2016 was suspended due to critical issues with the Seismic Experiment for Interior Structure (SEIS) instrument that could not be fixed prior to the planned launch period. This paper represents the state of the design for the 2016 mission. No attempt has been made to reflect the latest developments).

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AAS 16-259

NEW HORIZONS PLUTO ENCOUNTER MANEUVER PLANNING AND ANALYSIS

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With the Pluto phase of the New Horizons mission completed, analysis of propulsive maneuvers has been revisited. The analysis accounts for spacecraft state knowledge and control errors relative to target bodies, with consideration of various possible combinations of final maneuvers prior to Pluto closest approach. This paper also includes details of actual maneuvers planned and executed during and after the Pluto approach and flyby. This encompasses both statistical maneuvers and contingencies for collision avoidance of any newly encountered satellites during approach.

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REINFORCEMENT LEARNING FOR SPACECRAFT MANEUVERING NEAR SMALL BODIES

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We use neural reinforcement learning to control a spacecraft around a small celestial body whose gravity field is unknown. The small body is assumed to be a triaxial ellipsoid and its density and dimensions are left unknown within large bounds. We experiment with different proprioceptive capabilities of the spacecraft emphasising lightweight neuromorphic systems for optic flow detection. We find that even in such a highly uncertain environment and using limited perception capabilities, our approach is able to deliver a control strategy able to hover above the asteroid surface with small residual drift.

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AAS 16-285

THE LUNAR ICECUBE MISSION DESIGN: CONSTRUCTION OF FEASIBLE TRANSFER TRAJECTORIES WITH A CONSTRAINED DEPARTURE

David C. Folta,[*] Natasha Bosanac,[†] Andrew Cox[‡] and Kathleen C. Howell[§]

Lunar IceCube, a 6U CubeSat, will prospect for water and other volatiles from a low-periapsis, highly inclined elliptical lunar orbit. Injected from Exploration Mission-1, a lunar gravity assisted multi-body transfer trajectory will capture into a lunar science orbit. The constrained departure asymptote and value of trans-lunar energy limit transfer trajectory types that re-encounter the Moon with the necessary energy and flight duration. Purdue University and Goddard Space Flight Center's Adaptive Trajectory Design tool and dynamical system research is applied to uncover cislunar spatial regions permitting viable transfer arcs. Numerically integrated transfer designs applying low-thrust and a design framework are described.

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AAS 16-288

CONSTRUCTION OF SUPERSONIC FLIGHT DYNAMICS TEST (SFDT-2) VEHICLE MONTE CARLO SPLASHDOWN FOOTPRINTS FOR USE IN RANGE SAFETY AND RECOVERY OPERATIONS

William D. Strauss[*] and Mark C. Ivanov[†]

The Low-Density Supersonic Decelerator (LDSD) project performed the second test flight of a supersonic inflatable device (SIAD) and ring-sail parachute on June 8, 2015 splashing down in the Pacific Ocean west of Kauai. In order for recovery ships to quickly extract the test vehicle hardware from the ocean, and in the interest of safety to the population of the islands of Kauai and Nihau, statistical estimates of the splashdown location had to be performed. This paper describes the modeling assumptions used to generate the Monte Carlo splashdown trajectory simulation results and the use of the splashdown probability ellipses in support of satisfying range safety requirements.

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AAS 16-326

TRAJECTORY PLANNING FOR MULTI-ARM SPACE WALKING ROBOT

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In this paper, a trajectory planning algorithm for a multi-arm space robot is proposed. The robot is capable of walking on the exterior of a large space station. Based on the maneuver strategy of the walking, continuous and smooth trajectories of the manipulator end-effectors are firstly determined by a five times polynomial interpolation method. Then, the kinematics describing the relationship between the end-effector and the joint angles, as well as the platform, is formulated. An optimization solution of the joint motions is calculated to describe the motion of the manipulators. Finally, a collision detection algorithm is developed to guarantee the security during the operation. Numerical results of a triple-arm space robotic system are given to demonstrate the effectiveness of the proposed algorithms.

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AAS 16-359

MISSION DESIGN CONSIDERATIONS FOR MARS CARGO OF THE HUMAN SPACEFLIGHT ARCHITECTURE TEAM'S EVOLVABLE MARS CAMPAIGN

Waldy K. Sjauw,[*] Melissa L. McGuire[†] and Joshua E. Freeh[‡]

Recent NASA interest in human missions to Mars has led to an Evolvable Mars Campaign by the agency's Human Architecture Team. Delivering the crew return propulsion stages and Mars surface landers, SEP based systems are employed because of their high specific impulse characteristics enabling missions requiring less propellant although with longer transfer times. The Earth departure trajectories start from an SLS launch vehicle delivery orbit and are spiral shaped because of the low SEP thrust. Previous studies have led to interest in assessing the divide in trip time between the Earth departure and interplanetary legs of the mission for a representative SEP cargo vehicle.

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AAS 16-361

JUPITER TOUR OF THE JUPITER ICY MOON EXPLORER

Arnaud Boutonnet[*] and Johannes Schoenmaekers[†]

This paper presents the mission analysis of the Jupiter tour for JUICE. It starts with the design of the sequence after Jupiter's capture which complies with the Europa fly-bys illumination constraint. Then the Jupiter science phase is achieved via multiple Callisto fly-bys with different resonance ratios. The transfer to Ganymede is presented, showing how the DeltaV optimisation and the scientific constraints are tackled through the Ganymede-Callisto ladder sequence and the low energy endgame with Ganymede. The Ganymede in-orbit phase is also presented. The strong impact of the superior conjunctions on the design is highlighted throughout the entire tour.

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AAS 16-372

LOW ENERGY ESCAPE TRAJECTORY FOR THE MARS MOON SAMPLE RETURN MISSION

Makoto Horikawa,[*] Yasuhiro Kawakatsu[†] and Hiroaki Yoshimura[‡]

In this paper, we investigate the low-energy escape trajectory design for a mission called Martian Moons eXplorer to achieve the world's first sample return from Martian moon. The hybrid usage of chemical and electric propulsion with combination of the three-body and two-body problems has come into consideration in order to seek a fast low-energy escape from Mars. We first study the needs of pre-departure sequence. Then, we determine the transition point from a low-energy three-body phase to a low-thrust two-body phase, in which the tube dynamics is employed for the low-energy three-body phase. We finally develop charts to reveal the relation between the velocity in Mars Escape Injection maneuver and the required time of flight.

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AAS 16-393

DYNAMIC STRATEGIES FOR MISSION LAUNCHES AND OTHER SCENARIOS RELATED TO SECRETARY PROBLEMS

Ingo Althoefer*

For an interplanetary mission, the launch typically has to happen within a certain time slot, for instance within thirteen days. In case of problems on the current day (like bad weather) the launch may be postponed to the next day. We discuss and compute *dynamic* strategies, based on Bellman's dynamic programming, to get good launch decisions. The situation is a stopping problem, related to quantitative versions of the classical secretary problem. Variants are relevant for instance for missions to Mars (including returning from Mars) and for competitions like Google's Lunar X Prize. Good launch strategies may also play a role for the design and cost estimates of launch insurances.

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AAS 16-405

THE EARTH-MOON LOW-ENERGY TRANSFER IN THE 4-BODY PROBLEM

Kaori Onozaki,* Hiroaki Yoshimura† and Shane D. Ross‡

A low energy transfer from the Earth to the Moon is proposed in the context of the 4-body Problem. We propose a new model by regarding the Sun-Earth-Moon-Spacecraft (S/C) 4-body system as the coupled system of the Sun-perturbed 3-body system and the Moon-perturbed 3-body system. In particular, we clarify the tube structures of invariant manifolds of the 4-body Problem by investigating the Lagrangian coherent structures of such a coupled 3-body system with perturbations. Lastly, we construct a low-energy transfer trajectory from the Earth to the Moon by patching two trajectories obtained from the perturbed systems at a Poincare section. We develop an optimal trajectory by minimizing the Delta-v at the Poincaré section.

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AAS 16-418

TRANSFERS BETWEEN THE LAGRANGIAN POINTS AND THE PRIMARIES CONSIDERING RADIATION PRESSURE

Geraldo Magela C. Oliveira,* Vivian M. Gomes,† Antonio F. Bertachini de A. Prado‡ and Diogo M. Sanchez§

The idea of the present paper is to study transfers in the restricted three-body problem considering the effects of the radiation pressure in the trajectory of the spacecraft in a bi-impulsive maneuver. Three systems of primaries are used: Sun-Earth, a generic Sun-asteroid system and a system of asteroids. Transfers among the Lagrangian points and between the Lagrangian points and the primaries are considered. The results show that the radiation pressure has a significant participation in the process, in particular in the system formed by asteroids, because their gravitational forces are smaller compared with the systems having larger bodies. In the case of the asteroid system, it is possible to find solutions with lower fuel consumption by considering the solar radiation pressure. The idea is not to use the radiation pressure as a control, but just to measure its effects when performing the bi-impulsive transfer. It is very important to consider this force or the spacecraft will not reach the desired point.

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AAS 16-419

NEW HORIZONS ORBIT DETERMINATION PERFORMANCE DURING APPROACH AND FLYBY OF THE PLUTO SYSTEM

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Navigating the New Horizons spacecraft on approach to Pluto was not only a technical challenge; it was also a race against the clock. With 9 years of cruise behind, all of the navigation critical activity culminated in the last few months when the spacecraft could finally observe and learn from its target. Key functions of the orbit determination process are discussed, which includes the processing of radio metric and optical measurements, the estimation of the Pluto barycenter and satellites ephemerides as well as the characterization of the attitude control small forces acting on spacecraft. Performance and results of the overall navigation functions that enabled the successful flyby of the Pluto system are presented.

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AAS 16-435

DESIGNING AN ASTEROID DEFLECTION MISSION USING CONTINUOUS THRUST AND UNCERTAINTY

Stijn De Smet,[*] Jeffrey S. Parker[†] and Nathan Parrish[*]

This paper discusses the uncertainty quantification for future asteroid deflection concepts that utilize optimization under uncertainty (OUU) to minimize the fuel requirement. An essential part for OUU is the propagation of uncertainty: starting from the initial asteroid orbit uncertainty, under the influence of the natural dynamics and the continuous thrusting, and the uncertainty associated with this thrusting, the covariance matrix at the time of closest approach must be found. In this paper, multiple methods for determining this matrix are developed and compared. Furthermore, different maneuver execution models including correlations between the different maneuvers are developed and compared.

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AAS 16-456

STUDY OF PERTURBATION INTEGRALS APPLIED TO THE DYNAMICS OF SPACECRAFTS AROUND GALILEAN MOONS

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Several scientific missions have been proposed for a deeper exploration of planetary systems. These missions require a lot of specialized techniques in order to reach a better understanding of the dynamics involved in their planning. In order to help to get important features about each system under study, the present study proposes to use different definitions of integrals of the perturbing forces received by spacecrafts to help to find the best orbits for them. These computations present important information about level of perturbation acting in the spacecraft due to the effects of each force considered in the system and they also help to understand the evolution of these perturbations. The system of Galilean moons is explored to test these techniques.

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MULTI-BODY MISSION DESIGN USING THE DEEP SPACE TRAJECTORY EXPLORER

Diane C. Davis,[*] Sean M. Phillips[†] and Brian P. McCarthy[‡]

In this investigation, preliminary trajectory design in the vicinity of the smaller primary (P_2) in a three-body system is simplified by the use of periapsis Poincaré maps. The maps characterize behavior of both short- and long-term orbits. By employing a custom visualization and design tool, maps are combined to methodically select transfers into long-term, P_2-centered orbits, to design trajectories that transit the vicinity of P_2, and to transition between libration point orbits and trajectories centered at the smaller primary.

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AAS 16-467

L_4, L_5 SOLAR SAIL TRANSFERS AND TRAJECTORY DESIGN: SOLAR OBSERVATIONS AND POTENTIAL EARTH TROJAN EXPLORATION

Rohan Sood[*] and Kathleen C. Howell[†]

The Sun-Earth triangular Lagrange point, L_5, provides an ideal location to monitor the space weather. Furthermore, L_4, L_5 may harbor Earth Trojans and space dust that are of significant interest to the scientific community. No spacecraft has entered an orbit in the vicinity of Sun-Earth triangular points in part because of high propellant costs. By incorporating solar sail dynamics in the CR3BP, the concept of a mission to L_4, L_5 can be re-evaluated and the total ΔV can be reconsidered. A solar sail is employed to increase the energy of the spacecraft and deliver the spacecraft to an orbit about the artificial Lagrange point by leveraging solar radiation pressure and potentially without any insertion ΔV.

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AAS 16-473

TROJAN ASTEROID MISSION DESIGN: TARGET SELECTION AND SEQUENCING OPTIMIZATION

Owen P. Blough,[*] Tyler K. Farrington[†] and Jennifer Hudson[‡]

The Trojan Asteroids, which reside in the L4 and L5 Lagrange points of Jupiter's orbit, hold significant scientific interest. A mission to these asteroids requires large amounts of propellant, due to their distance and location. Identification of the most fuel-efficient paths between asteroids would improve mission feasibility. The selection of asteroids and the sequence of visitation is a complex trajectory optimization problem akin to the "Moving Target Traveling Salesman Problem". A Genetic Algorithm is developed that identifies asteroid sequences that significantly reduce fuel cost. The solution uses assumptions regarding starting point, flight times, and loiter time at each asteroid.

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EARTH-MOON MULTIPURPOSE ORBITING INFRASTRUCTURE

Simone Flavio Rafano Carnà,[*] Lorenzo Bucci[*] and Michèle Lavagna[†]

Nowadays interest on large structures, ISS like, to serve for a long time as orbiting outposts place in strategic, possibly long-term stable locations is increasing. They can serve as a support for far target robotic\manned missions, for planetary tele-operated robotic surface activities, as scientific labs for sample return missions in preserved environment avoiding contamination, for astronauts training, for refueling and maintenance of deep space vessels. Whatever the exploitation is such large structure would undergo numerous docking\undocking activities with a time dependent matrix of inertia; it should require a large lifetime along with orbital stability would be also needed and, being the structure extended, a strongly coupled attitude\orbital dynamics is expected. Lagrangian points are an evident appealing location for such an infrastructure offering stable trajectories as well as well suited relative positioning with respect to the Sun and the other planets to be considered in the 3 body system. The investigation of the relative dynamics on non-keplerian orbits is the topic of the paper: a case study is presented for the EMPIRE (Earth-Moon multiPurpose orbIting infRastructurE) scenario: EMPIRE is a long-term multipurpose extended structure placed on Halo around the L1 in the Earth-Moon system, many different space complex and articulated missions may benefit of. The rendez-vous and approach phases between EMPIRE and any attachable module are formalized for the CR3BP together with the guidance profile to gain the nominal final state vector. Effects of perturbations on the EMPIRE extended configuration in terms of attitude\CoM coupled effects are also discussed.

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AAS 16-493

COMMERCIAL CUBESAT TECHNOLOGY TO ENHANCE SCIENCE: COMMUNICATIONS, SPACE DEBRIS IDENTIFICATION AND MOON SURFACE RECONNAISSANCE USING LAGRANGIAN CYCLERS

Pedro J. Llanos[*] and Abdiel Santos[†]

This paper deals with novel cycler trajectories for cubesats that will depart from low-Earth orbit (LEO) to help determine the resources needed for interplanetary travel and infrastructure required for space colonization on the Moon. Our cubesats will depart from a 400-km parking orbit aboard the International Space Station (ISS) to provide significant opportunities to enhance communication and navigation strategies while improving space exploration capabilities. Different cycler orbits connecting the Lagrange points in the Earth-Moon system are explored, which will enable us to improve our communications and navigation from Earth via low ΔV connection nodes often referred to as the Interplanetary Superhighway.

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AAS 16-494

INITIAL RESULTS FOR PRELIMINARY TRAJECTORY DESIGN OF MULTI-TARGET ACTIVE DEBRIS REMOVAL MISSIONS USING THE ATOM SOLVER

Kartik Kumar,[*] Abhishek Agrawal,[†] Enne Hekma[†] and Francesco Topputo[‡]

Active Debris Removal is a burgeoning field of research that has recently gained prominence due to on-orbit collision events, e.g., the 2009 Iridium-Cosmos collision, and studies suggesting action must be undertaken to guarantee the sustainability of the near-Earth space environment. We present initial results obtained from computing and analyzing high-thrust, debris-to-debris, transfer trajectories using the Accurate Transfer Orbit Model (Atom) solver. We outline the theory behind the Atom solver, which accounts for perturbations around the Earth by employing the SGP4/SDP4 propagator, to solve the perturbed Lambert problem. The results are contrasted against those obtained using the classical Lambert problem solver. This paper serves as a first step in establishing a framework for preliminary trajectory design of Multi-Target Active Debris Removal (MTADR) missions using the Atom solver.

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AAS 16-529

TRAJECTORY CHARACTERISTICS OF SPACECRAFT PROPELLED BY PLANET/ASTEROID-BASED PHOTONIC LASER PROPULSION

Fu-Yuen Hsiao*

This project studies the trajectory characteristics of the spacecraft propelled by a planet/asteroid-based photonic laser propulsion (PLP) system. The trajectories of spacecraft propelled by an spaceborne PLP system were studied in the past years. However, a planet/asteroid-based PLP system may also helpful in space missions. For instance, trajectory about an asteroid is highly unstable and the stable margin is quite limited. A planet/asteroid-based PLP system may improve this condition. In this project, a PLP system is assumed to be installed in the surface of a celestial body. The equations of motion of the spacecraft in the body-fixed frame is derived, and the corresponded Jacobi integral is found. Contours of zero-velocity lines are presented.

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AAS 16-535

MISSION DESIGN TRADES FOR A NEAR TERM PLUTO ORBITER

Nitin Arora,[*] Anastassios E. Petropoulos[†] and John Elliott[‡]

Trajectory design trades for a near-term Pluto orbiter, launching between 2022 and 2030, are presented. Both, chemical and nuclear-powered electric propulsion (EP) trajectories are investigated. Low-thrust EP trajectories powered by either Radioisotope Thermoelectric Generators (RTG) or a high power nuclear reactor are found to be mission enabling. Trajectories using NASA Evolutionary Xenon Thruster (NEXT) or the Xenon Ion Propulsion System (XIPS) are studied and compared. While the XIPS prefer trajectories require lower power and longer flight times, the NEXT enable a shorter, high-powered, mission to Pluto. The effects of using different launch vehicles (including NASA's Space Launch System (SLS)) on flight time, delivered mass and propellant throughput are also studied.

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AAS 16-550

SYNCHRONIZED LUNAR POLE IMPACT AND PLUME SAMPLE RETURN TRAJECTORY DESIGN

Anthony L. Genova,* Cyrus Foster† and Tony Colaprete‡

The presented trajectory design enables two maneuverable spacecraft launched onto the same trans-lunar injection trajectory to coordinate a steep impact of a lunar pole and subsequent sample return of the ejecta plume to Earth. To demonstrate this concept, the impactor is assumed to use the LCROSS mission's trajectory and spacecraft architecture, thus the permanently-shadowed Cabeus crater on the lunar south pole is assumed as the impact site. The sample-return spacecraft is assumed to be a CubeSat that requires a complimentary trajectory design that avoids lunar impact after passing through the ejecta plume to enable sample-return to Earth via atmospheric entry.

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GUIDANCE AND CONTROL

Session Chairs:

Session 6: Morgan Baldwin

Session 19: Roberto Furfaro

The following paper was not available for publication:

AAS 16-403 Paper Withdrawn

AAS 16-205

THE CONTROL STRATEGY OF TERMINAL CORRECTION PROJECTILE BASED ON THE TRACK OF LASER SPOT

Xing-long Li,[*] Wen-jin Yao, Li-kun Zhu, Xiao-ming Wang and Ji-yan Yu

For the problem of the control strategy of semi-active laser terminal trajectory correction projectile, a strategy based on track of laser spot is proposed. By comparing the position error between the actual spot in non-rolling imaging plane and the reference spot, the missing distance between the target and the un-controlled trajectory impact point is derived, and the control strategy is obtained. With the Monte-Carlo simulations, the correction effect of a certain type of terminal correction projectile by the strategy is researched. The results indicate that, the proposed strategy can effectively reduce the miss distance, with the maximum CEP does not exceed 15m after trajectory correction, and meets the low cost and high precision requirements for smart munitions, and also it provides the theoretical basis for the realization of the project application.

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AAS 16-215

ORION ENTRY MONITOR

Kelly M. Smith*

NASA is scheduled to launch the Orion spacecraft atop the Space Launch System on Exploration Mission 1 in late 2018. When Orion returns from its lunar sortie, it will encounter Earth's atmosphere with speeds in excess of 11 kilometers per second, and Orion will attempt its first precision-guided skip entry. A suite of flight software algorithms collectively called the Entry Monitor has been developed in order to enhance crew situational awareness and enable high levels of onboard autonomy. The Entry Monitor determines the vehicle capability footprint in real-time, provides manual piloting cues, evaluates landing target feasibility, predicts the ballistic instantaneous impact point, and provides intelligent recommendations for alternative landing sites if the primary landing site is not achievable. The primary engineering challenges of the Entry Monitor is in the algorithmic implementation in making a highly reliable, efficient set of algorithms suitable for onboard applications.

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AAS 16-216

PREDICTIVE LATERAL LOGIC FOR NUMERICAL ENTRY GUIDANCE ALGORITHMS

Kelly M. Smith*

Recent entry guidance algorithm development[123] has tended to focus on numerical integration of trajectories onboard in order to evaluate candidate bank profiles. Such methods enjoy benefits such as flexibility to varying mission profiles and improved robustness to large dispersions. A common element across many of these modern entry guidance algorithms is a reliance upon the concept of Apollo-heritage lateral error (or azimuth error) deadbands in which the number of bank reversals to be performed is non-deterministic. This paper presents a closed-loop bank reversal method that operates with a fixed number of bank reversals defined prior to flight. However, this number of bank reversals can be modified at any point, including in flight, based on contingencies such as fuel leaks where propellant usage must be minimized.

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AAS 16-220

REENTRY TRAJECTORY OPTIMIZATION UNDER THE EFFECTS OF UNCERTAIN ATMOSPHERIC DENSITY AND WIND FIELD

Yuan Ren* **and Jinjun Shan†**

This paper investigates the reliability-based design optimization (RBDO) problem derived from the Earth reentry trajectory design, in which the uncertain factors of the atmospheric density, wind field, aerodynamic and structural coefficients are considered. First, the uncertain dynamic model is developed. The atmospheric density and horizontal wind filed are described by NRLMSISE-00 and HWM07 empirical models, respectively. The uncertain inputs, F10.7, F10.7|81 and Ap, of these empirical models are considered as the random design variables of RBDO. The aerodynamic and structural uncertainties are described by two random design variables. Second, by using the inverse cumulative distribution functions, the random design variables are denoted by five independent standard normal distributed variables. The profile of the control is discretized on a series of equally spaced time-nodes. The RBDO problem is introduced by adding random design variables and reliability constraints into the original deterministic optimization. The RBDO problem is solved by sequential optimization and reliability assessment (SORA) procedure, in which the deterministic optimization problem and the reliability analysis problem are solved, alternately. The differential evolution (DE) algorithm and penalty function are used to solve the constrained optimization problem and the first order reliability method (FORM) is used in the reliability analysis. Finally, a numerical example is given to demonstrate the effectiveness of the proposed technique.

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AAS 16-230

ATMOSPHERIC TRAJECTORY OPTIMIZATION OF A ROCKET REUSABLE FIRST STAGE WITH TURBOJET ENGINES

Eric Bourgeois,[*] Cédric Rommel,[†] Jean-Marc Bahu[‡] and Nicolas Praly[§]

We develop a method to take into account a turbojet engine in the trajectory optimization problem of a winged reusable launcher first stage, addressing both the dependence of thrust performance to flight conditions and the optimization of the thrust modulation. Two approaches are considered, one analytical derived from aeronautics and one numerical coming from advanced CNES rocket studies. Both of them are compared and combined to benefit from their respective assets; they are used to assess the influence of initial flight conditions on the down-range. The optimization of preceding phases (vacuum and non-thrusting aerodynamic phases) is then considered so as to perform a whole optimization of the entire return flight phase. This study is performed in the frame of CNES Future Launcher Prospective Program.

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AAS 16-245

SURROGATE MODEL FOR PROBABILISTIC MODELING OF ATMOSPHERIC ENTRY FOR SMALL NEO'S

Piyush M. Mehta,* Martin Kubicek,† Edmondo Minisci‡ and Massimiliano Vasile§

Near Earth Objects (NEOs) enter the Earth's atmosphere on a regular basis. Depending on the size, object and entry parameters; these objects can burn-up through ablation (complete evaporation), undergo fragmentation of varying nature, or impact the ground unperturbed. Parameters that influence the physics during entry are either unknown or highly uncertain. In this work, we propose a probabilistic approach for simulating entry. Probabilistic modeling typically requires an expensive Monte Carlo approach. In this work, we develop and present a novel engineering approach of developing surrogate models for simulation of the atmospheric entry accounting for drag, ablation, evaporation, fragmentation, and ground impact.

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AAS 16-273

LUNAR ENTRY DOWNMODE OPTIONS FOR ORION

Kelly M. Smith[*] and Jeremy R. Rea[†]

For Exploration Missions 1 and 2, the Orion capsules will be entering the Earth's atmosphere with speeds in excess of 11 km/s. In the event of a degraded Guidance, Navigation, and Control system, attempting the nominal guided entry may be inadvisable due to the potential for failures that result in a loss of vehicle (or crew, when crew are aboard). In such a case, a method of assuring Earth capture, water landing, and observance of trajectory constraints (heating, loads) is desired. Such a method should also be robust to large state uncertainty and variations in entry interface states. This document will explore four approaches evaluated and their performance in ensuring a safe return of the Orion capsule in the event of onboard system degradation.

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AAS 16-318

FINITE-TIME CONTROL FOR FLIGHT CLOSE TO ASTEROIDS VIA TERMINAL SLIDING-MODE GUIDANCE

Hongwei Yang,[*] Xiaoli Bai[†] and Hexi Baoyin[‡]

This paper studies guidance and control for body-fixed hovering and landing in irregular gravity with uncertainties and disturbances close to asteroids. A new terminal sliding guidance algorithm, which is suitable for asteroid both hovering and landing control, is proposed. With this new guidance, no reference trajectories are required and a spacecraft can achieve its target position and velocity in finite-time. The control is chattering free and nonsingular. The global stability is proven for the dynamical system with bounded uncertainties and disturbances. A parametric analysis is carried out to analyze the effects of the parameters of the guidance algorithm. Simulations of landing, hovering to hovering, and landing with a hovering phase before the final descent for the highly irregular asteroid 2063 Bacchus are presented and the effectiveness of the proposed method are validated.

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AAS 16-345

PRECISION ZEM/ZEV FEEDBACK GUIDANCE ALGORITHM UTILIZING VINTI'S ANALYTIC SOLUTION OF PERTURBED KEPLER PROBLEM

Jaemyung Ahn,* Yanning Guo† and Bong Wie‡

A new implementation of a zero-effort-miss/zero-effort-velocity (ZEM/ZEV) feedback guidance scheme, which utilizes the computational efficiency and accuracy of analytical orbit propagators, is proposed. Kepler's propagator and Vinti's algorithm for the solution of perturbed Kepler problem are used to predict the ZEM and ZEV state vectors and determine the acceleration command, which are often obtained by numerical integration of the equations of motion in the conventional approach. A procedure for optimal time-to-go estimation that can be used with the new guidance algorithm for intercept of moving target is introduced. The effectiveness of the proposed implementation is demonstrated by the performance comparison with the open-loop optimization approach through several case studies.

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MOVING-MASS ACTUATOR SYSTEM OPTIONS FOR ENTRY VEHICLES WITH DEPLOYABLE DECELERATORS

Kevin G. Lohan[*] and Zachary R. Putnam[†]

This study assesses internal moving-mass actuator configuration options for trajectory control in the hypersonic regime of planetary entry. Trajectory control is achieved by shifting the location of the center of gravity relative to the center of pressure to modify aerodynamic trim conditions. The vehicle is modeled as a cylinder with a deployable forebody and a moving-mass actuator that can translate along a linear track. Placing the track in the rear of the vehicle can reduce the required actuator mass fraction for a specific trim lift-to-drag ratio by up to 5%. Increasing the length of the track similarly reduces required mass fraction. Vehicle packaging density and size do not significantly influence the required actuator mass; geometric properties such as length-to-diameter ratio and the diameter of the deployable impact the required actuator mass. Using these design guidelines, and actuator mass fraction of approximately 13% is required to achieve a maximum lift-to-drag ration similar to the Mars Science Laboratory.

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AAS 16-388

A STUDY ON DECENTRALIZED AND PARALLEL CONTROL SCHEME IN FORMATION FLIGHT AND SPACECRAFT SYSTEMS

Junichiro Kawaguchi[*] and Yusuke Oki[†]

Current control schemes usually assume mutual exchange of information among whole members in a control system. This common strategy sometimes requests extremely heavy communication load, and the response tends to become very slow. In principle, there is no need to have such information to be gathered at the central facility just to make the system to be controlled, since it is, in most cases, associated only with each entity. The author devised a special type of decentralized approach excluding servers in the system consisting of plural members to be articulated. The method has only to share a limited number of information in the system, and leaves the performance of actuation to each entity that calculates and executes in parallel also independent of other members. This paper shows a typical example of the application to the formation flying that maintains relative distance uniformly, taking the priority into account based on the remaining fuel amount aboard each spacecraft. And the paper presents a few more applications to the spacecraft power and data management systems.

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AAS 16-391

ROBUSTIFICATION OF A CLASS OF GUIDANCE ALGORITHMS FOR PLANETARY LANDING: THEORY AND APPLICATIONS

Roberto Furfaro[*] and Daniel R. Wibben[†]

In this paper, we consider the problem of robustifying a class of closed-loop guidance algorithms for planetary landing. Generally, such algorithms are extremely important during the terminal powered descent phase as they are critically responsible for guiding the spacecraft to the desired location with high degree of accuracy. More specifically, we explicitly describe how sliding control theory can be employed to generate energy-optimal feedback trajectories that are robust against perturbing accelerations with a known upper bound. Indeed, we show that a properly defined sliding surface can yield an acceleration command comprising a) an energy-optimal component and b) a robust component that counteracts the effect of the perturbing accelerations. Since the acceleration command is function of time-to-go, the resulting algorithm has a very peculiar behavior, where the sliding surface moves in time during the descent phase and it is in a continuous reaching mode. Its dynamics critically affect the performance of the algorithm in terms of accuracy and fuel efficient especially in off-nominal conditions. A theoretical analysis via Lyapunov stability theory shows that such class of guidance algorithms are globally finite-time stable. Simulations show that the time-dependent sliding augmentation yields superior performances versus the non-sliding counterpart. Conversely, two alternative possible formulations of the OSG yield identical results.

[View Full Paper]

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AAS 16-407

MODEL PREDICTIVE CONTROL OF PLANETARY AEROCAPTURE USING TAKAGI-SUGENO FUZZY MODEL

Benjamin W. L. Margolis* **and Mohammad A. Ayoubi†**

In this paper, we present a control algorithm for a planetary entry vehicle during an aerocapture maneuver. The proposed algorithm utilizes the model predictive control technique with a Takagi-Sugeno fuzzy model of the vehicle to control the velocity and altitude of the entry vehicle along a specified trajectory using bank angle modulation. A Mars aerocapture case study is presented to demonstrate the stability, performance, and robustness of the proposed controller.

[View Full Paper]

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AAS 16-410

AUTONOMOUS GUIDANCE ALGORITHM FOR MULTIPLE SPACECRAFT AND FORMATION RECONFIGURATION MANEUVERS

Theodore Wahl* and Kathleen C. Howell†

Spacecraft formations operating autonomously have the potential to support a wide variety of missions. In this investigation, the creation of an autonomous guidance algorithm is explored for a formation reconfiguration maneuver involving an arbitrary number of spacecraft. The assessment process to construct a maneuver is decomposed into 2 problems: assignment and delivery. The guidance algorithm employs an auction process to assign each spacecraft a position in the formation. The guidance algorithm then uses Adaptive Artificial Potential Functions (AAPFs) to deliver each spacecraft to its target position. Ultimately, the guidance strategy requires from the user only the initial targets' states to complete the reconfiguration maneuvers.

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AAS 16-411

HYPERVELOCITY TERMINAL GUIDANCE OF A MULTIPLE KINETIC-ENERGY IMPACTOR VEHICLE (MKIV)

Joshua Lyzhoft* and Bong Wie†

This paper presents the initial preliminary study results of developing a hypervelocity terminal guidance scheme, employing visual and infrared sensors, for a non-nuclear MKIV (Multiple Kinetic-Energy Impactor Vehicle) system that can fragment or pulverize small asteroids (< 150 m) detected with short mission lead times (< 10 years). The proposed MKIV system with its total mass in the range of approximately 5,000 to 15,000 kg is comprised of a carrier vehicle (CV) and a number of attached kinetic-energy impactors (KEIs). Near to a target asteroid, the CV will dispense several KEIs and guide them to hit near-simultaneously different locations widely distributed across the target surface area and to cause shock waves to propagate more effectively through the target body. This paper is focused on developing an image processing algorithm for such coordinated terminal guidance and control of multiple KEIs. GPU-based simulations of a proposed image processing algorithm are conducted to verify the feasibility of impacting a small (< 150 m) asteroid by multiple KEIs. Noiseless as well as noisy visual and IR images are simulated using scaled polyhedron models of 433 Eros and 216 Kleopatra. Preliminary study results indicate that it is technically feasible to impact a small asteroid near-simultaneously at its multiple locations using the proposed MKIV system architecture.

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AAS 16-485

ORION EXPLORATION MISSION ENTRY INTERFACE TARGET LINE

Jeremy R. Rea*

The Orion Multi-Purpose Crew Vehicle is required to return to the continental United States at any time during the month. In addition, it is required to provide a survivable entry from a wide range of trans-lunar abort trajectories. The Entry Interface (EI) state must be targeted to ensure that all requirements are met for all possible return scenarios, even in the event of no communication with the Mission Control Center to provide an updated EI target. The challenge then is to functionalize an EI state constraint manifold that can be used in the on-board targeting algorithm, as well as the ground-based trajectory optimization programs. This paper presents the techniques used to define the EI constraint manifold and to functionalize it as a set of polynomials in several dimensions.

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AAS 16-491

MULTI-FIDELITY MODEL FUSION AND UNCERTAINTY QUANTIFICATION USING HIGH DIMENSIONAL MODEL REPRESENTATION

Martin Kubicek,[*] Piyush M. Mehta,[†] Edmondo Minisci[‡] and Massimiliano Vasile[§]

High-fidelity modeling based on experiments or simulations is generally very expensive. Low-fidelity models, when available, typically have simplifying assumptions made during the development and hence are quick but not so accurate. We present development of a new and novel approach for multi-fidelity model fusion to achieve the accuracy of the expensive high-fidelity methods with the speed of the inaccurate low-fidelity models. The multi-fidelity fusion model and the associated uncertainties is achieved using a new derivation of the high dimensional model representation (HDMR) method. The method can provide valuable insights for efficient placement of the expensive high-fidelity simulations in the domain towards reducing the multi-fidelity model uncertainties. The method is applied and validated with aerodynamic and aerothermodynamic models for atmospheric re-entry.

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AAS 16-504

SEMI-ANALYTICAL ADAPTIVE GUIDANCE COMPUTATION BASED ON DIFFERENTIAL ALGEBRA FOR AUTONOMOUS PLANETARY LANDING

Paolo Lunghi,[*] Roberto Armellin,[†] Pierluigi Di Lizia[‡] and Michèle Lavagna[§]

A novel algorithm for autonomous landing guidance computation is presented. Trajectory is expressed in polynomial form of minimum order to satisfy a set of 17 boundary constraints, depending on 2 parameters: time-of-flight and initial thrust magnitude. The consequent control acceleration is expressed in terms of differential algebraic (DA) variables, expanded around the point of the domain along the nominal trajectory followed at the retargeting epoch. The DA representation of objective and constraints give additional information about their sensitivity to variations of optimization variables, exploited to find the desired fuel minimum solution (if it exists) with a very light computational effort, avoiding less robust processes.

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AAS 16-527

REAL-TIME OPTIMAL CONTROL AND TARGET ASSIGNMENT FOR AUTONOMOUS IN-ORBIT SATELLITE ASSEMBLY FROM A MODULAR HETEROGENEOUS SWARM

Rebecca C. Foust,[*] Soon-Jo Chung[†] and Fred Y. Hadaegh[‡]

This paper presents a decentralized optimal guidance and control scheme to combine a heterogeneous swarm of component satellites, rods and connectors, into a large satellite structure. By expanding prior work on a decentralized auction algorithm with model predictive control using sequential convex programming (MPCSCP) to allow for the limited type heterogeneity and docking ability required for in-orbit assembly. The assignment is performed using a distributed auction with a variable number of targets and strict bonding rules to address the heterogeneity. MPC-SCP is used to generate the collision-free trajectories, with modifications to the constraints to allow docking.

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ATTITUDE DYNAMICS AND CONTROL

Session Chairs:

Session 9: Stefano Casotto

Session 13: Maruthi Akella

The following paper was not available for publication:

AAS 16-503 Paper Withdrawn

AAS 16-290

FAST AUTONOMOUS THREE-AXIS CONSTRAINED ATTITUDE PATHFINDING AND VISUALIZATION FOR BORESIGHT ALIGNMENT

Sergei Tanygin*

A new algorithm suitable for fast on-board implementation is presented for designing attitude maneuver paths that achieve desired boresight alignment in the presence of multiple three-axis attitude constraints. It is based on a recently proposed algorithm in which possible attitudes are discretized in a three-dimensional distortion-minimizing projected space. In that space grid points are enumerated and graph search pathfinding algorithms are employed to find the shortest constrained path between selected initial and target grid points. The new algorithm extends this approach from a single target point to a continuum of target points representing all possible attitudes that maintain the desired boresight alignment. It augments the original algorithm with the transformation that makes it possible to assign a single value to estimated distances for the whole continuum of target points. This, in turn, allows the pathfinding algorithms to efficiently determine the shortest overall path to the whole continuum, which corresponds to the shortest attitude maneuver path that achieves the desired boresight alignment.

[View Full Paper]

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CONSTRAINT FORCE ALGORITHM FOR DYNAMICS MODELING OF MULTIBODY SPACECRAFT IN ARBITRARY TOPOLOGY

Fei Liu,[*] Quan Hu,[†] Jingrui Zhang,[‡] Xiaoyu Chu,[§]
Youyi Wang,[**] Wenbo Li[††] and Liang Tang[‡‡]

The magnitudes of the constraint forces at the joints in a multibody spacecraft are critical parameters in designing the joints structure. Therefore, it is desirable to efficiently calculate the constraint forces in the dynamics simulation. In this work, a modified constraint force algorithm (MCFA) for dynamics of arbitrary multibody spacecraft is developed. The constraint forces can be directly obtained when solving for the system's motion. The MCFA is applicable to an arbitrary multibody spacecraft in tree topology or with closed-loop structures. The accuracy of MCFA is validated through numerical simulations of a space robot with multiple manipulators.

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AAS 16-337

FUZZY ATTITUDE CONTROL OF SOLAR SAIL WITH TRANSLATING CONTROL MASSES VIA LINEAR MATRIX INEQUALITIES

Joshua Baculi* and Mohammad A. Ayoubi†

We present a fuzzy model-based attitude controller for a solar-sail. First, a Takagi-Sugeno fuzzy model of solar-sail is derived based on the existing equations of motion. Then, by using the Parallel Distributed Compensation technique, a nonlinear fuzzy control law is developed. To estimate the unmeasurable states, a T-S fuzzy observer is considered. The proposed fuzzy controller/observer stabilizes the attitude of the solar-sail about the commanded input. Using the heuristic Ziegler-Nichols tuning technique, we propose a PID controller to examine and compare the stability and performance of the proposed T-S fuzzy controller/observer. In the end, the robustness of the proposed controller/observer is examined in the presence of uncertainties in the solar-sail's principle moments-of-inertia.

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AAS 16-340

STRATEGY AND ALGORITHM STUDY ON EVASION OF INCIDENT LIGHT OF SUN AND MOON FOR STAR TRACKER

Haiyong Wang,* Jingjin Li† and Tianmu Qin‡

To prevent the potential damage caused by strong light sources especially the sun to the imaging chip, a geometrical analytic method to evade incident sunlight and moonlight is proposed to get a command attitude or direction. First, the sun and the moon direction vectors at the observing time are calculated according to the astronomical equations. Then, by analyzing the vector distribution among the sun, the moon, the geocenter and the boresight of star tracker, all of the probable distributing situations are sorted into three. Under each situation an equation set to calculate the expected boresight direction is given, which covers all of the necessary vectors and exclusion angle parameters. Finally, the simulating tests are conducted based on the STK database scenarios, the results show that the strategy and the geometric analytic algorithm succeed in evading the incident light from the sun and the moon, as well as the part underneath geographic horizon. This strategy could be helpful for research groups confronted with the same adverse situation of sunlight and moonlight interference to star trackers.

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AAS 16-352

DYNAMICALLY SCALED IMMERSION AND INVARIANCE APPROACH FOR SPACECRAFT ATTITUDE TRACKING CONTROL

Sungpil Yang* and Maruthi R. Akella†

This paper addresses the rigid-spacecraft attitude tracking problem when model parameters are unknown but the lower bound of the smallest eigenvalue of the inertia matrix is known. Using the dynamic scaling method, Immersion and Invariance (I&I) adaptive controllers are proposed without employing a filter for the regressor matrix. A scalar scaling factor is implemented either in the control law for the filter-free design or in the filter dynamics for the filter-dependent controller to overcome the integrability obstacle that arises in I&I adaptive control design. First, a filter-free controller is proposed such that the rate feedback gain is proportional to the square of the scaling factor in the tracking error dynamics. Then the gain is shown to be bounded through the state feedback while achieving stabilization of the tracking errors. Since the dynamic scaling factor increases monotonically by design, it may end up with a finite but arbitrarily large value. However, by introducing three more dynamic equations, the non-decreasing scaling factor is removed from the closed-loop system. Moreover, the behavior of dynamic gain is controlled by design parameters so that its upper bound is limited by a known quantity and that the gain returns close to the initial value eventually. The similar approach for the dynamic gain design is also applied to the filter-dependent controller where the filter for the angular rate is utilized to build a parameter estimator. The performances of both controllers are demonstrated through simulations.

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AAS 16-354

USING SHIFTING MASSES TO REJECT AERODYNAMIC PERTURBATIONS AND TO MAINTAIN A STABLE ATTITUDE IN VERY LOW EARTH ORBIT

Josep Virgili-Llop,[*] Halis C. Polat[†] and Marcello Romano[‡]

The aerodynamic forces are the main orbital and attitude perturbations at very low orbital altitudes (≤ 450 km). To minimize them, it is desirable to design spacecraft with their center-of-mass (CoM) as close as possible to the spacecraft's center-of-pressure (CoP). Design constraints, poorly understood aerodynamics and environment variability, prevent this CoP and CoM match. The use of internal shifting masses, actively changing the location of the spacecraft CoM, and thus modulating, in direction and in magnitude, the aerodynamic torques is proposed as a method to reject these disturbances. First, the equations of motion of a spacecraft with internal moving parts are revisited. The atmospheric environment and the aerodynamic properties of a spherically shaped spacecraft are then provided. A single-axis controller is used to analyze the disturbance rejection capability of the method with respect to several parameters (shifting mass, shifting range and altitude). This analysis shows that small masses and a limited shifting range suffice if the nominal CoM is relatively close to the estimated CoP. For the full three rotational degrees-of-freedom analysis, a quaternion feedback controller and a Linear Quadratic Regulator are used. Finally, a practical implementation on a 3U CubeSat using commercial-off-the-shelf components is provided, demonstrating the technological feasibility of the proposed method.

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AAS 16-398

ATTITUDE CONTROL ACTUATOR DESIGN WITH MAGNETORHEOLOGICAL FLUID RINGS

Dongeun Seo[*] and Yongho Lee[†]

In this paper, a new application of magnetorheological (MR) fluid is proposed as an active ring actuator for the spacecraft attitude control system (ACS). By regulating the magnetic field around the MR fluid ring, a wide range of the viscoelastic property change can be achieved, which is not available to conventional passive/active fluid ring actuators. Computational fluid dynamics simulations reveal that the MR fluid produces, at certain conditions, a significant amount of increment in friction. Further, due to the characteristics of MR fluid, the MR fluid ring actuator may act in the range from the solid to the highly viscous fluid state. A time-varying but uniform magnetic field is assumed during the development of the ACS model. The dynamical properties of the proposed MR ring design are investigated by focusing on the effect of the applied magnetic field in the dynamical response of the simple ring system. In order to demonstrate the potential of the proposed actuator, numerical simulations are performed and compared with conventional passive fluid ring actuators.

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AAS 16-429

ATTITUDE ERROR KINEMATICS: APPLICATIONS IN CONTROL

Ahmad Bani Younes* and Daniele Mortari†

Several attitude error representations are presented for describing the tracking orientation error kinematics. Compact forms of attitude error kinematics are derived for each representation. The attitude error is initially defined as rotational error between the current and the reference orientation. The development of nonlinear kinematic models enables arbitrarily large relative rotations and rotation rates for several standard attitude representations. An optimal tracking control is developed where the optimal control is calculated by optimizing a universal quadratic penalty function. An open-loop optimal nonlinear control spacecraft maneuver is solved first for reference motion. The tracking error is defined yielding a nonlinear error dynamics in a compact form. Two distinct approaches to attitude error kinematics are presented. The first one is that the reference and current angular velocity vectors are defined in the same axes frame while in the second one is defined in the different attitude axes frame. By utilizing several attitude error kinematics methodologies to describe the spacecraft rotation error, we introduce a universal quadratic penalty function of tracking errors that is consistent in each of the coordinate choices and removes the dependency on the attitude coordinate choice.

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AAS 16-451

MINIMUM ENERGY, REACTION-WHEEL BASED, CUBESAT ATTITUDE CONTROL: A COMPARISON OF COST FUNCTIONS

Dmitriy Rivkin* and Gabriel Elkaim†

A Legendre pseudospectral method is used to solve the minimum energy reorientation problem for a 3U Cubesat with three orthogonal reaction wheels. Optimization is performed with respect to a cost functional that represents battery energy losses, and includes terms arising from resistive losses in the armature resistance, friction in the bearings, and mechanical kinetic energy, which is unrecoverable in the absence of a regenerative braking system. To overcome numerical challenges associated with this cost functional, an approximation method is used. Results are compared with those obtained using the convenient "integral of control torque squared" cost functional, and it is shown that, if the ratio between the moments of inertia of the satellite body and the reaction wheels is large, optimization with respect to the convenient cost functional does not produce an energy-optimal solution.

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AAS 16-458

ATTITUDE ERROR KINEMATICS: APPLICATIONS IN ESTIMATION

Ahmad Bani Younes[*] and Daniele Mortari[†]

Several attitude error representations are presented for describing the orientation error kinematics. Compact forms of attitude error kinematics are derived for each representation. The attitude error is initially defined as rotational error between the current and the reference orientation. The development of nonlinear kinematic models enables arbitrarily large relative rotations and rotation rates for several standard attitude representations. Two distinct approaches to attitude error kinematics are developed. In the first one the estimated angular velocity is defined in the true attitude axes frame while in the second one is defined in the estimated attitude axes frame. The first approach is of interest in simulation, where the true attitude is known, while the second approach is for real estimation/control applications. Two nonlinear kinematic models are derived that are valid for arbitrarily large rotations and rotation rates. The development of Multiplicative Kalman Filter (MKF) using the Gyro model has been revised. By utilizing several attitude error kinematics methodologies to describe the spacecraft rotation error, we introduce different compact and efficient forms of Multiplicative Kalman Filter (MKF). The results presented are expected to be broadly useful to nonlinear attitude estimation filtering formulations. A discussion of the benefits of the derived error kinematic models is included.

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AAS 16-462

STOCHASTIC MODELING OF HYPERVELOCITY IMPACTS ON ATTITUDE PROPAGATION OF SPACE DEBRIS

Luc B. M. Sagnières[*] and Inna Sharf[*]

Bombardment of orbital debris and micrometeoroids on active and inoperative satellites is becoming an increasing threat to space operations and has significant consequences on space missions. Concerns with orbital debris have led agencies to start developing debris removal missions and knowing a target's rotational parameters ahead of time is crucial to the eventual success of such a mission. A new method is proposed, enabling the inclusion of hypervelocity impacts into spacecraft attitude propagation models by considering the transfer of angular momentum from collisions as a stochastic jump process. In order to assess the importance of collisions on attitude propagation, the developed model is applied to two categories of space debris by using impact fluxes from ESA's Meteoroid and Space Debris Terrestrial Environment Reference (MASTER) model.

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AUTOMATED SPHERE GEOMETRY OPTIMIZATION FOR THE VOLUME MULTI-SPHERE METHOD

Philip Chow,[*] Joseph Hughes,[*] Trevor Bennett[*] and Hanspeter Schaub[†]

The Volume Multi Sphere Method (VMSM) is a recent method for approximating the electrostatic forces and torques acting on a spacecraft. VMSM reduces the conducting spacecraft shape to a collection of equipotential spheres spread throughout the spacecraft volume. The location and size of these spheres are dependent on the spacecraft geometry being modeled. Prior work illustrates the existence and prospect of this VMSM approach on a cylinder, but it took considerable hand tuning to arrive at a suitable VMSM solution. This paper investigates the VMSM setup process itself. In particular, a modified VMSM optimization approach is presented which seeks to avoid any time-consuming hand tuning. The symmetric cylinder problem is investigated with a range of VMSM spheres and a new capacitance constraint that significantly reduces computational time with minimal effect on accuracy.

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DEVELOPMENT OF CUBESAT ATTITUDE DETERMINATION AND CONTROL SYSTEM WITH A HYBRID CONTROL STRATEGY AND ITS SIMULATOR ON SO(3)

Dae Young Lee,[*] Hyeongjun Park[†] and James W. Cutler[‡]

An active attitude determination and control system (ADCS) with a hybrid control strategy is proposed and applied to the mission named CubeSat investigating Atmospheric Density Response to Extreme driving (CADRE). The payload of this satellite requires fine pointing accuracy within one degree. To accomplish this goal, pre-developed control and estimation algorithms are modified and unified into a hybrid strategy based on a finite-state machine. Each state and the transition conditions of the finite-state machine are also defined and verified through simulations. To demonstrate accurate simulation results, we develop a dynamic satellite simulator that implements a Lie Group Variational Integrator of a spacecraft with the reaction wheel assembly. Simulation results demonstrate that the active ADCS successfully performs the specified fine pointing control.

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AAS 16-511

REPETITIVE CONTROL USING REAL TIME FREQUENCY RESPONSE UPDATES FOR ROBUSTNESS TO PARASITIC POLES

Pitcha Prasitmeeboon[*] and Richard W. Longman[†]

Repetitive control (RC) can in theory completely cancel the effects of a periodic disturbance to a control system. It has application to vibration isolation of fine pointing equipment on spacecraft with vibrations caused by slight imbalance in CMGs or reaction wheels. Another spacecraft application is jitter suppression in optics for spacecraft laser communication. RC convergence require less than 90 degree model phase error at all frequencies up to Nyquist. A zero-phase cutoff filter is normally used to robustify to high frequency model error when this limit is exceeded. The result is failing to cancel errors above the cutoff. This paper investigates a series of methods to use real time data to update the frequency response model of the vibration or jitter suppression control system. These include the use of a moving window employing a recursive discrete Fourier transform (DFT), and use of a real time projection algorithm from adaptive control for each frequency. The results can be used directly to make repetitive control corrections that cancel each error frequency, or they can be used to update a repetitive control FIR compensator. A third application reduces the final error level by using real time frequency response model updates to successively increase the cutoff frequency, each time creating the improved model needed to produce convergence.

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AAS 16-515

DYNAMIC OBSERVABILITY ANALYSIS FOR ATTITUDE, ANGULAR VELOCITY, SHAPE, AND SURFACE PARAMETERS

Richard Linares[*] and John L. Crassidis[†]

This paper discusses a dynamic observability analysis for attitude, angular velocity, shape, and surface parameters of Space Objects (SOs) using non-resolved images or light curve measurements. The Fisher information matrix and Cramér-Rao lower bound are introduced for calculating the observability of parameters used in SO models. Light curve measurements are known to be functions of SO rotational states, shape geometry, and surface parameters. This dependency is captured in the bidirectional reflectance distribution functions models. The rotational dynamics of SOs can be difficult to model due to the fact that external and/or control torques are unknown. This work assumes that these torques are known, and under this assumption dynamic observability is analyzed. An illustrative two-dimensional example is considered. This example consists of a simplified system with one angle and one angle rate to model the rotational dynamics of the SO. The Cramér-Rao lower bound is used to study the effects of geometry on estimation performance. It was found that as the number of sides increases, and the SO shape tends to an axially symmetric one, the observability in the attitude estimates are lost. Finally, the Cramér-Rao lower bound is compared with actual performances from estimation approaches for estimating the attitude of an SO.

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AAS 16-532

CROSS FERTILIZATION BETWEEN ITERATIVE LEARNING CONTROL AND REPETITIVE CONTROL

Jianzhong Zhu[*] and Richard W. Longman[†]

The Repetitive Control (RC) and Iterative Learning Control (ILC) are methods to converge to zero tracking error in feedback control systems. ILC applies to repeated tasks, RC eliminates error following periodic commands or from periodic disturbances. Spacecraft applications include vibration isolation of fine pointing equipment. The objectives are similar, but ILC is a finite time problem, RC asks for zero error asymptotically, making control laws and stability conditions significantly different. This paper investigates how ILC laws can be converted for use in RC to improve performance, and vice versa. Also robustification by control penalty is compared to a frequency cutoff.

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AAS 16-540

MODIFYING ITERATIVE LEARNING CONTROL TO INCREASE TRACKING SPEED BY MARKOV PARAMETER UPDATES

Bing Song [*] **and Richard W. Longman** [†]

Similar to humans learning through repetitions of a task, iterative learning control (ILC) learns from previous experience executing a desired tracking maneuver. It observes the error in the current run, and adjusts the command to a feedback controller in the next run. Spacecraft applications include repeated maneuvers of scanning sensors. Some human learning tasks try to learn to track a trajectory as fast as possible. This paper aims to expand ILC methods to not only track the desired trajectory, but also learn to execute the trajectory faster. This raises the frequency content of the trajectory and can excite residual modes or parasitic poles, requiring one to create updated models as one learns. Various effective ILC laws use the system Markov parameters as a model. The recommended model update method from data during iterations is to identify the Markov parameters of an observer. This compresses the number of parameters needed, and allows one to construct as many system parameters as needed. The methods developed can produce high tracking accuracy when the trajectory is too fast for feedback control to be effective. It can also be used to keep learning transients small so that constraints are not violated during the learning process.

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AAS 16-541

MODIFIED HYBRID MODELING TECHNIQUE FOR FLEXIBLE SPIN-STABILIZED SPACECRAFT APPLIED TO NASA'S MAGNETOSPHERIC MULTISCALE (MMS) MISSION TABLESAT GENERATION IC (TABLESAT IC)

Christopher Hashem* **and May-Win L. Thein†**

This continued research uses a hybrid dynamic algorithm to mathematically model the attitude dynamics of a flexible spacecraft. The algorithm uses Euler's rigid body equation to propagate the dynamics of the spacecraft bus while finite element analysis is used to calculate the flexible boom displacements and update the systems mass moment of inertia tensor. This algorithm is iterative and should accurately model the system while still being computationally reasonable. Preliminary simulation results reveal that the hybrid algorithm produces qualitatively sufficient modeling results, although singularities do appear and are a part of further study.

[View Full Paper]

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AAS 16-549

HARDWARE IN LOOP SIMULATION FOR ATTITUDE DETERMINATION AND CONTROL OF ILLINISAT-2 BUS

Vedant,[*] Erik Kroeker,[†] Patrick Haddox[†] and Alexander Ghosh[‡]

The University of Illinois is developing the IlliniSat-2 bus which uses magnetometers and magnetorquers for attitude determination and control. To validate the attitude determination and control system (ADCS), a hardware-in-loop simulation package (CubeSim) was developed. CubeSim consists of a tri-axial Helmholtz cage driven by a custom power supply. The CubeSim software propagates the satellite's orbit and attitude state and the corresponding Earth magnetic field is output to the Helmholtz cage to be detected by a magnetometer. The satellite's attitude determination software estimates the spacecraft attitude from magnetic field measurements from the magnetometer as well as other sensors simulated in software. The satellite's attitude control program outputs a commanded torque to the control system which is used as an input to CubeSim. CubeSim then propagates the satellite's state and orbit again. This paper describes the setup of CubeSim and demonstrates testing of different magnetic attitude determination and control strategies using CubeSim.

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DYNAMICS AND PERTURBATIONS

Session Chairs:

Session 8: Diane Davis

Session 21: Felix Hoots

AAS 16-263

RE-ENTRY PREDICTION AND ANALYSIS USING TAYLOR DIFFERENTIAL ALGEBRA

Vincent Morand,* Jean Claude Berges, Valentin Guinet, Emmanuel Bignon† and Pierre Mercier

Taylor Differential Algebra (TDA) is one of many uncertainty propagation techniques an engineer can use in order to understand how the result of its computation is sensitive to initial conditions or parameters. CNES conducted a two-year research and technology action to study the benefits of using TDA in two specific cases: long term orbit propagation for lifetime estimation and re-entry trajectory computation for casualty-risk evaluation. The papers gives the results of this R&T action, experience feedback as well are concrete examples are detailed.

[View Full Paper]

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AAS 16-265

NONLINEAR UNCERTAINTY PROPAGATION IN ASTRODYNAMICS: COMPARING TAYLOR DIFFERENTIAL ALGEBRA WITH MONTE-CARLO ON GPUS

Mauro Massari,[*] Pierluigi Di Lizia[†] and Mirco Rasotto[‡]

In this paper two approaches for nonlinear uncertainty propagation in astrodynamics are compared. The first approach is based on Taylor Differential Algebra and is aimed at the improvement and generalization of standard linear methods. The second approach is aimed at increasing the computational performances of classical Monte-Carlo simulations exploiting their intrinsic parallel structure and taking advantage of the massively parallel architecture of modern GPUs. The two proposed approaches are applied to test cases considering both simple two-body dynamics and full n-body dynamics with JPL ephemeris. The results of the propagations are thoroughly compared with particular emphasis on the computational performances.

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AAS 16-279

ON THE ASTRODYNAMICS APPLICATIONS OF WEIERSTRASS ELLIPTIC AND RELATED FUNCTIONS

Dario Izzo[*] and Francesco Biscani[†]

Weierstrass elliptic and related functions have been recently shown to enable analytical explicit solutions to classical problems in astrodynamics. These include the constant radial acceleration problem, the Stark problem and the two-fixed center (or Euler's) problem. In this paper we review the basic technique that allows for these results and we discuss the limits and merits of the approach. Applications to interplanetary trajectory design are then discussed including low-thrust planetary fly-bys and the motion of an artificial satellite under the influence of an oblate primary including J_2 and J_3 harmonics.

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AAS 16-301

SSL COMMERCIAL GEOSYNCHRONOUS SPACECRAFT ORBIT RAISING CONSIDERATIONS

Gregory Lemieux[*] and Andrew E. Turner[†]

In a typical year more than five geosynchronous (GEO) spacecraft built by SSL for various customers are orbited by a variety of launch vehicles, a rate which has been maintained for decades. The spacecraft are first injected into Geosynchronous Transfer Orbit with apogee in the vicinity of GEO altitude, perigee at a low altitude and a typical inclination of 6˚ or 27˚. The orbit raising activities to insert the spacecraft into its assigned GEO slot are reviewed and historical launch data is presented and discussed.

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AAS 16-313

GPU-ACCELERATED COMPUTATION OF SRP AND DRAG FORCES AND TORQUES WITH GRAPHICAL ENCODING OF SURFACE NORMALS

Sergei Tanygin* **and Gregory M. Beatty†**

The forces and torques due to atmospheric drag and solar radiation pressure (SRP) acting on complex and articulated space objects are efficiently calculated by utilizing the highly parallelized hardware available in commodity desktop PC graphics processing units. The calculations are performed by combining traditional OpenGL rendering of 3D models with general-purpose computing on graphics processing units (GPGPU) techniques via OpenCL. In cases when the forces and torques include contributions that depend on surface normals, their directions are encoded as pseudo-colors which allows OpenCL kernel methods to efficiently unpack this additional information and perform the necessary computations. By utilizing the highly parallelized processing units available in commodity GPUs, the time required run the calculations is significantly reduced.

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AAS 16-315

DEVELOPMENT OF A HIGH PRECISION SIMULATION TOOL FOR GRAVITY RECOVERY MISSIONS LIKE GRACE

Florian Wöske,* Takahiro Kato,† Meike List† and Benny Rievers†

This paper presents the advantages of variable precision data types and the limits of the standard double data type in terms of achievable accuracy for orbit propagation. Exemplary, gravimetry missions using low-low satellite-to-satellite tracking determine the distance between satellites at a very high accuracy. For the simulation of reasonable relative orbit and system data the accumulated numerical errors should be kept beneath the measurement device accuracy. It is shown, that the standard double data type is a limiting factor for the purpose of high precision orbit modeling. It is possible to drop the achieved accuracy limit of simulations using double data type by introducing enhanced precision data types. We present a study of the behavior of commonly used Runge-Kutta and Adams-Bashforth-Moulton multistep integration methods which are adapted for the processing of data types with arbitrary precision. Results are obtained and discussed for simple Keplerian case as well as for high fidelity gravity models, utilizing a GRACE orbit. The influence of the order of the applied method and the chosen step size is analyzed with respect to accuracy, efficiency, and data type precision.

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ANALYTIC HIGH-ORDER REVERSION OF SERIES SOLUTION ALGORITHM FOR SOLVING LAMBERT'S PROBLEM

James D. Turner* and Ahmad Bani Younes†

This work presents a high-order perturbation expansion method for solving Lambert's problem. The necessary condition for the problem is defined by a third-order Taylor expansion of the terminal error vector. The Taylor expansion partial derivative models are generated by Computational differentiation tools. Two approached are presented for numerically computing the tensor-valued partial derivative models. Analytic coefficient solutions are presented for the perturbation expansion are recovered by introducing an artificial expansion variable, which is used as an ordering parameter for sorting out the contributions of individual non-linear terms. A third-order series solution is assumed for solving the problem, where the artificial perturbation parameter is the expansion variable. Numerical results are presented that compare the performance of first-, second-, and third-order expansions. The second- and third-order expansions are shown to provide accelerated convergence, when compared to a classical Newton method. One to two iterations are typically required.

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AAS 16-342

HIGH-ORDER STATE TRANSITION TENSORS OF PERTURBED ORBITAL MOTION USING COMPUTATIONAL DIFFERENTIATION

Ahmad Bani Younes[*] and James D. Turner[†]

The computation of high-order State Transition Tensors (STTs) for perturbed orbital motion using computational differentiation is presented. We first discuss the automatic differentiation tool that enables computation exact higher-order partial derivative models of the perturbed orbital motion. The perturbed two-body problem, where the earth gravity potential is the spherical harmonic Earth gravitational model, is studied. High-order gradient tensor models are required for computing the STTs model. Generating these gradient tensors is only practical by invoking the use of Computational Differentiation (CD) tools, which are briefly described. The general modeling methodology is expected to be broadly useful for science and engineering applications in general, as well as grand challenge problems that exist at the frontiers of computational science and mathematics.

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AAS 16-351

QUANTIFICATION OF THE PERFORMANCE OF NUMERICAL ORBIT PROPAGATORS

Hodei Urrutxua,* Javier Roa,† Juan Luis Gonzalo,†
Jesús Peláez‡ and Claudio Bombardelli§

The characterization of the performance of numerical orbit propagation methods is addressed using performance curves. A systematized algorithmic approach is presented to compute the performance curves, identify the linear and non-linear regimes, and parameterize the linear zone. Also, the performance index concept is introduced, which aims to reduce the meaningful information of a performance curve (ultimately, the performance of the propagation method) into a single figure of merit. Several such performance indices are proposed.

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AAS 16-353

IMPACT OF THE INTEGRATION STOP-CONDITION ON THE ACCURACY OF REGULARIZED ORBIT FORMULATIONS

Hodei Urrutxua,* Jesús Peláez† and Claudio Bombardelli‡

The tight relationship between the stop-condition of a numerical integrator and the resulting accuracy of regularized orbit propagators is addressed. It is noted that the use of events as a means to halt the numerical orbit propagation introduces timing or phasing errors in formulations involving a Sundman transformation. The fundamentals of this timing error are described, along with the mechanisms that produce this apparent loss in the achievable accuracy. This behavior is linked to the dynamical instabilities of the orbital motion. Examples are provided to support that the purely geometrical description provided by regularized methods is typically orders of magnitude more accurate than when the timing error is taken into account.

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AAS 16-382

A CONSTANT, RADIAL, LOW-THRUST PROBLEM INCLUDING FIRST ORDER EFFECTS OF J_2

Hodei Urrutxua[*] and Martín Lara[†]

Perturbation effects due to the Earth's oblateness are incorporated to the constant radial thrust problem. It is demonstrated that if the thrust remains small, and up to first order of J_2, these effects do not modify the integrability of the problem. The accuracy of the presented formulation is explored as a function of the oblateness, the radial thrust and the initial conditions.

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AAS 16-420

IMPROVING THE ACCURACY OF ORBIT LIFETIME ANALYSIS USING ENHANCED GENERAL PERTURBATIONS METHODS

Emma Kerr[*] and Malcolm Macdonald[†]

The general perturbations method for orbit lifetime analysis developed by the authors is improved by using spacecraft orbit decay tracking data to inform orbit lifetime predictions. This data is used to derive input parameters such as mass, and drag coefficient in order to make the method independent from error in these inputs, which can be a major source of error in orbit lifetime predictions. These derived inputs are then used to generate more accurate predictions while still maintaining the speed of the original method. The accuracy of the new method is validated against the authors' original method and historical data.

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AAS 16-438

B-PLANE VISUALISATION TOOL FOR UNCERTAINTY EVALUATION

Francesca Letizia,[*] Camilla Colombo,[†] Jeroen P. J. P. Van den Eynde[‡] and Rüdiger Jehn[§]

Launchers used for interplanetary missions may be inserted into orbits in resonance with the Earth or that may to cross other planets' orbits. To verify the compliance with planetary protection requirements, the impact of the uncertainty on the trajectory evolution is assessed and two visualisations are produced. The first one is the common representation of the trajectory distribution on the Earth b-plane, highlighting also areas of gravitational interactions with other bodies. The second one represents a colour map of different states (i.e. impact with the Earth, resonances, interaction with other planets) on the grid of velocity variation used to define the initial conditions.

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AAS 16-497

ADAPTIVE TWO-POINT BOUNDARY VALUE PROBLEM TOOL FOR ACCURATE AND EFFICIENT COMPUTATION OF PERTURBED ORBIT TRANSFERS

Robyn M. Woollands,[*] Julie L. Read,[*] Austin B. Probe[†] and John L. Junkins[‡]

We have developed a parallel compiled code tool that combines several of our recently developed methods for solving the perturbed Lambert problem using Modified Chebyshev Picard Iteration (MCPI). This tool consists of four individual algorithms, each of which is unique and better suited for solving a particular type of orbit transfer than the others. The first uses the standard MCPI two-point boundary value problem (TPBVP) solver and converges over about one third of an orbit. The second uses the Method of Particular Solutions (MPS) and Picard iteration for solving multi-revolution two-impulse transfers. The third is similar to the first but is capable of solving optimal control low thrust transfers. This algorithm is also convergent over about one third of an orbit. The fourth is again similar to the second but here we use MPS in six dimensions to solve the optimal control problem over multiple revolutions. In this paper we present four example test cases to demonstrate the accuracy and efficiency of our TPBVP algorithm compared with a Newton-type shooting method where RK12(10) is used as the numerical integrator. In all four cases our algorithm is more efficient while maintaining machine precision accuracy.

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AAS 16-500

HIGH GEOMETRIC FIDELITY MODELING OF SOLAR RADIATION PRESSURE USING GRAPHICS PROCESSING UNIT

Patrick W. Kenneally[*] and Hanspeter Schaub[†]

This paper presents a method for the fast computation of spacecraft force and torque due to solar radiation pressure (SRP). The method uses the highly parallel execution capabilities of commodity Graphics Processing Unit (GPU) and the Open Graphics Library (OpenGL) vector graphics software library to render a Computer Aided Design (CAD) generated spacecraft model on the GPU. The SRP forces and torques are resolved per model facet in the custom-developed render pipeline. Material properties are encoded with the model to provide realistic specular, diffuse and absorption surface light interactions.

[View Full Paper]

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AAS 16-520

MONTE CARLO PROPAGATION OF ORBITAL ELEMENTS USING MODIFIED CHEBYSHEV PICARD ITERATION

Julie L. Read,[*] Tarek A. Elgohary,[†] Austin B. Probe[*] and John L. Junkins[‡]

Prior works have shown promising efficiency while propagating perturbed two-body motion using orbital elements combined with a novel integration technique. While previous studies show that Modified Chebyshev Picard Iteration (MCPI) is a powerful tool used to propagate position and velocity, instead using orbital elements to propagate the state vector reduces the number of MCPI iterations required, which is especially useful for reducing the computation time when including computationally-intensive calculations such as Spherical Harmonic gravity, and it also converges for a larger number of revolutions using a single segment (up to 17 orbits compared with 3 orbits for the cartesian, fully spherical harmonic low-Earth orbit case). Results for the Classical Orbital Elements and the Modified Equinoctial Orbital Elements (the latter provides singularity-free solutions) show that state propagation using these variables is inherently well-suited to the propagation method chosen. The present study incorporates a Monte Carlo analysis using a local Taylor Series model that reduces the computational time and provides a high-accuracy solution for propagating the Modified Equinoctial Orbital Elements both in serial and in parallel on a compute cluster.

MCPI is an iterative numerical method used to solve linear and nonlinear, ordinary differential equations (ODEs). It is a fusion of orthogonal Chebyshev function approximation with Picard iteration that approximates a long-arc trajectory at every iteration. Previous studies have shown that it outperforms the state of the practice numerical integrators of ODEs in a serial computing environment; since MCPI is inherently massively parallelizable, this capability increases the computational efficiency of the method presented.

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AAS 16-542

ANALYTIC CONTINUATION POWER SERIES SOLUTION FOR THE TWO-BODY PROBLEM WITH ATMOSPHERIC DRAG

Kevin Hernandez,[*] Tarek A. Elgohary,[†]
James D. Turner[‡] and John L. Junkins[§]

In this paper the two-body problem with atmospheric drag is considered. A cannonball drag model is utilized and the problem is solved with the analytic continuation power series technique. Recent developments of the method have made it possible to sum the series to arbitrary order enabling machine precision power series solutions for the two-body problem and the zonal gravitational perturbations. Based on these recent developments a simple drag model is considered and the corresponding recursion formulas are derived and presented. Additionally, the method will be evaluated in terms of computational cost and accuracy including a sensitivity analysis to the method parameters (number of terms in the series and step size control).

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ORBITAL DEBRIS AND SPACE ENVIRONMENT

Session Chair:

Session 10: Thomas Starchville

The following papers were not available for publication:

AAS 16-330 Paper Withdrawn

AAS 16-386 Paper Withdrawn

AAS 16-233

USING SPACE POPULATION MODELS TO GENERATE REPRESENTATIVE SPACE OBJECT CATALOGS

Daniel L Oltrogge[*] and Vitali Braun[†]

A method is presented for generating Resident Space Object (RSO) catalogs which include RSOs smaller than those currently included in today's RSO catalogs. Such catalogs can be very useful in assessing anticipated sensor performance, throughput and coverage for new sensor concepts, locations and phenomenologies than those in use today. The method is general and supports RSO catalog creation down to any specified minimum or maximum fragment size. As an example, the method is invoked to generate both LEO-crossing and GEO-crossing RSO catalogs containing the representative population for all RSOs larger than 2 cm in size. The method's only assumptions are that at any altitude of interest, (1) the 2-dimensional PDF distribution at that same altitude of semi-major axis versus eccentricity derived from today's public catalog is representative of such distributions for smaller object sizes; and (2) the proportion of prograde-to-retrograde orbits is also representative.

[View Full Paper]

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AAS 16-240

RE-ENTRY PREDICTION OF SPENT ROCKET BODIES IN GTO

David Gondelach,[*] Aleksander Lidtke,[†] Roberto Armellin,[†]
Camilla Colombo,[†] Hugh Lewis,[†] Quirin Funke[‡] and Tim Flohrer[‡]

Spent upper stages are bodies consisting of components likely to survive re-entry, for example propellant tanks. Therefore, the re-entry of upper stages might be associated with high on-ground casualty risk. This paper presents a tool for re-entry prediction of spent rocket bodies in GTO based exclusively on Two Line Element set (TLE) data. TLE analysis and filtering, spacecraft parameters estimation, and combined state and parameters estimation are the main building blocks of the tool. The performance of the tool is assessed by computing the accuracy of the re-entry prediction of 92 GTO objects, which re-entered in the past 50 years.

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AAS 16-254

EVALUATION OF NET CAPTURE OF SPACE DEBRIS IN MULTIPLE MISSION SCENARIOS

Eleonora M. Botta,[*] Inna Sharf[†] and Arun K. Misra[‡]

One proposed method to mitigate the space debris problem is to actively capture and remove debris by means of tether-nets. In this paper, the effectiveness of the capture maneuver in multiple net deployment and debris tumbling conditions is evaluated. The sensitivity study is performed by means of simulations based on a lumped-parameter modeling approach with inclusion of bending stiffness for the net, a rigid body model for the debris, and regularized contact dynamics to represent all relevant impact and contact conditions. The effectiveness of capture is evaluated by inspection of the simulation results, to identify preferred capture conditions.

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AAS 16-278

MISSION DESIGN AND DISPOSAL METHODS COMPARISON FOR THE REMOVAL OF MULTIPLE DEBRIS

Lorenzo Casalino[*] and Dario Pastrone[†]

In this paper, detailed mission design for multiple debris removal is performed by selecting the most favorable sequences of the objects to be removed. Debris among a population with similar inclination values are considered. An approximate analysis, based on the use of J2 effect to minimize propellant consumption, provides accurate estimations of actual transfer times and ΔV between any debris pair in order to evaluate the costs of any possible sequence. The mass of the removal kit for any debris is evaluated, based on debris orbit and mass, and on the selected removal method. The overall mission mass budget is thus evaluated. All the possible sequences are compared by means of this fast procedure and the best opportunities in terms of mass and mission time are selected. Transfer trajectories are verified by a local search module, which evaluates rendezvous transfers between two given orbits taking J2 perturbation into account for an accurate evaluation of the mission costs. Up to four impulses are considered for the transfer between debris pairs.

[View Full Paper]

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AAS 16-406

A SMOOTH AND ROBUST HARRIS-PRIESTER ATMOSPHERIC DENSITY MODEL

Noble Hatten[*] and Ryan P. Russell[†]

The modified Harris-Priester model is a computationally inexpensive method for approximating atmospheric density in the thermosphere and lower exosphere – a vital step in low-Earth orbit trajectory propagation. This work introduces a revision, dubbed cubic Harris-Priester, which ensures continuous first derivatives, eliminates singularities, and adds a mechanism for introducing smooth functional dependencies on environmental conditions. These changes increase the accuracy, robustness, and utility of the model, particularly for preliminary propagation, estimation, and optimization applications in which fast, reasonably accurate force models and sensitivities are desirable. Density results and computational efficiency are compared to other density models.

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AAS 16-416

ROTATIONAL DYNAMICS OF THE GOES 8 AND GOES 10 SATELLITES DUE TO THE YORP EFFECT

Antonella A. Albuja,[*] Rita L. Cognion,[†] William Ryan,[‡] Eileen V. Ryan[§] and Daniel J. Scheeres[**]

The Yarkovsky-O'Keefe-Radzievskii-Paddack (YORP) effect is a proposed explanation for the observed rotation behavior of inactive satellites in Earth orbit. This paper propagates the rotational dynamics of the GOES 8 and GOES 10 satellites and compares the simulated rotation periods to the observed rotation periods. The observations of each satellite are taken over a few months, therefore, the short period terms are included in the propagation of the satellite's rotational dynamics. The comparison between YORP theory and the observed changes in rotation rate for both satellites show that the YORP effect could be the cause for the observed behavior.

[View Full Paper]

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AAS 16-430

STRUCTURE AND EVOLUTION OF A DEBRIS CLOUD IN THE EARLY PHASES

Liam Healy,[*] Scott Kindl,[*] Eric Rolfe[*] and Christopher Binz[*]

The early phases of a debris cloud from an instantaneous fragmentation on orbit are dominated by the effect of the two-body gravitational force on the delta-v imparted on each fragment, which gives an in-track spreading of the cloud. This spreading is seen to form radial bands opposite to the fragmentation point. The bands may be motivated by straightforward orbit mechanics. Accurate density maps are computed with the transformation of variables technique, which opens a world of *cloud dynamics* to contrast with the point dynamics of traditional astrodynamics. Structure and evolution of the bands and finer details are noted and discussed.

[View Full Paper]

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AAS 16-437

A PARTICLE FILTER FOR ORBIT DETERMINATION OF SPACE DEBRIS BASED ON MONO- AND MULTI-STATIC LASER RANGING

Christoph Bamann[*] and Urs Hugentobler[†]

Orbit determination of space debris is typically complicated by rather imprecise and ill-distributed tracking data. Mono- and multi-static laser ranging are promising techniques to overcome such issues. To properly process their precise but sparse data we present a particle filter, which fully captures system nonlinearities and is capable of considering process noise characteristics. For statistical consistency our particle filter is provided with a probabilistic initialization obtained by Monte Carlo runs of initial orbit determination (IOD). We propose a method to obtain such IOD solutions based on data from several simultaneously observing stations. Eventually, we analyze the resulting state probability density functions with regard to the considered observation techniques and tracking scenarios.

[View Full Paper]

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AAS 16-465

SPATIAL DENSITY APPROACH FOR MODELLING OF THE SPACE DEBRIS POPULATION

Camilla Colombo,[*] Francesca Letizia[†] and Hugh G. Lewis[‡]

This article proposes a continuum density approach for space debris modelling. The debris population in Low Earth Orbit (LEO) is represented through its density in semi-major axis, eccentricity and inclination. The time evolution of the density in orbital elements is modelled through the continuity equation. The perturbing effect of aerodynamic drag is included in the divergence term, while the effect of fragmentation can be seen as source term in the equation. The spatial density is then calculated from the orbital element density at each time. The proposed continuum method is used to analyse the evolution of the debris population in LEO; as initial condition the debris 2013 population is used. Then, the effect of a breakup event is superimposed onto the global population of space debris and its effect analysed; the fragment distribution caused by the breakup up of satellite DMSP-F13 is considered as test case scenario.

[View Full Paper]

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AAS 16-474

BOUNDARY MODEL FOR SATELLITE BREAKUP DEBRIS CLOUDS

Felix R. Hoots*[*] and Brian W. Hansen[†]

A satellite breakup caused by a hypervelocity impact or explosion will create a large number of debris particles. Eventually these particles spread into a shell around the Earth and can be essentially characterized as an enhancement to the existing debris background. However, prior to this complete spreading, the particles can be described more as a cloud which poses an elevated risk to any spacecraft passing through the cloud. We provide a method to rapidly characterize the size, shape and density evolution of the cloud over time.

[View Full Paper]

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SATELLITE CONSTELLATIONS

Session Chair:

Session 12: Jeff Parker

AAS 16-203

AN "ADJACENT SWATH" METHOD TO DESIGN EFFICIENT LEO CONSTELLATIONS

Thomas J. Lang*

This study examines an "Adjacent Swath" approach to minimize the maximum revisit time (MRT) for coverage of the entire earth surface using constellations of low earth orbit (LEO) satellites. Since the portion of the earth that a single satellite can cover is quite small at LEO, it is clear that many satellites will be required to achieve low values of MRT. To make this economically feasible, the satellites must be small enough that a number of them could be launched into a single orbit plane using one launch vehicle. For this reason, it is important to minimize not only the MRT for a specified number of satellites but also the number of orbit planes used in the constellation. The Adjacent Swath approach seeks to do this by arranging the satellites so that their swaths are edge-to-edge at the equator. This eliminates equatorial gaps, reduces overlapping coverage at higher latitudes, and increases constellation efficiency. The resulting constellations offer the lowest values of MRT of any found in current publications. In addition, a simple first-order method has been developed that predicts the MRT results for Adjacent Swath constellations with an accuracy of about one minute. While the current study concentrates on polar LEO orbits covering the entire globe, the same approach can be applied to non-polar orbits and coverage of the region between two latitudes.

[View Full Paper]

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AAS 16-218

OPERATIONAL CONSIDERATIONS FOR SATELLITE CONSTELLATIONS IN TUNDRA ORBITS

James R. Wilson,* Joseph W. Gangestad,†
Thomas J. Lang‡ and Chia-Chun Chao‡

Tundra constellation design and the stationkeeping costs of operating a Tundra satellite have been periodically studied by satellite constellation designers. However, there has been little research done on how constellation design affects stationkeeping costs, and vice versa. This paper synthesizes these two distinct design points to inform the overall design of a Tundra satellite constellation. Coverage patterns for different numbers of satellites and plane configurations are shown. Mean longitude and eccentricity maintenance is shown to reduce stationkeeping costs by 33 percent while largely conserving coverage. Judicious selection of orbital elements can reduce stationkeeping costs by up to 95 percent.

[View Full Paper]

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AAS 16-224

CORRECTIONS ON REPEATING GROUND-TRACK ORBITS AND THEIR APPLICATIONS IN SATELLITE CONSTELLATION DESIGN

David Arnas,* Daniel Casanova* and Eva Tresaco*

The aim of the constellation design model shown in this paper is to generate constellations whose satellites share the same ground-track in a given time, making all the satellites pass over the same points of the Earth surface. The model takes into account a series of orbital perturbations such as the gravitational potential of the Earth, the atmospheric drag, the Sun and the Moon as disturbing third bodies or the solar radiation pressure. It also includes a new numerical method that improves the repeating ground-track property of any given satellite subjected to these perturbations. Moreover, the whole model allows to design constellations with multiple tracks that can be distributed in a minimum number of inertial orbits.

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AAS 16-253

A GNC SIMULATION OF A FAR-RANGE APPROACH TOWARDS A TARGET IN GEOSTATIONARY ORBIT

Sofya Spiridonova[*] and Ralph Kahle[†]

This paper describes a GNC simulation as part of a feasibility analysis conducted by DLR/GSOC for future on-orbit servicing missions in near-geostationary orbit. The simulation addresses a far-range approach from several kilometers down to a few hundred meters, which includes relative orbit determination based on simulated optical measurements, and autonomous maneuver planning for relative trajectory control. One hundred simulation runs are performed with varying initial conditions based on the expected absolute orbit determination errors prior to the approach initiation. The safety of the formation is granted, as the servicer satellite never enters a pre-defined collision-avoidance area around the target spacecraft.

The results of the simulation show that a low-cost far range approach based on optical measurements is feasible up to a safe transition to a mid-range sensor. The results of the paper as well as the proposed GNC algorithm itself can find applications in future on-orbit servicing missions in near-geostationary orbit.

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AAS 16-271

REDUCING WALL-CLOCK TIME OF METAHEURISTIC-DRIVEN CONSTELLATION DESIGN WITH COARSE PARAMETRIC MAPPING

Lake A. Singh,[*] Marc D. DiPrinzio,[†]
William R. Whittecar[‡] and Patrick M. Reed[§]

This work presents a technique to reduce the wall-clock convergence time of metaheuristic constellation design by emulating the most computationally intensive components of the design space. Study of a constellation design problem which seeks to maximize global coverage and minimize station-keeping requirements is used to demonstrate application of the technique. Accurately calculating the station-keeping requirements requires high fidelity orbit propagation, which leads to intractability on sub-petascale computing resources. By mapping the dominant drivers of station-keeping requirements in orbital element space ahead of time, the study converges on an efficient frontier of the design space in a wall-clock time that is demonstrated to be up to three orders of magnitude less than using the original high fidelity evaluation. This enables a careful exploration of the design space in a matter of wall clock hours instead of computational years. The quality of the resulting designs is confirmed through re-evaluations using the high-fidelity station-keeping simulation.

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AAS 16-298

THE THEORY OF LATTICE FLOWER FORMATIONS AND ITS APPLICATION TO INTENSITY CORRELATION INTERFEROMETRY

Daniele Mortari* **and David C. Hyland†**

This paper introduces the theory of Lattice Flower Formations to extend the Flower Constellations theory to design configurations of satellites with small relative distances. To that purpose, a fictitious sphere (orbiting on a circular orbit) is introduced to bound the distances between the formation satellites. Using the Lattice Flower Constellation framework, a variety of formation flying configurations are introduced as Lattice Flower Formations. The bounded sphere allows to compute the eccentricity and inclination of all orbits. The proposed theory can be applied to design a multi-spacecraft systems based on Hyland's intensity correlation interferometry for missions targeting to observe a set of celestial objects in various directions. However, to observe a single object String-of-Pearls are optimal configurations. The optimality consists of maximizing the resolution disk coverage (frequency content) in one orbit period. Genetic algorithms are used to derive the satellite positions to obtain optimal reconstruction of images in terms of frequency content. Numerical tests using LEO satellites are performed for four different images. Comparisons with the Golomb ruler String-of-Pearls configuration is also provided.

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AAS 16-347

CONTROL OF HIGH FIDELITY LINEARIZED MODEL FOR SATELLITE FORMATION FLIGHT USING AERODYNAMIC DRAG

M. S. Shouman* and A. M. Atallah†

This paper approves the viability of maintaining a Low-Earth orbit (LEO) satellite formation flight using aerodynamic drag. It firstly looks insight the relative motion between two satellites using high-fidelity modified equations of Clohessy–Wiltshire. These equations are derived from Hill's relative equations and extended to consider the effects of main perturbations: J_2 and aerodynamic drag. Based on them, a control algorithm is designed to achieve relative position by dynamically adapting drag plate cross-sectional areas to meet the desired formation keeping. The control technique uses the linear quadratic regulator (LQR) which is developed to track periodic trajectory input. The main goal of this effort is to provide high precise and practical control algorithm based on more realistic relative motion equations and to test its performance using high-fidelity perturbations-based orbit propagator.

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AAS 16-360

SATELLITE CONSTELLATION DESIGN FOR THE SOLVE MISSION INVESTIGATING DIURNAL CYCLES OF VEGETATION PHENOMENA

Luzius Kronig,* Sung Wook Paek,† Anton Ivanov‡ and Olivier de Weck§

This paper discusses the problem of finding an optimal satellite constellation for the SOLVE (Satellites Observing Lakes and Vegetation Environments) Mission. A key requirement of this mission is a temporal resolution of several observations per day. A semi-analytical approach is proposed. A few analytical design steps are identified in order to determine all orbital parameters, so that the constellation satisfies the requirements. The result is an easy to use tool which allows to study cost impact from given science requirements enabling a good understanding of the relation between temporal and spatial resolution and cost.

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AAS 16-363

A NOTE ON A GEOMETRICAL METHOD TO SOLVE SPACECRAFT FORMATION FLYING CONTROL

Aureliano Rivolta,[*] Diogene A. Dei Tos[*] and Daniele Filippetto[*]

Spacecraft formation flying is becoming more important since the use of multiple satellites has been demonstrated to be cost-effective. In some applications, the spacecraft need to satisfy certain geometrical constraints; e. g. regarding formation pointing. In this paper an efficient method has been devised that minimises the variation of orbital elements to achieve the requested states. The positions that minimise displacement from a reference plane are computed, and the compatible velocities that reduce shape and plane variation for all S/C are evaluated. This allows to find optimal values for a TPBVP. The algorithm has been applied to close-range GEO formations.

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AAS 16-469

EMULATING OF THE STATIONARY OBSERVATION OF THE EARTH LOCAL REGION USING LOCALLY GEOSTATIONARY ELLIPTIC ORBITS

Yury N. Razoumny*

The problem of optimization of the satellite orbits for local Earth coverage is considered. The class of so-called locally geostationary orbits is suggested and substantiated. It is shown that this class of orbits includes the famous geostationary orbit, the only one circular orbit in the class, as well as an infinite do-main of elliptical orbits corresponding to the maximum criterion for the visibility zone of the local Earth region among all possible elliptical orbits. Particular cases of the locally geostationary orbits are Molniya and Supertundra orbit types and some other known orbits. It is shown that optimization in the class of locally geostationary orbits, while the problem of local coverage on elliptic orbits is considered, leads to maximum effectiveness of the resulting choice of orbits and constellations and minimum cost of the optimization process.

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AAS 16-478

FORMATION FLYING CONCEPT FOR BI-STATIC SAR MAPPING OF TITAN SURFACE

Tommaso Guffanti[*] and Michèle Lavagna[†]

Multiple spacecrafts flying in close formation allow the effective implementation of single pass Synthetic Aperture Radar interferometry. Thanks to the separation of the orbiting vehicles along the cross-track direction, the derivation of the Digital Elevation Model (DEM) of the illuminated ground is enabled and, thanks to the separation in the along-track direction, the measurement of ground objects velocity (e.g. sea currents) is attainable. This technology has been recently and successfully implemented in Low Earth Orbit missions. The performances provided by the system in terms of mapping accuracy make of great interest the extension of this space segment architecture to interplanetary mission for mapping different celestial bodies. Attention is here focused on Saturn's moon Titan. Titan surface high accurate mapping is of great interest considering the presence of hydrocarbon lakes detected by Cassini-Huygens mission in the polar regions. In the framework of a phase A feasibility study, this paper proposes the methodology already applied to design formations around Earth as TanDEM-X and Prisma,[1,2] to develop a suitable formation flying concept around Titan, compliant with the baselines constraints posed by the SAR interferometry, while minimizing the powered station and formation keeping maneuvers under a safe collision free design in proximity operations. The formation flying concept hereby presented stresses the smart exploitation of the natural perturbations affecting the dynamics around Titan for fuel saving, and comes out with a solution that provides big variety of baselines at all the latitudes and therefore high resolution and unambiguous DEM off the whole Titan surface. The specific strategy adopted to answer the mapping requirements with fuel consumption minimization is described in details, supported by the discussion of the obtained results.

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AAS 16-490

METHOD FOR CONSTELLATION DESIGN FOR EARTH PERIODIC COVERAGE USING COMPOUND SATELLITE STRUCTURES ON ORBITS WITH SYNCHRONIZED NODAL REGRESSION

Yury N. Razoumny*

The problem of optimization of the satellite orbits and constellations for Earth periodic coverage is considered. The method for constellation design using compound satellite structures on orbits with synchronized nodal regression is developed. Compound, multi-tiered, satellite structures (constellations) are based on orbits with different values of altitude and inclination providing nodal regression synchronization. It is shown that using compound satellite constellations for Earth periodic coverage makes it possible to sufficiently improve the Earth coverage, as compared to the traditional constellations based on the orbits with 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 regarding increasing the quality of observations or minimization of the number of the satellites required.

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DYNAMICS: MODELS

Session Chair:

Session 14: Brandon Jones

AAS 16-276

EXTENDED ANALYSIS ON THE FREE-MOLECULAR FLOW EFFECTS ON A GRACE-LIKE SATELLITE

Takahiro Kato,[*] Florian Wöske,[†] Benny Rievers[*] and Meike List[*]

This paper investigates the effects of the free-molecular flow on the dynamics of LEO satellites, especially for gravimetry missions like GRACE. Based on the contributions from the previous gravimetry missions, follow-on missions are planned to determine even higher accuracy and resolution. This motivates the development of precise non-gravitational force models and a high fidelity dynamics simulator which incorporates them. We focus on the dynamical effects of free-molecular flow on a LEO satellite regarding its geometry and surface temperature variations on orbit. The GRACE satellite and orbit configurations are employed for the illustration and demonstrated. Under the selected conditions, realistic force coefficients are obtained reflecting the dynamic surface temperature variations.

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AAS 16-282

ADVANCED THERMAL RADIATION PRESSURE MODELING AND ITS BENEFITS FOR THE MICROSCOPE MISSION

Benny Rievers,[*] Meike List[†] and Stefanie Bremer[‡]

A thorough modeling of the propagation of spacecraft motion is of utmost importance for scientific space missions. As a consequence, models of non-gravitational effects need to employ an accuracy corresponding to the designated mission goal. We show a high-precision approach for the analysis of thermal radiation pressure (TRP) and apply the method to the French space mission MICROSCOPE aiming at an analysis of a possible violation of the Weak Equivalence Principle (WEP) at an accuracy of $\eta = 10^{-15}$. We discuss the influence of the mission profile, the evolving surface temperatures and the effect of surface degradation during the mission on the resulting TRP.

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AAS 16-308

CARTESIAN DEVELOPMENT OF THE GRAVITATIONAL POTENTIAL WITHIN THE HOTINE SPHERE

Stefano Casotto* **and Roberto Casotto†**

A new method to develop the internal gravitational potential near the surface of highly irregular bodies is presented. The expansion, carried out fully in Cartesian coordinates, converges within the Hotine sphere and leads to the introduction of the Hotine inertial integrals, a generalization of the inertial integrals introduced by MacMillan in 1930. A method for analytically computing these coefficients is given for the case of a polyhedral body of uniform density. To ensure convergence, the integrations of the Hotine inertial integrals must be separately carried out over up to 24 subregions of the body.

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AAS 16-314

SEMI-ANALYTIC ELECTRODYNAMIC TETHER GUIDANCE USING ROTATING DIPOLE MODEL OF EARTH'S MAGNETIC FIELD

Scott J. D. Silver* and Steven G. Tragesser†

An electrodynamic tether provides a propellantless means of propulsion for spacecraft in Low Earth Orbit. Several proposed applications of the electrodynamic tether require a general change in the orbit, such as rendezvous for space surveillance or debris mitigation. This paper derives a current control law for electrodynamic tethers to achieve a specific general orbital change using a tilted, rotating dipole model of Earth's magnetic field. The control law is developed using a modified, semi-analytic derivation of the Gaussian Variation of Parameters equations. A semi-analytic method is used to solve the problem of integrating the perturbation equations with respect to time and true anomaly. This method takes advantage of the different time scales between Earth's rotation and the orbital motion of the spacecraft, approximating the position of the dipole as fixed for a single orbital period. The resulting guidance scheme allows for rapid calculation of the open-loop control law while allowing for the added complexity of a tilted, rotating dipole as well as the changing orbital elements of the spacecraft during the maneuver. The solution is more accurate than the fixed dipole model while maintaining greater computing efficiency than numeric solutions.

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AAS 16-331

A NOVEL SEMI-ANALYTICAL SOLAR RADIATION PRESSURE MODEL WITH THE SHADOW EFFECT FOR SPACECRAFT OF COMPLEX SHAPE

Satoshi Ikari,* Takuji Ebinuma,† Ryu Funase‡ and Shinichi Nakasuka§

The calculation of Solar Radiation Pressure (SRP) for complex shape spacecraft is complicated because the calculation cost increases along with the number of facets, and the error caused by the shadow effect tends to increase by the complexity of the spacecraft's structure. This research newly proposes a generalized semi-analytical SRP calculation method for such complex shape spacecraft. It was derived from the ideas of Generalized Sail Model, which is a technique for solar sails, and a computer graphics rendering method called Pre-computed Radiance Transfer. In order to verify the utilities of our method, comparison results with the ray-tracing method and the optical property estimation will be shown in this paper.

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AAS 16-338

A NEW KINETIC THEORY OF PARTICLE COLLISIONS

James K. Miller,[*] Gerald R. Hintz[†] and Pedro J. Llanos[‡]

The kinetic theory of gasses is used in deep space navigation for modeling small forces acting on a spacecraft. Acceleration of a spacecraft occurs as a result of the energy and momentum transfer from molecules leaving the spacecraft through evaporation or gas leaks or from molecules impacting the spacecraft from an external source such as a cometary atmosphere. In performing analysis of these events, a model of molecules in a closed container was developed. This model revealed a probability distribution of molecular velocity magnitudes that differs from the Maxwell-Boltzmann distribution. At first it was assumed that the model is not correct. However, further analysis has not revealed an error source. The difference is small but can be detected by direct measurement. A definitive measurement performed in 1955 confirms a small error which was attributed to the apparatus. The error is consistent with the computer model developed for navigation and seems to confirm that the Maxwell-Boltzmann theory is not correct.

Over the years, considerable evidence has been developed that supports the computer model. However, there has been no independent confirmation. Furthermore, it seems to upset settled science and questions the application of entropy to molecules in a container. The absence of a mathematical proof hinders acceptance of the computer model, but has not hindered its application to deep space navigation. Finally, a mathematical proof has been developed and is the subject of this paper. The complete probability distribution is not described as a closed form mathematical equation. The proof only applies to a single point where the error is greatest. However, the approach developed here may lead to a new mathematical function to replace the Maxwell-Boltzmann distribution.

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AAS 16-444

EXPLORATION OF NON-CONVENTIONAL TECHNIQUES FOR THE GENERATION OF ELEMENT-BASED ANALYTICAL EPHEMERIDES

Hodei Urrutxua,[*] Francesca Letizia,[†]
Jeroen Van den Eynde[‡] and Camilla Colombo[§]

A comprehensive description is presented of the many approaches to modern ephemeris generation that are found in the literature. Particularly, the generation of ephemerides build upon series of basis functions has been discussed, comparing Chebyshev, Fourier and Poisson series and supporting the arguments with factual data. For the case of Taylor series approximations, the relationship between the degree of the approximating polynomial and the total number of terms in the approximation have been qualitatively discussed as a function of the number of segments in which the time interval is split. A few examples are provided to show the accuracy and investigate the computational cost of various analytical and numerical ephemerides.

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AAS 16-483

POTENTIAL EFFECTS OF A REALISTIC SOLAR SAIL AND COMPARISON TO AN IDEAL SAIL

Jules Simo[*] and Colin R. McInnes[†]

Solar sail technology offers new capabilities for space missions due to the opportunities for non-Keplerian orbits. In this paper, novel families of highly non-Keplerian orbits for spacecraft utilising solar sail at linear order are investigated in the Earth-Moon circular restricted three-body problem. Firstly, it is assumed implicitly that the solar sail is a perfect reflector. Based upon the first-order approximation, an analytical formulation of the periodic orbits at linear order is presented. The approximate analytical solutions offer useful insights into the nature of the motion in the vicinity of the libration points, and are used to give periodic solutions numerically in the full nonlinear system. These orbits were accomplished by using an optimal choice of the sail pitch angle, which maximize the out-of-plane distance. Thereafter, the resulting effects of the non-ideal flat sail model have been computed and compared with an ideal solar sail. A square sail configuration, which is likely to be chosen for various near-term sail missions is used to illustrate the concept. The main effect of the non-perfect sail is to reduce the out-of-plane displacement distance which may be achieved for a given characteristic acceleration. It is also observed that there is a significant deviation in force magnitude between the realistic solar sail and the ideal solar sail model.

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AAS 16-508

THE EFFECT OF TIDAL FORCES ON THE EVOLUTION OF MINIMUM ENERGY CONFIGURATIONS OF THE FULL THREE-BODY PROBLEM

Edward C. Levine[*] and Christine Hartzell[†]

We investigate the evolution of minimum energy configurations for the Full Three Body Problem (3BP). A stable ternary asteroid system will gradually become unstable due to the Yarkovsky-O'Keefe-Radzievskii-Paddack (YORP) effect and a chaotic trajectory will ensue. Through the complex interaction of tidal torques, energy in the system will dissipate in the form of heat until a stable minimum energy configuration is reached. We present a simulation that describes the dynamical evolution of three bodies under the mutual effects of gravity and tidal torques. Simulations show bodies cycle between different available equilibria configurations throughout evolution and approach a terminal minimum energy configuration.

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ORBIT DETERMINATION

Session Chair:

Session 15: Thomas Starchville

PROBABILISTIC INITIAL ORBIT DETERMINATION

Roberto Armellin[*] and Pierluigi Di Lizia[†]

Future space surveillance requires dealing with uncertainties directly in the initial orbit determination phase. We propose an approach based on Taylor differential algebra to both solve the initial orbit determination (IOD) problem and to map uncertainties from the observables space into the orbital elements space. This is achieved by approximating in Taylor series the general formula for pdf mapping through nonlinear transformations. In this way the mapping is obtained in an elegant and general fashion. The proposed approach is applied to both angles-only and two position vectors IOD for objects in LEO and GEO.

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AAS 16-256

PRELIMINARY INVESTIGATION OF ONBOARD ORBIT DETERMINATION USING DEEP SPACE ATOMIC CLOCK BASED RADIO TRACKING[*]

Todd A. Ely,[†] Jeanette Veldman[‡] and Jill Seubert[§]

The Deep Space Atomic Clock mission is developing a small, mercury ion atomic clock with Allan deviation of less than 1e-14 at one day (current estimates < 3e-15) for a year-long space demonstration beginning late-2016/early-2017. DSAC's stability yields one-way radiometric data precision on par with current two-way data. Uplink one-way tracking with an appropriately configured radio enables the possibility of onboard, autonomous radio navigation. This study examines the modeling needed to efficiently process this data for an onboard implementation.

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AAS 16-258

DEEP SPACE ATOMIC CLOCK TECHNOLOGY DEMONSTRATION MISSION ONBOARD NAVIGATION ANALOG EXPERIMENT[*]

Jill Seubert[†] and Todd Ely[‡]

The timing and frequency stability provided by the Deep Space Atomic Clock (DSAC) is on par with the Deep Space Network's ground clocks, and will enable one-way radiometric measurements with accuracy equivalent to current two-way tracking data. A demonstration unit of the clock will be launched into low Earth orbit in early 2017 for the purpose of validating DSAC's performance in the space environment. GPS data collected throughout the mission will be utilized not only for precise clock estimation, but also as a proxy for deep space tracking data. Through careful processing of GPS Doppler data and limited modeling fidelity representative of onboard capabilities, onboard orbit solutions can be compared to higher-fidelity ground solutions, demonstrating DSAC's viability as an onboard navigation instrument in conditions typical for a low altitude Mars orbiter.

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ON SELECTING THE CORRECT ROOT OF ANGLES-ONLY INITIAL ORBIT DETERMINATION EQUATIONS OF LAGRANGE, LAPLACE, AND GAUSS

Bong Wie* **and Jaemyung Ahn†**

This paper is concerned with a classical yet still mystifying problem regarding multiple roots of the angles-only initial orbit determination (IOD) polynomial equations of Lagrange, Laplace, and Gauss of the form: $f(x) = x^8 + ax^6 + bx^3 + c = 0$ where $a,c < 0$. A possibility of multiple non-spurious roots of this 8th-order polynomial equation with $b > 0$ has been extensively treated in the celestial mechanics literature. However, the literature on applied astrodynamics has not treated this multiple-root issue in detail, and not many specific numerical examples with multiple roots are available in the literature. Recently, Gim Der has claimed that the 200-year-old, angles-only IOD riddle associated with the discovery and tracking of asteroid Ceres has been finally solved by using a new angles-only IOD algorithm that doesn't utilize any *a priori* knowledge and/or additional observations of the object. In this paper, a very simple method of determining the correct root from two or three non-spurious roots is presented. The proposed method exploits a simple approximate polynomial equation of the form: $g(x) = x^8 + ax^6 = 0$. An approximate polynomial equation, either $g(x) = x^8 + c = 0$ or $g(x) = x^8 + ax^6 = x^6(x^2 + a) = 0$, can also be used for quickly estimating an initial guess of the correct root.

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AAS 16-349

A COMPARISON BETWEEN GIBBS AND HERRICK-GIBBS ORBIT DETERMINATION METHODS

Arvind Kaushik,[*] Kohei Fujimoto,[†]
Kyle T. Alfriend,[‡] John E. Hurtado[‡] and John L. Junkins[§]

There is a strong need for accurate resident space object (RSO) state estimates. For radar RSO measurements, these estimates are initiated by Gibbs and Herrick-Gibbs algorithms. Presently, there is no clear distinction on when to switch between these two methods. In this paper, we present a statistical comparison between Gibbs and Herrick-Gibbs, taking into account measurement error via Monte Carlo. The overall trend of the performances of the methods is consistent with what is expected. However, the results also show that Herrick-Gibbs can remain the more accurate method for much larger track length arclengths than is suggested in the literature.

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AAS 16-364

ON-BOARD ORBIT DETERMINATION USING SUN SENSOR AND OPTICAL NAVIGATION CAMERA FOR INTERPLANETARY TRAJECTORY

Yosuke Kawabata* **and Yasuhiro Kawakatsu†**

On-board Orbit Determination (OD) using the sun sensor and the Optical Navigation Camera (ONC) for the Autonomous Navigation (AutoNav) is focused on in this paper. In deep space missions, the OD has been performed by Range and Range-Rate (RARR), which is the traditional ground tracking approach by radio wave. The RARR enables the accuracy of the OD to be higher than the other methods. However, such the radio navigation has the inevitable problems, e.g. the delay of radio wave, the reduction of radio wave strength and the transmitter limitation. The influence of these problems becomes significant especially for deep space missions. Furthermore, people must stay and operate the spacecraft on the ground station, which makes the operating cost considerable. Therefore, there has been a growing interest in the AutoNav of the spacecraft in recent years because the AutoNav can solve the above-mentioned problems. The realization of the AutoNav in deep space can eliminate the complexity of operation on the ground station, and especially it has the significant impact on the operation cost reduction. This paper focuses on the case of the Earth resonant trajectory as an actual mission. The usefulness of the sun observation by sun sensors is discussed for the proposed method. Then, the observation of asteroids is also argued.

[View Full Paper]

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AAS 16-380

ROBUST ON-ORBIT OPTICAL POSITION DETERMINATION OF NON-COOPERATIVE SPACECRAFT

Tomohiro Narumi,[*] Daisuke Tsukamoto[†] and Shinichi Kimura[‡]

Autonomous proximity operation with a non-cooperative space object is one of the essential technique for preventing exponential growth of space debris. Direct rendezvous and removal of large objects is the only practical way to stop degradation of the space environment under the present circumstances. In order to approach closely and attach safely a decelerating device to a target space object, it is important to know the orbital motion of the object in advance precisely. However, since a remover satellite is required to be low-cost because of its auxiliary role, its performance is restricted by financial constraints of sensors. In this paper, we propose a novel batch accurate orbit determination method using a luminous dot taken by a small camera that can be installed even on a small satellite. This method is stable and robust *vis-a-vis* various noise sources and problems of non-observability.

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AAS 16-475

PRECOMPUTING PROCESS NOISE FOR ONBOARD SEQUENTIAL FILTERS

Corwin Olson[*] and Ryan P. Russell[†]

Process noise is often used in estimation filters to account for unmodeled and mismodeled accelerations in the dynamics. The process noise acts to inflate the covariance over propagation intervals, increasing the uncertainty in the state. In scenarios where the acceleration errors change significantly over time, the standard process noise approach can fail to provide effective representation of the state and its uncertainty. Consider covariance analysis techniques provide a method to precompute a process noise profile along a reference trajectory, using known model parameter uncertainties. The process noise profile allows significantly improved state estimation and uncertainty representation. The new formulation also eliminates the trial-and-error tuning currently required of navigation analysts. As a result, estimation performance on par with the consider filter is achieved without the additional computational cost of the consider filter. A linear estimation problem as described in several previous consider covariance analysis publications is used to demonstrate the effectiveness of the precomputed process noise, as well as a nonlinear descent scenario at the asteroid Bennu with optical navigation.

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AAS 16-477

SATELLITE NAVIGATION IN CIS-LUNAR SPACE USING HIGH DEFINITION TELEVISION SIGNALS

Ryan E. Handzo,[*] Jeffrey S. Parker,[†] George H. Born,[‡] Austin Anderson[§] and Jorge Cervantes[**]

This paper considers using terrestrial HDTV transmissions for satellite navigation in cis-lunar space. The work presented in this paper constructs navigation simulations using a Conventional Kalman Filter for both initial orbit determination and for continuing orbit determination. The filters use observations obtained from HDTV signals transmitted from North America. These signals utilize the ATSC transmission standard and provide a Doppler count measurement, a pseudorange measurement, and a differential time offset measurement.

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SPACECRAFT RELATIVE MOTION

Session Chair:

Session 23: Alan Lovell

AAS 16-204

RELATIVE ORBIT TARGETING USING ARTIFICIAL POTENTIAL FUNCTIONS

David A. Spencer*

The relative orbital element formulation succinctly captures relative motion of a deputy spacecraft about a chief spacecraft with a set of algebraic expressions, within the framework of the Clohessy-Wiltshire assumptions. This work investigates an approach for artificial potential functions that are expressed in terms of relative orbital elements, in order to target a desired relative orbit. Through defining a scalar potential function in terms of relative orbital elements, the resulting potential field may be shaped such that the path of steepest descent lies in the direction of the desired elements. A major advantage of the relative orbital elements-based approach is that the artificial potential functions allow targeting of a specified relative orbit geometry, whereas prior formulations only allow targeting of discrete Cartesian state vectors.

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AAS 16-262

ANALYTIC SOLUTION FOR SATELLITE RELATIVE MOTION: THE COMPLETE ZONAL GRAVITATIONAL PROBLEM

Bharat Mahajan,* Srinivas R. Vadali† and Kyle T. Alfriend‡

A state transition matrix for satellite relative motion for the complete zonal gravitational problem is presented. Using the canonical perturbation methods the generalized analytic formulae, closed-form in eccentricity, for second-order secular and short-period effects with first-order long-period effects for an arbitrary zonal harmonic are computed. This approach avoids symbolic manipulations required for the Delaunay normalizations of the zonal gravity potential in addition to significant savings in storage requirements by having generalized formulae valid for any arbitrary zonal harmonic. Using differential perturbations, the secular and periodic effects are included in the analytic solution in the form of a state transition matrix of the satellite relative motion. The perturbation effects are computed for the Equinoctial elements to avoid singularities for circular and equatorial reference orbits. Verification of the proposed analytic solution for the perturbed relative motion is carried out by comparing propagation results with a numerically propagated formation of two satellites using the GMAT simulation software.

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AAS 16-357

COMPARISON OF ORBIT ELEMENT SETS FOR MODELING PERTURBED SATELLITE RELATIVE MOTION[*]

Kirk W. Johnson,[†] Srinivas R. Vadali[‡] and Kyle T. Alfriend[§]

This study models the motion of satellites perturbed by the Earth's zonal gravitational harmonics J_2 through J_6 using an analytic approach based on Lie-series averaging methods, using orbit elements due to Hoots that are nonsingular for all eccentricities and inclinations. The models include mean secular rates and mean-to-osculating element transformation terms up to second order in J_2. The relative motion of two satellites in a Projected Circular Orbit (PCO) formation is modeled via direct differencing and via a new version of the Gim-Alfriend State Transition Matrix (GA STM), accurate to first order in J_2 and in the relative coordinates, based on the Hoots elements. Simulations are compared for accuracy against numerically integrated trajectories.

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[*] The views expressed in this article are those of the authors and do not reflect the official policy or position of the United States Air Force, Department of Defense, or the U.S. Government.

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AAS 16-375

ANALYSIS OF AMBIGUOUS ORBITS IN SEQUENTIAL RELATIVE ORBIT ESTIMATION WITH RANGE-ONLY MEASUREMENTS

Jingwei Wang,* Eric A. Butcher† and T. Alan Lovell‡

A classification of ambiguous spacecraft relative orbits in sequential orbit estimation is formulated based on the use of linear dynamics with continuous range-only measurements. Using relative orbit elements the ambiguous orbits are categorized into two cases: mirror orbits, which conserve the size and shape but transform the orientation of the true relative orbit, and deformed orbits, which both distort the shape and change the orientation. Furthermore, it is shown that the inclusion of nonlinearities in the filter model can help resist the tendency of an extended Kalman filter to converge to the ambiguous orbits.

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AAS 16-432

PLANNING MANEUVERS BETWEEN PERIODIC RELATIVE ORBITS USING GEOMETRIC RELATIVE ORBITAL ELEMENTS

Liam M. Healy*

Periodic relative motion about a circular orbit may be described in terms of the geometric orbital elements, constants of the linearized motion analogous to the classical orbit elements for two-body inertial motion. They describe the three-dimensional motion of the secondary spacecraft about the primary in the apocentral coordinates, which are defined by that motion and are analogous to the perifocal coordinates for inertial motion. With simple computations for relative plane change and relative orbit size change, circumnavigation and inspection planning can be done with simple computation suitable for a low-performance flight processor.

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AAS 16-436

DEVELOPING A HARMONIC-BALANCE MODEL FOR SPACECRAFT RELATIVE MOTION

Ayansola D. Ogundele,[*] Andrew J. Sinclair[†] and S. C. Sinha[‡]

In this paper, the harmonic-balance method is applied to develop a new linearization of the nonlinear equations of motion for satellite relative motion. A cubic approximation of the equations of motion is evaluated along a reference linear solution for the relative motion. From this, a linear approximation which is a function of the initial-conditions used to describe the reference solution is extracted. Thus, the model takes the form of an initial-condition dependent linear system. Solutions of the harmonic-balance model can provide better approximation of the relative motion with less error than the Clohessy-Wiltshire model.

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AAS 16-486

APPROPRIATE FIDELITY ELECTROSTATIC FORCE EVALUATION CONSIDERING A RANGE OF SPACECRAFT SEPARATIONS

Joseph Hughes* and Hanspeter Schaub†

Charged spacecraft experience electrostatic forces and torques from both charged neighboring spacecraft and the local space environment itself. The Multi Sphere Method (MSM) is a recent methodology to numerically approximate electrostatic forces significantly faster than realtime. This allows the simulation of the complex charged astrodynamics that can occur with Coulomb tugging and detumbling operations, as well as predicting the charged debris dynamics. This paper develops reduced order electrostatic force models suitable for locally flat electric fields (large separations) and radial fields (medium separation larger than 5-10 craft radii). Unlike MSM, this reduced order expansion derives the force and torque from a first-principles manner, and has no tuning parameters. This adds analytical insight but can sacrifice accuracy in contrast with MSM by removing the tuning parameters.

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AAS 16-496

THIRD ORDER CARTESIAN RELATIVE MOTION PERTURBATION SOLUTIONS FOR SLIGHTLY ECCENTRIC CHIEF ORBITS

Eric A. Butcher,[*] T. Alan Lovell[†] and Andrew Harris[‡]

A perturbation method is used to obtain third order solutions for spacecraft relative motion in Cartesian coordinates for the case of a slightly eccentric chief orbit and a large chief/deputy separation distance. Both the chief eccentricity and the normalized separation are considered to be of order ε. The solution obtained includes as subsets both second order solutions for circular chief orbits previously obtained by perturbation and quadratic Volterra theory as well as a linear solution to third order in the chief eccentricity. Simulations confirm the improved accuracy of the third order solution.

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AAS 16-531

SPHERICAL COORDINATE PERTURBATION SOLUTIONS TO RELATIVE MOTION EQUATIONS: APPLICATION TO DOUBLE TRANSFORMATION SPHERICAL SOLUTION

Eric A. Butcher* and T. Alan Lovell†

Perturbation solutions are obtained in spherical coordinates for the spacecraft relative motion problem in the case of a slightly eccentric chief orbit. The use of spherical coordinates eliminates many of the secular terms in the Cartesian coordinate solution and extends the range of validity of these solutions to larger in-track separations. Both the chief eccentricity and the normalized separation are treated as order ε. Finally, the third order solution is used in the "double transformation" to improve the accuracy of the "approximate double transformation" Cartesian solution and as an alternative method to obtain the proposed third order spherical solution.

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A SATELLITE RELATIVE MOTION MODEL INCLUDING J_2 AND J_3 VIA VINTI'S INTERMEDIARY

Ashley D. Biria[*] and Ryan P. Russell[†]

Vinti's potential is revisited for analytical propagation of the main satellite problem, this time in the context of relative motion. A particular version of Vinti's spheroidal method is chosen that is valid for arbitrary elliptical orbits, encapsulating J_2, J_3, and approximately two thirds of J_4 in an orbit propagation theory without resorting to perturbation methods. As a child of Vinti's solution, the proposed relative motion model inherits these properties. Furthermore, the problem is solved in oblate spheroidal elements, leading to large regions of validity for the linearization approximation. After offering several enhancements to Vinti's solution, including boosts in accuracy and removal of some singularities, the proposed model is derived and subsequently reformulated so that Vinti's solution is piecewise differentiable. While the model is valid for the critical inclination, singularities remain in the coordinate transformation from ECI coordinates to spheroidal elements when the eccentricity nears zero or for nearly circular equatorial orbits. The new state transition matrix is evaluated against numerical solutions including the J_2 through J_5 terms for a wide range of chief orbits and separation distances. The solution is also compared with side-by-side simulations of the original Gim-Alfriend state transition matrix, which considers the J_2 perturbation. Code for computing the resulting state transition matrix and associated reference frame and coordinate transformations is provided online as supplementary material.

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AAS 16-548

SIX DEGREE OF FREEDOM MOTION EMULATION FOR PROXIMITY OPERATIONS AND CONTACT EXPERIMENTS

Austin B. Probe,[*] Malak Samaan,[†] Tim Woodbury,[*] John E. Hurtado[‡] and John L. Junkins[§]

Future efforts for the removal of space debris will require the development of new technologies. To support this development, the Texas A&M LASR Laboratory has engineered several systems for ground based testing of technologies for space based proximity operations, rendezvous, and contact dynamics. The centerpiece of this suite is the Holonomic Omnidirectional Motion Emulation Robot (HOMER), a 6 degree of freedom platform for reproducing motion based on the input of a dynamic simulation. This paper details recent upgrades made to HOMER to support active debris removal experiments including the integration of a load cell and inertial measurement units as well as an upgrade to its estimation and control algorithms.

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ASTEROID AND NON-EARTH ORBITING MISSIONS

Session Chairs:

Session 16: Ryan Weisman

Session 18: Paul Thompson

The following papers were not available for publication:

AAS 16-376 Paper Withdrawn

AAS 16-390 Paper Withdrawn

AAS 16-219

THE DEPLOYMENT OF MASCOT-2 TO DIDYMOON

Simon Tardivel,[*] Caroline Lange,[†] Stephan Ulamec[‡] and Jens Biele[‡]

This paper presents a strategy for the deployment of the Mascot-2 lander of the Asteroid Impact Monitoring (AIM) candidate mission, to the secondary of the binary asteroid system Didymoon. The spacecraft would release the lander with a spring, near the L_2 region. The lander would free fall to the surface and come to rest after several bounces. Considering inaccuracies of the spacecraft navigation and of the spring mechanism, the different trade-offs of mission design are analyzed. Pushing the strategy to its working limits, the paper investigates whether it could be applied to the deployment of objects from smaller and less capable spacecraft.

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AAS 16-229

DEVELOPMENT OF A TOOL FOR ANALYZING ORBITS AROUND ASTEROIDS

Julian Niedling,[*] David Gaylor,[†] Marcus Hallmann[‡] and Roger Foerstner[§]

In this paper orbit dynamics around asteroids are analyzed. Since asteroid orbital environments are some of the most highly perturbed environments in the solar system, it is of particular interest to demonstrate the effects of gravitational perturbations, solar radiation pressure (SRP) and solar gravity. In order to show and compare the importance of satellite and asteroid properties, the theory of asteroid dynamics is applied on both the relatively massive asteroid Eros and the relatively small asteroid Itokawa. Special orbits, such as terminator orbits and hovering, are analyzed through the example of both asteroids. The analyses are performed using a tool written in MATLAB, which allows to parametrically study orbits around asteroids. The tool is capable of analyzing stability of orbits around asteroids, designing terminator orbits and determining Δv, thrust magnitude and propellant for hovering.

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GROUND-BASED NAVIGATION AND DISPERSION ANALYSIS FOR THE ORION EXPLORATION MISSION 1

Christopher D'Souza,[*] Greg Holt,[†] Renato Zanetti[*] and Brandon Wood[‡]

This paper presents the Orion Exploration Mission 1 Linear Covariance Analysis for the DRO mission using ground-based navigation. The $|\Delta V|$ statistics for each maneuver are presented. In particular, the statistics of the lunar encounters and the Entry Interface are presented.

[View Full Paper]

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AAS 16-242

A GPU-ACCELERATED MULTIPHASE COMPUTATIONAL TOOL FOR ASTEROID FRAGMENTATION/PULVERIZATION SIMULATION

Ben J. Zimmerman[*] and Bong Wie[†]

The simulation of asteroid target fragmentation or pulverization is a challenging task which demands efficient and accurate numerical methods with large computational power. To this end, the high-order Spectral Difference (SD) method is implemented with Graphics Processing Unit (GPU) computing. Hypervelocity kinetic-energy impactors are of practical interest, which generate high-pressure, deformational shock waves in the target bodies upon impact. Due to the extremely short deformation time associated with hypervelocity impact, the material behaves in a similar manner to a compressible fluid, and the compressible Euler equations can be applied. To model the multiple material interactions, an n-phase equation model is adopted into the SD method. All simulations presented were solved with GPUs, producing solutions at orders of magnitudes faster than the Central Processing Unit (CPU) counterpart. Several impact cases are compared, including a heavy impactor and multiple impactor system, against an asteroid target. Orbital dispersion effectiveness is evaluated and results indicate that the multiple impactor system outperforms the single heavy impactor.

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AAS 16-250

ANALYSIS OF SOLAR RADIATION PRESSURE EFFECTS ON THE OSIRIS-REX SPACECRAFT IN ORBIT AROUND BENNU

Siamak G. Hesar,[*] Daniel J. Scheeres[†] and Jay W. McMahon[‡]

This study presents an analysis of solar radiation pressure (SRP) effects on the OSIRIS-REx spacecraft in orbit about the asteroid Bennu. It utilizes a Fourier series expansion to represent the solar radiation force that is imparted on the spacecraft. We identify a set of dominant Fourier coefficients that account for a majority of the SRP effect and its uncertainty. Analytical solutions are derived to shed light on the secular effects of the SRP on the orbit of the spacecraft around the asteroid. Finally, we implement a set of covariance analyses to evaluate the expected level of estimation precision possible for the dominant coefficients.

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AAS 16-274

TWO BODY FORMULATION FOR MODELING TETHER-BALLAST ASTEROID DIVERSION SYSTEMS

Nickolas J. Sabey * and Steven G. Tragesser†

Attention has been focused on the dangers of Earth impacting asteroids as the discovery rates of new hazardous bodies are increasing. Consequently, mitigation techniques have been proposed to prevent catastrophic events. Previous work has shown through numerical analysis that by attaching a tether and ballast to an asteroid over long periods of time, an asteroid may be diverted sufficiently to avoid an Earth impact event. This study demonstrates that a closed-form solution can be obtained, through the two-body formulation of perturbed motion. Using an analytic approach, Monte Carlo simulations and sensitivity studies see improvements to performance without sacrificing accuracy.

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AAS 16-281

STUDY ON IMPACT EXPERIMENT OF HAYABUSA2 MISSION

Takanao Saiki,[*] Hiroshi Imamura,[†] Yuya Mimasu[‡] and Yuichi Tsuda[§]

Hayabusa2 is a current sample return mission of JAXA and it was launched on 3 December 2014. Hayabusa2 is the successor of Hayabusa, however, it is equipped with some new components. Small carry-on impactor (SCI) is one of the new components of Hayabusa2. SCI is a compact kinetic impactor and in the latter half of the proximity operation phase of Hayabusa2, the impact experiment will be performed. Because SCI has no attitude and orbit control functions, its impact accuracy depends on the separation accuracy. In this study, the results of the impact accuracy analysis are shown.

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PERFORMANCE CHARACTERIZATION OF A LANDMARK MEASUREMENT SYSTEM FOR ARRM TERRAIN RELATIVE NAVIGATION

Michael A. Shoemaker,[*] Cinnamon Wright,[†] Andrew J. Liounis,[‡] Kenneth M. Getzandanner,[†] John M. Van Eepoel[§] and Keith D. DeWeese[§]

This paper describes the landmark measurement system being developed for terrain relative navigation on NASA's Asteroid Redirect Robotic Mission (ARRM), and the results of a performance characterization study given realistic navigational and model errors. The system is called Retina, and is derived from the stereophotoclinometry methods widely used on other small-body missions. The system is simulated using synthetic imagery of the asteroid surface and discussion is given on various algorithmic design choices. Unlike other missions, ARRM's Retina is the first planned autonomous use of these methods during the close-proximity and descent phase of the mission.

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AAS 16-293

DELTA-V ASSISTED PERIODIC ORBITS AROUND SMALL BODIES

Shota Kikuchi,* Yuichi Tsuda† and Jun'ichiro Kawaguchi‡

Delta-V assisted periodic orbits (DVAPOs) are introduced as a new type of periodic orbit around small bodies subject to strong solar radiation pressure. DVAPOs are made periodic by introducing a small deterministic delta-V within each period. This type of orbit has a simpler shape and provides higher flexibility than other periodic orbits and therefore enables missions with higher scientific value. The general theory of DVAPOs is described, including the orbit design methodology, solution-space analysis, and stability analysis. This paper clarifies that DVAPOs are a useful and feasible option for small-body missions and exhibit unique dynamic characteristics.

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AAS 16-320

ON THE DYNAMICS OF A SPACECRAFT IN THE IRREGULAR HAUMEA-HI'IAKA BINARY SYSTEM

Diogo M. Sanchez,[*] Kathleen C. Howell[†] and Antonio F. B. A. Prado[‡]

This work aims to describe the dynamics of a small spacecraft around a binary system comprised of irregular the bodies Haumea and Hi'iaka. In this model, the dynamics of Haumea and Hi'iaka is assumed as a full two body problem, and the equations of motion of the spacecraft incorporate the information from this model. We assume some configurations for the ellipticity of the primaries and seek orbits of interest for future missions to this system.

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THE ANALYTICAL STUDY OF PARTICLE SWARM OPTIMIZATION AND MULTIPLE AGENT PATH PLANNER APPROACHES FOR EXTRATERRESTRIAL SURFACE SEARCHES

Michael Andrew Johnson*[*] and May-Win L. Thein[†]

Discovering and mining precious ores, water, and other natural resources from extraterrestrial bodies (e.g. planets, moons, and asteroids) are some examples of potential benefits of human space exploration. Robotic extraction and mining missions in which any indigenous resource(s) could not be sensed by satellite would greatly benefit from a prior separate prospecting mission. Here, probes are not intended to carry specialized mining equipment to mine the resource(s), but to search for high(est) concentrations of the resource(s). In a previous paper, the authors examined a methodology for a generic search mission on an extraterrestrial surface. This methodology was based on the control of a swarm of autonomous vehicles (i.e., rovers) using Particle Swarm Optimization (PSO) to explore the extraterrestrial body. In this work, this previous analysis is expanded to include an examination of a decentralized path planner, referred to as Multiple Agent Path Planner (MAPP), and its effects on the quality of the search results produced by PSO. This path planning algorithm allows the swarm to navigate between and about obstacles in a given search space, as well as among other rovers in the swarm. (It is assumed that these obstacles and corresponding locations are identified *a priori.*) For proof of concept, the authors present a sample search scenario (without loss of generality) in which a swarm of rovers incorporates PSO and MAPP to identify maximum and minimum elevations on an extraterrestrial surface in an optimized fashion. It is found that the MAPP path planning algorithm can be configured so that it does not bias PSO search locations. Regardless, this same procedure may be easily be modified to suit other types of searches (e.g., the search water and for precious natural resources) or other mission objectives.

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THE LIFT-OFF VELOCITY ON SOLAR SYSTEM SMALL BODIES

Stefaan Van wal[*] and Daniel J. Scheeres[*]

The lift-off velocity is defined as the velocity at which a particle, moving tangentially on the surface of some arbitrary body, will lift off from that surface and enter orbit. We derive a vectorial expression for this velocity on smooth, continuous bodies, by locally approximating their surface with some radius and associated center of curvature. To first order, the lift-off velocity is shown to be independent of the particle size when the latter is much smaller than the target body. The lift-off velocity expression is directly applicable to the reference ellipsoid of a small body, as the curvature of an ellipsoid is analytically defined. Using a numerical averaging technique from literature, we can also apply the expression to polyhedra, which model complex small body shapes as discrete surfaces consisting of a large number of triangular facets. The polyhedron model also permits an alternative, more localized definition of lift-off, which does not require surface averaging and is relevant to the motion of a particle across a small surface protrusion. We apply these approaches to asteroids 25143 Itokawa and the fast rotator 1999 KW_4 Alpha, as well as the Mars moon Phobos, to yield lift-off velocity distributions across the surfaces of their reference ellipsoids and polyhedra. These results have numerous applications to the design of lander/rover operations, manned missions, and geophysical processes on the considered bodies.

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AAS 16-387

LOW-THRUST TRAJECTORY DESIGN FOR THE DESTINY MISSION TO (3200) PHAETHON

Bruno Victorino Sarli,[*] Chit Hong Yam,[*] Makoto Horikawa[†] and Yasuhiro Kawakatsu[‡]

This work explores the target selection and trajectory design of the mission candidate for ISAS/JAXA's small science satellite series, DESTINY. This mission combines unique aspects of the latest satellite technology and exploration of transition bodies to fill a technical and scientific gap in the Japanese space science program. The spacecraft is targeted to study the comet-asteroid transition body (3200) Phaethon through a combination of low-thrust propulsion and Earth Gravity Assist. The trajectory design concept is presented in details together with the launch window and flyby date analysis. Alternative targets for a possible the mission extension scenario are also explored.

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AAS 16-409

CONSOLIDATED PHASE A DESIGN OF ASTEROID IMPACT MISSION: MASCOT-2 LANDING ON BINARY ASTEROID DIDYMOS

Fabio Ferrari[*] and Michèle Lavagna[†]

The Asteroid Impact Mission (AIM) is a European mission aimed at the exploration of the binary asteroid 65803 Didymos. Among its mission objectives, AIM is planned to release a small and passive probe, called MASCOT-2, to land on the smallest asteroid of the binary couple. The paper presents the modeling strategy adopted to support the design of MASCOT-2 release. The modeling assumptions regarding the dynamical environment of such binary asteroid are discussed. The gravity field around the couple is modeled using shape-based models of the asteroids. A suitable model of the asteroid's surface is used to properly simulate the local interaction between the probe and the soil at touch down. Uncertainties regarding the release accuracy are modeled and results related to the AIM scenario are presented in terms of successful landing probability and final position of the lander at rest.

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AAS 16-439

ORBITAL STABILITY REGIONS FOR HYPOTHETICAL NATURAL SATELLITES OF 101955 BENNU (1999 RQ_{36})

Samantha Rieger,[*] Daniel Scheeres[†] and Brent Barbee[‡]

The Origins, Spectral Interpretation, Resource Investigation, Security-Regolith Explorer (OSIRIS-REx) mission will be orbiting and returning a sample form near-Earth asteroid 101955 Bennu. Ground-based observations have determined that no object greater than 15 m in diameter is orbiting Bennu. This investigation explores the possible size and stability of a natural satellite around Bennu. The focus of this research is solely on the existence of stable orbits for a natural satellite and purposefully places how the natural satellite migrated to this orbit outside the bounds of this research. Numerical simulations modeling J_2, third body dynamics and solar radiation pressure is used on a large set of initial conditions that vary in semi-major axis, inclination, longitude of periapsis and natural satellite diameter. Stable orbital initial conditions for a given natural satellite diameter must remain in orbit for more than a thousand years without escape or collision from Bennu. The data found the possible existence of natural satellites in orbit around Bennu as small as 0.75 cm. Certain mechanisms such as the modified Laplace plane, Kozai resonance and the Sun-terminator plane are explored for yielding stable orbits of a given natural satellite.

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USING SOLAR RADIATION PRESSURE TO MANEUVER A SPACECRAFT IN THE TRIPLE ASTEROID 2001SN$_{263}$

J. B. Silva Neto,[*] D. M. Sanchez,[†] A. F. B. A. Prado[‡] and J. K. S. Formiga[§]

The number of missions which with an asteroid as a target has increased and this type of exploration will become even more frequent in the future. Space missions require high costs and methods that may reduce them should be studied. An alternative is the use of solar radiation pressure, using a solar sail or similar devices. This study presents a solution for the final phase of the Aster mission, which aims to collide a probe with the surface of the body Alpha of the system 2001SN$_{263}$ using solar radiation pressure. As noted during the study, the low gravity of the system makes it very sensitive to solar radiation pressure. The high angular velocity of Gamma around Alpha causes collisions and involuntary gravity assisted maneuvers, which are obstacles in the search of initial conditions for the use of such devices.

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AAS 16-450

POLYHEDRAL POTENTIAL MODELS FOR CLOSE PROXIMITY ORBITAL SIMULATIONS ABOUT SMALL CELESTIAL OBJECTS

S. R. Wood,[*] J. M. Pearl[*] and D. L. Hitt[†]

The imaging capabilities of the current generation of deep space probes are such that detailed, 3-D topological data can be obtained for small celestial bodies, thus enabling the reconstruction of a 'digital' version of the body. Using this information, a polyhedral potential-based approach can be used to predict the non-uniform, time-varying gravitational potential environment about these small bodies. A detailed potential model is critical to the accurate orbital trajectory planning of spacecraft when operating in close proximity of the body. In this work, the performance and limitations of two variants of a polyhedral potential approach are examined in this context. In particular, a spherical harmonic expansion of the gravitational potential field is analyzed. The ESA Rosetta mission to comet 67P/Churyumov - Gerasimenko and NASA's OSIRIS REx Mission to the near-earth asteroid 101955 Bennu are selected as test cases.

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AAS 16-464

LUNAR ADVANCED RADAR ORBITER FOR SUBSURFACE SOUNDING (LAROSS): LAVA TUBE EXPLORATION MISSION

Rohan Sood,* H. Jay Melosh† and Kathleen C. Howell‡

With the goal of expanding human presence beyond Earth, sub-surface empty lava tubes on other worlds form ideal candidates for creating a permanent habitation environment safe from cosmic radiation, micrometeorite impacts and temperature extremes. In a step towards Mars exploration, the Moon offers the most favorable pathway for lava tube exploration. In-depth analysis of GRAIL gravity data has revealed several candidate empty lava tubes within the lunar maria. The goal of this investigation is a proposed subsurface radar sounding mission to explore the regions of interest and potentially confirm the presence and size of buried empty lava tubes under the lunar surface.

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AAS 16-502

INITIAL NAVIGATION ANALYSIS FOR THE EUROPA MULTIPLE FLYBY MISSION CONCEPT

Sumita Nandi,* Julie Kangas,* Powtawche Valerino,* Brent Buffington,† Rodica Ionasescu* and Dylan Boone*

Earth and spacecraft-based observations of the Jovian moon Europa have identified it as the most plausible habitat for extraterrestrial life in our solar system. Recently, NASA has formed a Europa Mission Concept to potentially explore this icy world with a sophisticated instrument suite operating from a spacecraft in orbit about Jupiter. Candidate trajectories have been designed that would use the Jovian moons to repeatedly bring the spacecraft near Europa, providing multiple observation opportunities over the mission duration. This paper describes navigation analyses associated with these trajectories that are being assessed for their operational feasibility. The analysis includes determination of the ΔV requirements for the mission concept and notional spacecraft ephemeris knowledge capability.

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SPACE SITUATIONAL AWARENESS

Session Chairs:

Session 17: Matthew Wilkins

Session 27: Marcus Holzinger

AAS 16-207

UNCERTAIN ANGLES-ONLY TRACK INITIATION FOR SSA USING DIFFERENT IOD METHODS[*]

Christopher W. T. Roscoe,[†] Matthew P. Wilkins,[*] Islam I. Hussein[*] and Paul W. Schumacher, Jr.[‡]

Uncertainty in initial orbit determination (IOD) resulting from sparse optical data is a topic of great interest in modern space situational awareness (SSA). Uncertainty propagation has been investigated in detail in SSA research for the purposes of collision probability analysis, data association, and Bayesian estimation, but all of these investigations have assumed prior knowledge of the initial uncertainty. For optical observations with long arcs of data, uncertainty is usually assumed to be Gaussian and the initial covariance is determined from the error statistics of the differential correction algorithm. This paper continues previous work to investigate the characterization of IOD uncertainty for sparse, short-arc data. This will include mapping uncertain measurements through the Gooding IOD method and comparing to previous results obtained using the method of Gauss. Several examples will be presented, with different observation geometries, measurement timings, and orbit parameters.

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SPACE BORNE IMAGING VIA NOISE FILTERING PHASE RETRIEVAL

David. C. Hyland*

To enable ultra-fine resolution imaging with inexpensive flux collector apertures using the Brown-Twiss effect, this paper describes a phase retrieval algorithm capable of producing high quality images despite large amounts of noise in the coherence magnitude measurement data. Previously the problem was conceived as two distinct steps: coherence magnitude estimation, followed by image construction. The present unified formulation accepts highly noisy data and estimates both the measurement noise and the image using the numerous constraints on the coherence data, the image, and their interrelations. The technique is shown to reduce the necessary imaging time by many orders of magnitude.

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AAS 16-241

APPROACHES TO EVALUATING PROBABILITY OF COLLISION UNCERTAINTY

Matthew D. Hejduk* and Lauren C. Johnson†

While the two-dimensional probability of collision (Pc) calculation has served as the main input to conjunction analysis risk assessment for over a decade, it has done this mostly as a point estimate, with relatively little effort made to produce confidence intervals on the Pc value based on the uncertainties in the inputs. The present effort seeks to try to carry these uncertainties through the calculation in order to generate a probability density of Pc results rather than a single average value. Methods for assessing uncertainty in the primary and secondary objects' physical sizes and state estimate covariances, as well as a resampling approach to reveal the natural variability in the calculation, are presented; and an initial proposal for operationally-useful display and interpretation of these data for a particular conjunction is given.

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AAS 16-266

HARDWARE-IN-THE-LOOP COMPARISON OF SPACE OBJECT DETECTION AND TRACKING METHODOLOGIES

Jared Lee,[*] Lubna Zubair,[*] Shahzad Virani,[†] Timothy Murphy[†] and Marcus J. Holzinger[‡]

Space Domain Awareness relies on a network of surveillance architectures to catalog passive and active space object data. This paper analyzes the performance of several detection and tracking algorithms using different hardware-in-the-loop test configurations. Several image sources are tested, including simulated images generated with the Hipparcos and Space Object catalogs, and real images taken from a Nocturn XL camera. The Moving Target Indicator (MTI), Multiple Hypothesis Tracking, and Finite Set Statistics algorithms are tested, implemented, and compared in this study.

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AAS 16-267

IMPACT RISK ANALYSIS OF NEAR-EARTH ASTEROIDS WITH MULTIPLE SUCCESSIVE EARTH ENCOUNTERS

George Vardaxis[*] and Bong Wie[†]

Accurate estimation of the impact risk associated with hazardous asteroids is essential for planetary defense. Based on observations and the risk assessment analyses of those near-Earth objects (NEOs), mission plans can be constructed to deflect/disrupt the body if the risk of an Earth impact is large enough. Asteroids in Earth resonant orbits are particularly troublesome because of the continuous threat they pose to the Earth in the future. The problem of analyzing the impact risk associated with NEOs on a close-encounter with the Earth has been studied in various formats over the years. However, the problem of multiple, successive encounters with the Earth need to be further investigated for planetary defense. Incorporating methods such as analytic encounter geometry, target B-planes, analytic keyhole theory, and numerical simulations presents a new computational approach to accurately estimate the impact probability of NEOs, especially those in Earth resonant orbits.

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AAS 16-289

SPACE OBJECT COLLISION PROBABILITY VIA MONTE CARLO ON THE GRAPHICS PROCESSING UNIT

Vivek Vittaldev* and Ryan P. Russell†

Fast and accurate collision probability computations are essential for protecting space assets. Monte Carlo (MC) simulation is the most accurate but computationally intensive method. A Graphics Processing Unit (GPU) is used to parallelize the computation and reduce the overall runtime. Using MC techniques to compute the collision probability is common in literature as the benchmark. An optimized implementation on the GPU, however, is a challenging problem and is the main focus of the current work. The MC simulation takes samples from the uncertainty distributions of the Resident Space Objects (RSOs) at any time during a time window of interest and outputs the separations at closest approach. Therefore, any uncertainty propagation method may be used and the collision probability is automatically computed as a function of RSO collision radii. Integration using a fixed time step and a quartic interpolation after every Runge Kutta step ensures that no close approaches are missed. Two orders of magnitude speedups over a serial CPU implementation are shown, and speedups improve moderately with higher fidelity dynamics. The tool makes the MC approach tractable on a single workstation, and can be used as a final product, or for verifying surrogate and analytical collision probability methods.

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AAS 16-302

FRAGMENTATION EVENT TRACKING WITH THE GM-CPHD FILTER

Daniel S. Bryant[*] and Brandon A. Jones[†]

The tracking of space objects generated by fragmentation events has been a significant challenge for the space situational awareness community. In a multi-target random finite set framework, such events are ideally modeled as spawning processes, allowing for the joint estimation of catalogued objects and initialization of new tracks. Implementations of the Cardinalized Probability Hypothesis Density (CPHD) filter have recently been developed for the explicit use of spawn models and this paper presents the first application of such implementation to the tracking of space objects. Configured with a Zero-inflated Poisson spawn model, the Gaussian Mixture CPHD filter is applied to the tracking of objects generated by fragmentation and similarly modeled events. Efficacy of the filter implementation is demonstrated through simulation of low-Earth orbit objects.

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AAS 16-303

SPACE EVENT DETECTION VIA ROBUST TIME SERIES FORECASTING

Pradipto Ghosh*

The ability to detect sudden and unexpected changes in the ephemerides of tracked space objects is a crucial feature of space event monitoring systems. These changes may arise from actual space events such as satellite maneuvers or collisions, from cross-tagging of space objects as might occur during a fly-by, or even from inadvertently introduced defects in the orbit determination (OD) workflow. Utilizing robust time series forecasting techniques, this paper introduces a new method for detecting sudden changes in the ephemeris of a tracked object. Test cases drawn from known space events demonstrate that the software implementation of this method is able to flag each sequentially supplied orbit-determined state as in- or out-of-family depending on whether the state is statistically typical relative to a configurable look-back interval.

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AAS 16-306

TLE GENERATION FROM SPARSE TRACKING DATA AND ITS PERFORMANCE

Bin Li,[*] Jizhang Sang[†] and Jinsheng Ning[‡]

TLE/SGP4 provides a fast analytic method for propagating orbits of space objects and thus is widely used in many space applications. However, its advantage in the computation efficiency is shadowed by large errors in the propagated orbits. Therefore, the numerical or semi-analytic orbit propagations are preferred. This paper presents a two-step method to represent numerically-propagated accurate orbit. In the first step, TLE is generated from the numerically-propagated positions. Then, three polynomials of sine functions are developed to model the prediction errors of the generated TLE (GenTLE). Through this two-step procedure, users would be able to propagate orbits in much better accuracy than the pure TLE/SGP4 algorithm. Four geodetic satellites at different altitudes are tested and 100 independent computations are conducted for each satellite. Results show that the RMS of the 30-day prediction errors using the GenTLE/SGP4 is several hundred meters or less. When the corrections, which are computed from the correction polynomials, are applied to the GenTLE/SGP4-propagated orbit, the RMS of the 30-day prediction errors are reduced to only dozens of meters. Also, the storage of the 30-day prediction positions (output every 1 minute) reduces from 5 MB to only 4 KB in the form of the TLE and coefficients of correction functions, saving significantly in the hard space. The presented method can be used anywhere the TLE/SGP4 is used.

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AAS 16-319

UCT CORRELATION USING THE BHATTACHARYYA DIVERGENCE*

Islam I. Hussein,† Christopher W. T. Roscoe,* Paul W. Schumacher, Jr.‡ and Matthew P. Wilkins*

In this paper, we build on recent work to further investigate the use of information theoretic criteria to solve the track-to-track association problem, in which we have multiple uncorrelated tracks (UCTs) to be tested for correlation against a given set of tracks given at a different time instance. Both the tracks and the UCTs are uncertain and are probabilistically described using multivariate normal distributions. This allows for a closed-form solution, based on the unscented transform and on the Bhattacharyya information divergence for Gaussian distributions. We first mathematically describe the approach and make connections to the covariance-based track association (CBTA) technique existing in the literature. We then summarize recent and current results comparing the two approaches in Cartesian and equinoctial element coordinates. We show that while the Bhattacharyya approach is superior to CBTA in Cartesian coordinates, the two approaches are nearly identical in performance when the analysis is done in equinoctial elements with CBTA outperforming the Bhattacharyya metric in certain orbital regimes for the more ambiguous correlation problems. We conclude the paper with a summary of the main outcomes of this paper.

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AAS 16-327

OPTIMIZED COLLISION AVOIDANCE OF SPACECRAFT IN ULTRA CLOSE PROXIMITY FOR FAILED SATELLITE

Xiaoyu Chu,* Jingrui Zhang† and Fei Liu‡

In this paper, a trajectory planning algorithm for optimized collision avoidance is presented regarding a chasing spacecraft. The spacecraft is supposed to operate in the ultra-close proximity around a failed satellite. The complex configuration and tumbling motion of the failed satellite are considered. Two-spacecraft rendezvous dynamics is formulated in the target body frame, while collision avoidance constraints are detailed, especially concerning the position uncertainties. An error ellipsoid is particularly involved corresponding to the uncertainties. An optimization solution of the approaching problem is generated with the Gauss Pseudospectral method, and modified in a close loop control. Numerical results are given to demonstrate the effectiveness of the proposed algorithms.

[View Full Paper]

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AAS 16-365

COLLISION AVOIDANCE AS A ROBUST REACHABILITY PROBLEM UNDER MODEL UNCERTAINTY

Massimiliano Vasile,[*] Chiara Tardioli,[†] Annalisa Riccardi[‡] and Hiroshi Yamakawa[§]

The paper presents an approach to the design of an optimal collision avoidance maneuver under model uncertainty. The dynamical model is assumed to be only partially known and the missing components are modeled with a polynomial expansion whose coefficients are recovered from sparse observations. The resulting optimal control problem is then translated into a robust reachability problem in which a controlled object has to avoid the region of possible collisions, in a given time, with a given target. The paper will present a solution for a circular orbit in the case in which the reachable set is given by the level set of an artificial potential function.

[View Full Paper]

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AAS 16-366

AN ANALYTICAL SOLUTION TO QUICK-RESPONSE COLLISION AVOIDANCE MANEUVERS IN LOW EARTH ORBIT

Jason A. Reiter* and David B. Spencer†

Collision avoidance maneuvers to prevent orbital collisions between two catalogued objects are typically planned multiple days in advance. If the warning time is decreased to less than half-an-orbit in advance, the problem becomes more complex. Typically, the burn (assumed to be impulsive) would be placed at perigee or apogee and oriented in the direction that allows for a fuel-optimal maneuver to be performed well before the predicted collision. Instead, for quick-response scenarios, finite burn propagation was applied to determine the thrust duration and direction required to reach a desired minimum collision probability. Determining the thrust time and direction for a wide range of orbits and spacecraft properties resulted in a semi-analytical solution to the collision avoidance problem anywhere in Low Earth Orbit. The speed at which this method can be applied makes it valuable when minimal time is available to perform such a maneuver.

[View Full Paper]

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AAS 16-395

PARALLEL IMPLICIT RUNGE-KUTTA METHODS APPLIED TO COUPLED ORBIT/ATTITUDE PROPAGATION

Noble Hatten[*] and Ryan P. Russell[†]

A variable-step Gauss-Legendre implicit Runge-Kutta (GLIRK) propagator is applied to coupled orbit/attitude propagation. Concepts previously shown to improve efficiency in 3DOF propagation are modified and extended to the 6DOF problem, including the use of variable-fidelity dynamics models. The impact of computing the stage dynamics of a single step in parallel is examined using up to 23 threads and 22 associated GLIRK stages; one thread is reserved for an extra dynamics function evaluation used in the estimation of the local truncation error. Efficiency is found to peak for typical examples when using approximately 8 to 12 stages for both serial and parallel implementations. Accuracy and efficiency compare favorably to explicit Runge-Kutta and linear-multistep solvers for representative scenarios. However, linear-multistep methods are found to be more efficient for some applications, particularly in a serial computing environment, or when parallelism can be applied across multiple trajectories.

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AAS 16-447

ATHENA: A DATA-DRIVEN ANOMALY DETECTION AND SPACE OBJECT CLASSIFICATION TOOL FOR SSA

Navraj Singh,[*] Joshua T. Horwood,[†]
Jeffrey M. Aristoff[‡] and Jeremy Murray-Krezan[§]

We present *Athena*, a data-driven system we have developed for space object anomaly detection and classification. Although our algorithmic framework is designed for processing multiple data types, *Athena v1.0* focuses primarily on exploiting non-resolved photometric data (light-curves) obtained from optical sensors. The main techniques developed can be viewed as components of a machine learning pipeline, and include (i) feature extraction using ideas inspired by compressed sensing, (ii) unsupervised learning (via robust principal component analysis) for anomaly detection, (iii) supervised learning for object classification, and (iv) a unifying database that enables all of the above. This paper describes the Athena system components and demonstrates some of its use cases on both real and simulated photometric data.

[View Full Paper]

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AAS 16-453

DIRECT IMAGE-TO-LIKELIHOOD FOR TRACK-BEFORE-DETECT MULTI-BERNOULLI FILTER

Timothy S. Murphy,[*] Marcus J. Holzinger[†] and Brien Flewelling[‡]

This paper aims to apply the random finite set-based multi-Bernoilli filter to frame-to-frame tracking of space objects observed in electro optical imagery for space domain awareness applications. First, this paper will review random finite set filters applied to frame to frame tracking and their applications to space. A new likelihood function for space based imagery will be presented, based on the matched filter. A more educated birth model will be proposed which better models potential SO using observer characteristics and object dynamics. Simulation results will explore the range of objects that can be tracked. The final algorithm is able to perform completely uncued detection down to a total object SNR of 5.6 and a per pixel SNR of 1.5. Promising but inconclusive results are shown for total object SNR of 3.35 and per pixel SNR of 0.7.

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AAS 16-455

COMVECS: A SPECIAL PERTURBATIONS COVARIANCE-BASED TOOL FOR DUPLICATE ORBIT IDENTIFICATION

A. M. Segerman,[*] A. B. Hoskins[*] and Z. J. Sibert[*]

In operational space situational awareness, duplicate representations of an orbit can sometimes be produced. To maintain the uniqueness of space object catalog entries, the operations centers have employed techniques for duplicate resolution that were developed prior to the widespread use of special perturbations catalog maintenance and the proliferation of closely located orbits. A new special perturbations duplicate identification tool has been developed that leverages the covariances from special perturbations orbit determination and uses the Mahalanobis distance between orbits as a metric. A full description of the tool is presented, along with test results using actual and simulated orbits.

[View Full Paper]

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AAS 16-457

A CLASS OF CONVEX OPTIMIZATION PROBLEMS FOR TEMPLATE-BASED STAR SUBTRACTION

Brad Sease,[*] Brien Flewelling[†] and Jonathan Black[‡]

Common approaches to star removal rely on assumptions about sensor motion, which limit the applicability of the technique, or computationally expensive nonlinear iterative signal fitting processes. This paper proposes an algorithm related to conventional point spread function fitting but with reduced computational requirements. With a prior estimate of the expected behavior of a star in an image, it is possible to build template star signals. These templates then enable a global fitting process which approximates all of the star signals in an image simultaneously. Further, this problem may be formulated as a convex linear program.

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AAS 16-482

EVIDENTIAL REASONING APPLIED TO SINGLE-OBJECT LOSS-OF-CUSTODY SCENARIOS FOR TELESCOPE TASKING

Andris D. Jaunzemis[*] and Marcus J. Holzinger[†]

Evidential reasoning and modern data fusion models are applied to the single-object loss-of-custody scenario in ground-based tracking. Upon a missed observation, the cause of non-detection must be quickly understood to improve follow-up decision-making. Space domain awareness (SDA) sensors, including a brightness sensor and an All-Sky camera with an optical-flow-based cloud detection algorithm, are conditioned as Dempster-Shafer experts and used to assess the cause of a non-detection. Telescope re-tasking is also approached using Dempster-Shafer theory by planning the next observation to minimize an estimated lack-of-information. Results from real-world operational sensors show the algorithm's ability to adjust to changing observation conditions and re-task the primary electro-optical sensor accordingly.

[View Full Paper]

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AAS 16-510

PRELIMINARIES OF A SPACE SITUATIONAL AWARENESS ONTOLOGY

Robert J. Rovetto[*] and T. S. Kelso[†]

Space situational awareness (SSA) is vital for international safety and security, and the future of space travel. By improving SSA data-sharing we improve global SSA. Computational ontology may provide one means toward that goal. This paper develops the ontology of the SSA domain and takes steps in the creation of the space situational awareness ontology. Ontology objectives, requirements and desiderata are outlined; and both the SSA domain and the discipline of ontology are described. The purposes of the ontology include: exploring the potential for ontology development and engineering to (i) represent SSA data, general domain knowledge, objects and relationships (ii) annotate and express the meaning of that data, and (iii) foster SSA data-exchange and integration among SSA actors, orbital debris databases, space object catalogs and other SSA data repositories. By improving SSA via data- and knowledge-sharing, we can (iv) expand our scientific knowledge of the space environment, (v) advance our capacity for planetary defense from near-Earth objects, and (vi) ensure the future of safe space flight for generations to come.

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AAS 16-514

RESIDENT SPACE OBJECT SHAPE INVERSION VIA ADAPTIVE HAMILTONIAN MARKOV CHAIN MONTE CARLO

Richard Linares[*] and John L. Crassidis[†]

This paper presents a method to determine the shape of a space object while simultaneously recovering the observed space object's inertial orientation. This paper employs an Adaptive Hamiltonian Markov Chain Monte Carlo estimation approach, which uses light curve data to infer the space object's orientation, shape, and surface parameters. This method is shown to work well for relatively high dimensions and non-Gaussian distributions of the light curve inversion problem.

[View Full Paper]

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AAS 16-518

SPACE OBJECT CLASSIFICATION USING MODEL DRIVEN AND DATA DRIVEN METHODS

Richard Linares[*] and John L. Crassidis[†]

In recent years there has been an increase in the number of inactive and debris Space Objects (SOs). This work examines both data driven and model driven SO classification. The model driven approach investigated for this work is based on the Multiple Model Adaptive Estimation approach to extract SO characteristics from observations while estimating the probability the observations belonging to a given class of objects. The data driven methods are based on Principle Component Analysis and Convolutional Neural Network Classification approaches. The performance of these strategies for SO classification is demonstrated via simulated scenarios.

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AAS 16-538

RESIDENT SPACE OBJECT DETECTION USING ARCHIVAL THEMIS FLUXGATE MAGNETOMETER DATA

Julian Brew[*] and Marcus J. Holzinger[†]

Although the detection of space objects is generally achieved using optical and radar measurements, these methods are limited in the capability of detecting small space objects at geosynchronous altitudes. This paper examines the use of magnetometers to detect space objects by introducing a matched filter scoring approach and evaluating it using archival fluxgate magnetometer data from the NASA THEMIS mission. Relevant data-set processing and reduction is discussed in detail. Supporting evidence for using magnetometers to detect resident space objects is presented. Plausible detections of charged space objects are reviewed.

[View Full Paper]

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SPECIAL SESSION: RESULTS FROM GTOC8

Session Chair:

Session 24: Anastassios Petropoulos

The following paper was not available for publication:

AAS 16-421 Paper Withdrawn

AAS 16-248

GTOC8: RESULTS AND METHODS OF TEAM 3 – TSINGHUA UNIVERSITY

Gao Tang,[*] Hongwei Yang,[†] Fanghua Jiang,[‡] Hexi Baoyin[§] and Junfeng Li[§]

In this paper the methods proposed by team 3 in the 8th Global Trajectory Optimization Competition (GTOC8) are introduced. The final formation of the three spacecraft is obtained by analyzing the major factors which affect the performance index. Then the optimal trajectories to construct the final formation are generated which are then used as nominal trajectories. All the possible chances for observing the radio sources are calculated using the nominal trajectories. Followed by a global search algorithm to determine the observing sequence and time, indirect methods are applied to obtain the transfers which satisfy all the constraints for observations.

[View Full Paper]

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AAS 16-275

GTOC8: RESULTS AND METHODS OF ESA ADVANCED CONCEPTS TEAM AND JAXA-ISAS

Dario Izzo,* Daniel Hennes, Marcus Märtens, Ingmar Getzner, Krzysztof Nowak, Anna Heffernan, Stefano Campagnola, Chit Hong Yam, Naoya Ozaki and Yoshihide Sugimoto

We consider the interplanetary trajectory design problem posed by the 8th edition of the Global Trajectory Optimization Competition and present the end-to-end strategy developed by the team ACT-ISAS (a collaboration between the European Space Agency's Advanced Concepts Team and JAXA's Institute of Space and Astronautical Science). The resulting interplanetary trajectory won 1st place in the competition, achieving a final mission value of J = 146:33 [Mkm]. Several new algorithms were developed in this context but have an interest that go beyond the particular problem considered, thus, they are discussed in some detail. These include the Moon-targeting technique, allowing one to target a Moon encounter from a low Earth orbit; the 1-k and 2-k fly-by targeting techniques, enabling one to design resonant fly-bys while ensuring a targeted future formation plane; the distributed low-thrust targeting technique, admitting one to control the spacecraft formation plane at 1,000,000 [km]; and the low-thrust optimization technique, permitting one to enforce the formation plane's orientations as path constraints.

[View Full Paper]

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AAS 16-283

GTOC8: RESULTS AND METHODS OF TEAM 22

Lorenzo Casalino,[*] Guido Colasurdo,[†] Alessandro Zavoli[‡] and Marco Berga[§]

This paper describes the methods used and the results obtained by Team 22, composed of Politecnico di Torino, Università di Roma Sapienza, and Thales Alenia Space - Torino, in the eighth edition of the Global Trajectory Optimisation Competition (GTOC8). The strategy to define the mission architecture on the basis of the performance index is first described. The method to optimize the trajectory legs is then illustrated. Results and lesson learned are finally discussed.

[View Full Paper]

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AAS 16-362

GTOC8: RESULTS AND METHODS OF POLIMI-UPM

Francesco Topputo,* Diogene A. Dei Tos,† Daniele Filippetto,† Aureliano Rivolta,† Mauro Massari,* Amedeo Rocchi,‡ Pierluigi Di Lizia,† Juan Luis Gonzalo,§ Hodei Urrutxua, Claudio Bombardelli,†† Vincenzo Pesce,† Andrea Colagrossi† and Daniel Pastor Moreno‡‡**

In this work the solution to the 8th Global Trajectory Optimisation Competition proposed from the PoliMi-UPM team is presented. With the aim of maximizing the objective function, a two-stage strategy has been devised. First, two spacecraft target selenoflybys to significantly modify their orbital parameters, in particular increasing the semi-major axis. Later, the formation is steered with low-thrust propulsion to point radio sources within the assigned tolerance. The latter is achieved by means of a geometrical method that minimises the orbital parameters variation, and that provides boundary condition for an indirect method solution of the Two-point Boundary Value Problem. No constraints on the number of seen radio sources have been applied. On a higher level, a genetic algorithm is used to identify the optimal flyby parameters.

[View Full Paper]

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AAS 16-377

GTOC8: RESULTS AND METHODS OF THE UNIVERSITY OF COLORADO BOULDER

Jeffrey S. Parker,[*]
Jonathan D. Aziz,[†] Daniel Case,[‡] Luca Corpaccioli,[§] Carlos Deccia,[†] Ryan E. Handzo,[†] Jonathan Herman,[†] Nathan L. Parrish[†] and Stijn De Smet[†]

The University of Colorado Boulder participated in the 8th Global Trajectory Optimisation Competition, ultimately ranking sixth place. The submitted objective function of ~76,301,536 was achieved by focusing effort on placing the three spacecraft into a very desirable final constellation, where many high-value radio sources could be observed with very high *H*-values. The route to arrive at this constellation was designed to observe the same radio sources from lower *H*-values. The resulting mission included six radio sources observed three times each, four radio sources observed twice each, and six radio sources observed once each within the mission timeline.

[View Full Paper]

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AAS 16-384

GTOC8: RESULTS AND METHODS OF STATE KEY LABORATORY OF ASTRONAUTIC DYNAMICS

Hong-Xin Shen,[*] An-Yi Huang,[†] Zhi-Bin Zhang[‡] and Heng-Nian Li[§]

The paper presents the trajectory designed by the team State Key Laboratory of Astronautic Dynamics (Team10), for the 8th edition of the Global Trajectory Optimization Competition (GTOC8). The global and local optimization methods, which have been used at team10 to compute the GTOC8 trajectory, are presented. In particular, the generalities of the very long baseline formation configuration design strategy, the optimal maneuvers for lunar gravity-assist, the procedure for finding suitable radio sources, and the mathematics for the boundary value problem are described; the details of the solution are also given.

[View Full Paper]

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AAS 16-425

CONSTRUCTION AND VERIFICATION OF A SOLUTION OF THE 8TH GLOBAL TRAJECTORY OPTIMIZATION COMPETITION PROBLEM. TEAM 13: GLASGOWJENA+

Alessandro Peloni,[*] Dietmar Wolz,[†] Matteo Ceriotti[‡] and Ingo Althöfer[§]

This paper describes the methodology to find and verify the solution to the 8th Global Trajectory Optimization Competition (GTOC) problem, developed by Team 13, Glasgow-Jena+. We chose a stochastic approach to quickly assess a large number (about 10^{10}) of 3-spacecraft formations. A threshold was used to select promising solutions for further optimization. Our search algorithm (implemented in Java) is based on three C++ algorithms called via Java native interface (JNI). A great deal was given to the verification process, which became a core part of our solution. Our final solution has a performance index of J = 5.97×10^7 km, 40 distinct observations, and the sum of the final masses of the three spacecraft is 5846.57 kg.

[View Full Paper]

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AAS 16-501

GTOC8: PROBLEM DESCRIPTION AND SUMMARY OF THE RESULTS

Anastassios E. Petropoulos*

The Global Trajectory Optimisation Competition was inaugurated in 2005 by Dario Izzo of the Advanced Concepts Team, European Space Agency, as a means of fostering innovation in trajectory design and cross-fertilisation with other fields. GTOC2 through GTOC7 were organised by the winning teams of the preceding GTOC editions. Keeping this tradition, the Outer Planet Mission Analysis Group and Mission Design and Navigation Section of the Jet Propulsion Laboratory organised the eighth edition of the competition, GTOC8. The problem posed may loosely be described as mission design for high-resolution mapping of radio sources in the universe using space-based Very-Long-Baseline Interferometry (VLBI). Three low-thrust, Earth-orbiting spacecraft, which can perform lunar flybys, are to arrange and re-arrange themselves with as suitable baselines as possible to observe as many radio sources as possible over the course of a three-year mission. After the release of the precise problem statement, the 36 registered teams had four weeks to return their solutions to JPL for verification and ranking. A total of 18 teams returned solutions. In this paper we describe the GTOC8 problem, and give an overview of the solutions and their verification and ranking. Nine teams presented their work at a special GTOC8 session of the Meeting, including the winning team led jointly by the Advanced Concepts Team of the European Space Agency and the Institute of Space and Astronautical Science of the Japanese Aerospace Exploration Agency.

[View Full Paper]

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AAS 16-552

GTOC8: RESULTS AND METHODS OF TEAM 8/CHINESE ACADEMY OF SCIENCES

Shengmao He,[*] Zhengfan Zhu[†] and Yang Gao[‡]

We have proposed a series of Moon-to-Moon transfer orbits (a family of elliptical Keplerian orbits starting from the Moon and returning to the Moon) that possess an orbital resonance mechanism, and a unified model is developed to accommodate three typical transfers in literature: resonant orbits, backflip orbits, and consecutive collision orbits. These Moon-to-Moon transfer orbits could be patched together to construct long-chain trajectories involving a large number of lunar gravity assists, which is termed in this paper the consecutive lunar-flyby orbits. Assuming each spacecraft moves in a properly designed consecutive lunar-flyby orbit, spatial observing triangles with variable sizes and orientations can be established, enabling flexible interferometry observations towards radio sources. This idea is employed by Team 8 affiliated to the Chinese Academy of Sciences for designing medium- and small-size triangular formations to fulfill repeat observations of a number of selected radio sources. In addition, the large-size triangular formations are designed by constructing symmetric circular orbits, each of which has a radius of 1-million km. Finally, we submitted a solution with J = 49-million km that ranks 10th, and a revised result with J = 158.75 million km is obtained after the competition.

[View Full Paper]

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SPACECRAFT RENDEZVOUS

Session Chair:

Session 25: Andrew Sinclair

The following papers were not available for publication:

AAS 16-280 Paper Withdrawn

AAS 16-513 Paper Withdrawn

AAS 16-261

RELATIVE LAMBERT TRANSFER BASED ON RELATIVE ORBIT ELEMENTS AND THE APPLICATION IN HOVERING FORMATION CONTROL

Huan Chen,* Yinrui Rao,† Chao Han‡ and Jingjin Li§

Motivated by Lambert transfer orbit, the relative lambert transfer orbit between two different relative positions in the orbital coordinate of a reference satellite is proposed and deduced based on relative orbit elements. And the relative lambert transfer strategy is proposed. Then, the relative lambert transfer orbit is applied in the hovering formation analysis and design. And relative lambert transfer strategy is applied in the hovering formation control of initialization, maintain, movement and reconfiguration. Finally, a numerical simulation example of the hovering formation design and control is shown.

[View Full Paper]

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AAS 16-350

AUTONOMOUS TIME-OPTIMAL SPACECRAFT RENDEZVOUS AND PROXIMITY OPERATIONS USING STABILIZED CONTINUATION

Emily Kollin* **and Maruthi R. Akella†**

This paper addresses the minimum time rendezvous optimal control problem by implementing continuation with a stabilizing input. The rendezvous problem is first formulated as an optimal control problem which is then parameterized to enable the inclusion of the continuation parameter. A stabilizing input is then applied to attenuate the errors accumulated during the process of numerical integration. By applying stabilized continuation to a rendezvous scenario in which two spacecraft are initialized in the same planar, circular orbit separated by some phase angle, a family of minimum time rendezvous solutions is obtained for variable levels of thrust, mass flow rate, or initial phase angle separation. The approach is first demonstrated on a linear harmonic oscillator problem, and then applied to the Keplerian two-body motion model. The effectiveness of the stabilized continuation scheme when used to generate minimum time rendezvous trajectories is demonstrated through simulations.

[View Full Paper]

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AAS 16-356

NON-ITERATIVE APPROXIMATE SOLUTION TO THE ANGLES-ONLY INITIAL RELATIVE ORBIT DETERMINATION PROBLEM IN SPHERICAL COORDINATES

David K. Geller[*] and T. Alan Lovell[†]

An approximate solution to the angles-only Initial Relative Orbit Determination problem is presented and evaluated in the context of two-body orbital motion. The algorithm is noniterative and requires the singular value decomposition of a 4 x 4 matrix and the solution to a sixth-order polynomial. Four observations of the line-of-sight vector from a chief to a deputy in a nearby orbit are required. The position and velocity of the chief are assumed known. The development of the algorithm is based upon the Clohessy-Wiltshire equations in spherical coordinates and a second-order expansion of the nonlinear relative azimuth and elevation measurement equations. The accuracy of the algorithm is evaluated in the context of two-body orbital motion, a circular orbit chief, a variety of different deputy orbits, and different measurement time intervals. It is also shown that the initial approximate solution can be improved with a simple iterative procedure.

[View Full Paper]

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AAS 16-369

PRELIMINARY STUDY ON RELATIVE MOTION AND RENDEZVOUS BETWEEN SPACECRAFT IN THE RESTRICTED THREE-BODY PROBLEM

Davide Conte* and David B. Spencer†

The focus of this paper is to present a preliminary study concerning relative motion and rendezvous in the restricted three-body problem. This paper presents full numerical simulations compared with linearized results of relative motion around well-known Lagrangian orbits such as halo orbits around Earth-Moon L_2. Additionally, an initial linearization study is performed and presented to understand the general dynamics of such relative motion. Previous work on this topic relies on simplifications and assumptions that constrain the results to specific spatial domains and geometries. The reason to analyze such motion in linearized form as opposed to purely numerically integrate the equations of motion is to being able to study rendezvous and formation flying maneuvers around multiple families of Lagrangian orbits at once. Additionally, analytical and linearized analyses can provide important physical insight and help to quickly determine optimal solutions when searching through a large tradespace of orbital transfers and rendezvous maneuvers for both control-free and controlled dynamics. Future work is aimed to develop algorithms that, given a nominal Lagrangian orbit of interest, can describe the relative motion of two spacecraft that are operating "close" to each. Thus a more streamlined analytical work will be developed to compute which maneuvers are optimal to reduce Δv consumption, time of flight, or other parameters of interest.

[View Full Paper]

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AAS 16-400

NUMERICALLY APPROXIMATED RECEDING HORIZON CONTROL FOR UNCERTAIN PURSUIT-EVASION GAMES

Brian Janisch,[*] John E. Hurtado[†] and Kevin Brink[‡]

A robust technique for handling parameter and strategy uncertainty in a pursuit-evasion framework is developed. The method uses a receding horizon controller designed for singularly perturbed trajectories. The controller approximates the optimal feedback solution with small loss in optimality while remaining robust to incorrect information about an opposing player's dynamics or strategy. A simple analytic pursuit-evasion game motivates the method by demonstrating that the receding horizon solution closely approximates the optimal solution and may be solved much faster. Simulations of a nonlinear game show that the receding horizon controller is especially useful when it is unknown whether the opposing player is enacting an active or passive maneuver. In several cases, the receding horizon controller is shown to become more effective than a game-optimal controller acting with an incorrect strategy estimate. The major limitation of the technique for a nonlinear system is the expensive solution time; therefore, the optimal control problem is transformed to a nonlinear programming problem and the test cases are repeated to validate the method for real-time hardware operation.

[View Full Paper]

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AAS 16-459

EXPERIMENTS ON AUTONOMOUS SPACECRAFT RENDEZVOUS AND DOCKING USING AN ADAPTIVE ARTIFICIAL POTENTIAL FIELD APPROACH

Richard Zappulla II,[*] Hyeongjun Park,[†] Josep Virgili-Llop[†] and Marcello Romano[‡]

Numerous missions over the past decades have pushed the state-of-the-art in autonomous rendezvous and proximity operations (RPO). The paramount requirement for the various guidance algorithms performing RPO is obstacle avoidance. The Artificial Potential Function (APF) method is one such method that provides robust obstacle avoidance while attempting to complete RPO objectives. However, inherent to its formulation, it is not optimal; as such, an Adaptive Artificial Potential Function (AAPF) method has been developed in an effort to reduce fuel consumption while still providing effective and flexible obstacle avoidance that is offered by traditional (APF) guidance methods. In this paper, the APF and AAPF guidance methods are developed from a theoretical standpoint and experimentally tested in a RPO-like environment in order to validate previous simulations. The experiments are performed using the Spacecraft Robotics Laboratory (SRL) Floating Spacecraft Simulator (FSS) test bed. The FSS test bed consists of a highly planar, polished, 15-ton granite-monolith, atop which spacecraft simulators float on approximately five microns of compressed air. Lastly, implementation considerations and experimental results are discussed.

[View Full Paper]

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AAS 16-495

NONLINEAR ANALYTICAL EQUATIONS OF RELATIVE MOTION ON J_2-PERTURBED ECCENTRIC ORBITS

Bradley Kuiack[*] and Steve Ulrich[†]

Future spacecraft formation flying missions will require accurate autonomous guidance systems to calculate a reference, or desired, relative motion during reconfiguration maneuvers. However, the efficiency in terms of propellant used for such maneuvers depends on the fidelity of the dynamics model used for calculating the reference relative motion. Therefore, an efficient method for calculating relative motion should have an analytical solution, be applicable to an eccentric orbit, and should take into account the J2 perturbation. This paper accomplishes this through an exact analytical solution of the relative motion between two spacecraft based on the orbital elements of each spacecraft. Specifically, by propagating the J2-perturbed osculating orbital elements forward in time and solving the exact solution at each time step, an accurate representation of the true spacecraft relative motion is obtained. When compared to a numerical simulator, the proposed analytical solution is shown to accurately model the relative motion, with bounded errors on the order of meters over a wide range of eccentricity values.

[View Full Paper]

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AAS 16-507

COUPLED TRANSLATIONAL AND ROTATIONAL DYNAMICS FOR PRECISE CONSTRAINED RENDEZVOUS AND DOCKING WITH PERIODIC REFERENCE GOVERNORS

Christopher Petersen[*] and Ilya Kolmanovsky[†]

This paper derives a set of spacecraft translational and rotational equations of motion that are coupled and model the relative motion between an arbitrary point on a deputy spacecraft and an arbitrary point on a chief spacecraft. A periodic linear quadratic controller with a periodic reference governor for collision avoidance while docking is constructed based on the linearized system. Simulations demonstrate precise, rendezvous and docking using the coupled fully nonlinear model and proposed control scheme which successfully enforces constraints.

[View Full Paper]

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NAVIGATION

Session Chair:

Session 28: Kyle DeMars

AAS 16-201

ABSOLUTE NAVIGATION PERFORMANCE OF THE ORION EXPLORATION FLIGHT TEST 1

Renato Zanetti,[*] Greg Holt,[†] Robert Gay,[*] Christopher D'Souza[*] and Jastesh Sud[‡]

Launched in December 2014 atop a Delta IV Heavy from the Kennedy Space Center, the Orion vehicle's Exploration Flight Test-1 (EFT-1) successfully completed the objective to stress the system by placing the un-crewed vehicle on a high-energy parabolic trajectory replicating conditions similar to those that would be experienced when returning from an asteroid or a lunar mission. Unique challenges associated with designing the navigation system for EFT-1 are presented with an emphasis on how redundancy and robustness influenced the architecture. Two Inertial Measurement Units (IMUs), one GPS receiver and three barometric altimeters (BALTs) comprise the navigation sensor suite. The sensor data is multiplexed using conventional integration techniques and the state estimate is refined by the GPS pseudorange and deltarange measurements in an Extended Kalman Filter (EKF) that employs UDU factorization. The performance of the navigation system during flight is presented to substantiate the design.

[View Full Paper]

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AAS 16-228

NAVIGATION AND STATISTICAL DELTA-V ANALYSIS FOR DOUBLE-SATELLITE-AIDED CAPTURE AT JUPITER

Alfred E. Lynam* and Alan M. Didion†

Double-satellite-aided capture substantially reduces a mission's deterministic ΔV by using gravity assists of two of Jupiter's massive Galilean moons in addition to a Jupiter orbit insertion (JOI) maneuver. The statistical ΔV savings of double-satellite-aided capture vs. single-satellite-aided capture is more difficult to characterize because they are strongly dependent on the specifics of navigation technologies and methodologies. In this paper, we estimate the statistical ΔV required to execute Ganymede-Io-JOI (GIJ), Ganymede-Europa-JOI (GEJ), and Callisto-Ganymede-JOI (CGJ) double-satellite-aided capture using two different navigation assumptions with two different degrees of conservatism. Results show that updating the navigation solution and including a trajectory correction maneuver in between flybys results in a statistical ΔV of around 10 m/s (in addition to the deterministic JOI ΔV). The more conservative scenarios with no corrections until the JOI cleanup maneuver days later have higher statistical ΔV 's, but the CGJ scenario is the only one that has a small risk (0.265%) of crashing into a moon.

[View Full Paper]

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AAS 16-232

INDEPENDENT NAVIGATION TEAM CONTRIBUTION TO NEW HORIZONS' PLUTO SYSTEM FLYBY[*]

Paul F. Thompson,[†] Shyam Bhaskaran,[‡]
Dylan Boone,[§] Stephen B. Broschart,[§] Gerhard Kruizinga,[§]
William Owen[§] and Tseng-Chan M. Wang[**]

The New Horizons spacecraft made its closest approach to Pluto on 14 July 2015. The most significant challenge of this mission was that the Pluto system ephemeris was initially known with a precision of ~1000 km. This needed to be improved significantly on approach in order to meet the science requirements. During the final six months leading to the flyby, a JPL Independent Navigation (INAV) Team was included in the ephemeris knowledge update process as a cross-check on the Project Navigation (PNAV) Team's results. This paper discusses the INAV team's experiences and challenges navigating New Horizons through the Pluto planetary system encounter.

[View Full Paper]

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AAS 16-358

EFFECT OF UPDATE FREQUENCY ON EKF AND UKF PERFORMANCE

Paul J. Frontera,[*] Ronald J. Proulx,[†] Mark Karpenko[‡] and I. Michael Ross[§]

Physical parameters often cannot be measured directly and must be estimated using available measurements. These measurements may be related to the unknown parameter by nonlinear kinematic equations. Nonlinear recursive estimation techniques, such as the Extended Kalman Filter (EKF) and the Unscented Kalman Filter (UKF), may be employed to estimate unmeasurable parameters using noisy measurement data. Each technique employs different approximation methods to allow the application of the linear Kalman filter structure. This paper investigates the impact of measurement update frequency on EKF and UKF performance for a parameter estimation problem.

[View Full Paper]

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AAS 16-401

EXTENDED KALMAN FILTER BASED ATTITUDE AND DRIFT ESTIMATION OF A LUNAR LANDER USING STAR SENSOR AND GYROSCOPE

Deepana Gandhi,[*] P. Natarajan,[†]
Karthic Balasubramanian[*] and Cheerudeep Chintha[*]

Team Indus GLXP Mission is to soft land on moon, traverse 500 meters and send back HD imagery to earth. To accomplish this objective, Team Indus' strategy includes the design and realization of a lunar lander which would deliver a rover to the lunar surface. Attitude determination, using star sensor and gyroscope, is an important task of the on board Attitude Determination and Control System (ADCS). As time proceeds the gyroscope accumulates drift which is a major source of error to the ADCS. This paper discusses a Multiplicative Extended Kalman Filter (MEKF) to estimate the gyroscope drift and attitude of the spacecraft. The filter performance, demonstrated through simulation results, is satisfactory and is expected to meet the objectives.

[View Full Paper]

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AAS 16-424

DISTRIBUTED PARAMETER SYSTEM FOR OPTIMIZATION AND FILTERING IN ASTRODYNAMIC SOFTWARE

Jonathon Smith, William Taber, Theodore Drain, Scott Evans, James Evans, Michelle Guevara, William Schulze, Richard Sunseri and Hsi-Cheng Wu*

The Mission Analysis, Operations, and Navigation Toolkit Environment (MONTE) is JPL's signature astrodynamic computing platform. It supports all phases of space mission development, from early stage mission design and analysis through flight navigation services. A central component of MONTE's optimization and filtering modules is its distributed parameter system, which allows partial derivatives to be computed for flexible sets of supported astrodynamic parameters on request. This paper outlines the object-oriented design MONTE uses for its parameter system, and provides concrete set of examples showing the power of this approach.

[View Full Paper]

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VISION-BASED RELATIVE NAVIGATION USING 3D SCALE SPACE THEORY

Ashish Jagat,* Andrew Rhodes† and John Christian‡

Objects that are far away often appear small and unresolved in optical imagery. Conversely, objects appear fully resolved when closer. Thus, during an on-orbit rendezvous that begins far away and concludes with a docking, it is not uncommon for the relative navigation system to be challenged with processing unresolved, partially resolved, and fully resolved imagery. While a great deal of prior work exists on processing images containing unresolved and fully resolved objects, fundamentally different techniques are used in the processing of these data. Therefore, this manuscript explores the use of scale space theory and multi-scale 3D modeling as a means for unifying the image processing approach across all scales during a complete spacecraft rendezvous sequence.

[View Full Paper]

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AAS 16-441

PARAMETRIC COVARIANCE MODEL FOR HORIZON-BASED OPTICAL NAVIGATION

Jacob Hikes[*] and John A. Christian[†]

Images of the Earth and Moon may be used to autonomously navigate a spacecraft in cislunar space. New optical navigation (OPNAV) techniques have revitalized interest in horizon-based methods. While the generation of precise OPNAV measurements is well understood, the measurement covariance can be rather cumbersome to compute in practice. This problem is addressed by developing a simple parametric covariance model that fully captures the geometry of measuring the lit horizon of an ellipsoidal. These simple models provide insight into the nature of the horizon-based OPNAV covariance that was previously obscured by long and difficult to understand equations.

[View Full Paper]

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AAS 16-442

PRELIMINARY INVESTIGATION IN INTERSTELLAR NAVIGATION TECHNIQUES

Stoian Borissov*[*] and Daniele Mortari[†]

The classic methods of position estimation become invalid once a spacecraft leaves the local vicinity of our solar system. Parallax starts to have a noticeable effect on star identification as near as 100 AU from Earth. In order to compensate for the changing appearance of the stars multiple approaches are possible. In this paper we develop a new method of interstellar navigation based on identifying observed stars and measuring stellar parallax. A running on-board range estimate must be used to update the visible star catalog to perform star ID. Additionally, once stars are identified each of these stars can then act as a beacon for position estimation. This problem, known as the perspective-n-point (PnP) Problem has been well studied in the field of computer science and robotics. This paper also investigates the use of pulsars for interstellar navigation has been studied extensively and offers a baseline for comparing other position estimation methods. Final recommendations are made on future work based on the most promising methods.

[View Full Paper]

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AAS 16-445

SPACECRAFT NAVIGATION USING A ROBUST MULTI-SENSOR FAULT DETECTION SCHEME

Samuel J. Haberberger[*] and Kyle J. DeMars[†]

Redundant sensor networks of inertial measurement units (IMUs) provide inherent robustness and redundancy to a navigation solution obtained by dead reckoning the fused accelerations and angular velocities sensed by the IMU. However, IMUs have been known to experience faults risking catastrophic mission failure creating large financial setbacks and an increased risk of human safety. Robust on-board fault detection schemes are developed and analyzed for a multi-sensor distributed network specifically for IMUs. Simulations of a spacecraft are used to baseline several cases of sensor failure in a distributed network undergoing fusion to produce an accurate navigation solution. The presented results exhibit a robust fault identification scheme that successfully removes a failing sensor from the fusion process while maintaining accurate navigation solutions. In the event of a temporary sensor failure, the fault detection algorithm recognizes the sensors' return to nominal operating conditions and processes its sensor data accordingly.

[View Full Paper]

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AAS 16-492

AN OPTIMIZATION BASED APPROACH TO CORRELATION OF OBSERVATIONS WITH UNCERTAINTY

Johnny L. Worthy III,[*] Marcus J. Holzinger[†] and Daniel J. Scheeres[‡]

The observation to observation correlation problem can be addressed by determining if the probabilistic admissible regions produced from each observation have a point of intersection. An observation association method is developed which uses an optimization based approach to identify the point of intersection between two probabilistic admissible regions. A binary hypothesis test with a selected false alarm rate is used to probabilistically determine whether an intersection exists at the point(s) of minimum distance. The distribution of states about a point of intersection, if it exists, is the initial orbit estimate. If a point of intersection does not exist, then the observations are uncorrelated. The efficacy of the correlation method is demonstrated on observation data collected from the Georgia Tech Space Object Research Telescope.

[View Full Paper]

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AAS 16-509

CELESTIAL NAVIGATION DEVICE FOR FUTURE AUTONOMOUS APPLICATIONS

Thomas Fuller,[*] William Nitsch[*] and May-Win Thein[†]

Determination of an extraterrestrial rover's latitude and longitude will be an essential part of the exploration of other planets. This paper presents a self-contained, Digital Single Lens Reflex (DSLR) camera based celestial navigation device that is based on nautical Sight Reduction techniques. This paper discusses a novel method for observing the altitude angle of a star. Also presented are simulation results for two different categories of observations, three stars sighted simultaneously and a single star sighted at three different times. Simulation parameters are derived using measurement uncertainty analysis with both published and experimental values of uncertainty. Experimental results suggest that a navigational error of approximately 4.5 nautical miles is possible and are presented along with a discussions and analysis on possible improvements.

[View Full Paper]

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INDEX

INDEX TO ALL AMERICAN ASTRONAUTICAL SOCIETY PAPERS AND ARTICLES 1954 - 1992

This index is a numerical/chronological index (which also serves as a citation index) and an author index. (A subject index volume will be forthcoming.)

It covers all articles that appear in the following:

Advances in the Astronautical Sciences (1957 - 1992)
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NUMERICAL INDEX*

VOLUME 158 I, II, III & IV

ADVANCES IN THE ASTRONAUTICAL SCIENCES, SPACEFLIGHT MECHANICS 2016 (2016)

(26th AAS/AIAA Space Flight Mechanics Meeting, February 14–18, 2016, Napa, California, U.S.A.)

* Unless otherwise indicated all papers appear in Volume 158, *Advances in the Astronautical Sciences*. Part I, Part II, Part III and Part IV indicate in which part in the hard copy version of the proceedings that the paper appears.

AAS 16-219 The Deployment of Mascot-2 to Didymoon, Simon Tardivel, Caroline Lange, Stephan Ulamec and Jens Biele (Part IV)

AAS 16-220 Reentry Trajectory Optimization under the Effects of Uncertain Atmospheric Density and Wind Field, Yuan Ren and Jinjun Shan (Part II)

AAS 16-221 LDSD POST2 Modeling Enhancements in Support of SFDT-2 Flight Operations, Joseph White, Angela L. Bowes, Soumyo Dutta, Mark C. Ivanov and Eric M. Queen (Part I)

AAS 16-222 Post-Flight Assessment of Low Density Supersonic Decelerator Flight Dynamics Test 2 Simulation, Soumyo Dutta, Angela L. Bowes, Joseph P. White, Scott A. Striepe, Eric M. Queen, Clara O'Farrell and Mark C. Ivanov (Part I)

AAS 16-223 Not Assigned

AAS 16-224 Corrections on Repeating Ground-Track Orbits and Their Applications in Satellite Constellation Design, David Arnas, Daniel Casanova and Eva Tresaco (Part III)

AAS 16-225 Optimization of a 3D Printed CubeSat Baffle Using Ray Tracing, Tjorven Delabie, Diego Gómez Ramírez, Matt Boucher, Gert Raskin and Dirk Vandepitte (Part I)

AAS 16-226 Not Available (Withdrawn)

AAS 16-227 Broad Search for Direct Trajectories from Earth to Double-Satellite-Aided Capture at Jupiter with Deep Space Maneuvers, Alfred E. Lynam (Part I)

AAS 16-228 Navigation and Statistical Delta-V Analysis for Double-Satellite-Aided Capture at Jupiter, Alfred E. Lynam and Alan M. Didion (Part IV)

AAS 16-229 Development of a Tool for Analyzing Orbits around Asteroids, Julian Niedling, David Gaylor, Marcus Hallmann and Roger Foerstner (Part IV)

AAS 16-230 Atmospheric Trajectory Optimization of a Rocket Reusable First Stage with Turbojet Engines, Eric Bourgeois, Cédric Rommel, Jean-Marc Bahu and Nicolas Praly (Part II)

AAS 16-231 Interplanetary Nanospacecraft Travel Capabilities, Simon Tardivel, Stefano Campagnola and Andrew T. Klesh (Part II)

AAS 16-232 Independent Navigation Team Contribution to New Horizons' Pluto System Flyby, Paul F. Thompson, Shyam Bhaskaran, Dylan Boone, Stephen B. Broschart, Gerhard Kruizinga, William Owen and Tseng-Chan M. Wang (Part IV)

AAS 16-233 Using Space Population Models to Generate Representative Space Object Catalogs, Daniel L Oltrogge and Vitali Braun (Part III)

AAS 16-234 BepiColombo Trajectory Options to Mercury in 2018 and 2019, Rüdiger Jehn and Yves Langevin (Part II)

AAS 16-235 Ground-Based Navigation and Dispersion Analysis for the Orion Exploration Mission 1, Christopher D'Souza, Greg Holt, Renato Zanetti and Brandon Wood (Part IV)

AAS 16-236 Probabilistic Initial Orbit Determination, Roberto Armellin and Pierluigi Di Lizia (Part III)

AAS 16-237 Maven Navigation Overview, Mark Jesick, Stuart Demcak, Brian Young, Drew Jones, Sarah Elizabeth McCandless, Maximilian Schadegg, Eric Graat, Mark Ryne, Hui Ying Wen, Paul Stumpf, Min-Kun Chung, Andrew Vaughan, Eric Gustafson, Try Lam and David Folta (Part II)

AAS 16-238 Not Assigned

AAS 16-239 Global Optimization of Low-Thrust Interplanetary Trajectories Subject to Operational Constraints, Jacob A. Englander, Matthew A. Vavrina and David W. Hinckley, Jr. (Part I)

AAS 16-240 Re-Entry Prediction of Spent Rocket Bodies in GTO, David Gondelach, Aleksander Lidtke, Roberto Armellin, Camilla Colombo, Hugh Lewis, Quirin Funke and Tim Flohrer (Part III)

AAS 16-241 Approaches to Evaluating Probability of Collision Uncertainty, Matthew D. Hejduk and Lauren C. Johnson (Part IV)

AAS 16-242 A GPU-Accelerated Multiphase Computational Tool for Asteroid Fragmentation/ Pulverization Simulation, Ben J. Zimmerman and Bong Wie (Part IV)

AAS 16-243 Cassini Maneuver Experience Through the Last Icy Satellite Targeted Flybys of the Mission, Sonia Hernandez, Sean V. Wagner, Mar Vaquero, Yungsun Hahn, Powtawche N. Valerino, Frank E. Laipert, Mau C. Wong and Paul W. Stumpf (Part I)

AAS 16-244 Lunar Near Rectilinear Orbits and Cis-Lunar Transfer Trajectories in Support of the Deep Space Proving Ground, Michel Loucks, Kevin Post and John Carrico (Part II)

AAS 16-245 Surrogate Model for Probabilistic Modeling of Atmospheric Entry for Small NEO's, Piyush M. Mehta, Martin Kubicek, Edmondo Minisci and Massimiliano Vasile (Part II)

AAS 16-246 Not Assigned

AAS 16-247 Not Available (Withdrawn)

AAS 16-248 GTOC8: Results and Methods of Team 3 – Tsinghua University, Gao Tang, Hongwei Yang, Fanghua Jiang, Hexi Baoyin and Junfeng Li (Part IV)

AAS 16-249 Not Assigned

AAS 16-250 Analysis of Solar Radiation Pressure Effects on the OSIRIS-REx Spacecraft in Orbit around Bennu, Siamak G. Hesar, Daniel J. Scheeres and Jay W. McMahon (Part IV)

AAS 16-251 Multiple Design Options for Interplanetary Orbiter Missions Using Pseudostate Technique, S. P. Parvathi and R. V. Ramanan (Part II)

AAS 16-252 Not Assigned

AAS 16-253 A GNC Simulation of a Far-Range Approach Towards a Target in Geostationary Orbit, Sofya Spiridonova and Ralph Kahle (Part III)

AAS 16-254 Evaluation of Net Capture of Space Debris in Multiple Mission Scenarios, Eleonora M. Botta, Inna Sharf and Arun K. Misra (Part III)

AAS 16-255 End-to-End Trajectory for Conjunction Class Mars Missions Using Hybrid Solar-Electric/Chemical Transportation System, Patrick R. Chai, Raymond G. Merrill and Min Qu (Part II)

AAS 16-256 Preliminary Investigation of Onboard Orbit Determination Using Deep Space Atomic Clock Based Radio Tracking, Todd A. Ely, Jeanette Veldman and Jill Seubert (Part III)

AAS 16-257 Final Mission and Navigation Design for the 2016 Mars Insight Mission, Fernando Abilleira, Allen Halsell, Ken Fujii, Eric Gustafson, Clifford Helfrich, Eunice Lau, Julim Lee, Neil Mottinger, Jill Seubert, Evgeniy Sklyanskiy, Mark Wallace and Jessica Williams (Part II)

AAS 16-279 On the Astrodynamics Applications of Weierstrass Elliptic and Related Functions, Dario Izzo and Francesco Biscani (Part III)

AAS 16-280 Not Available (Withdrawn)

AAS 16-281 Study on Impact Experiment of Hayabusa2 Mission, Takanao Saiki, Hiroshi Imamura, Yuya Mimasu and Yuichi Tsuda (Part IV)

AAS 16-282 Advanced Thermal Radiation Pressure Modeling and its Benefits for the Microscope Mission, Benny Rievers, Meike List and Stefanie Bremer (Part III)

AAS 16-283 GTOC8: Results and Methods of Team 22, Lorenzo Casalino, Guido Colasurdo, Alessandro Zavoli and Marco Berga (Part IV)

AAS 16-284 Not Assigned

AAS 16-285 The Lunar IceCube Mission Design: Construction of Feasible Transfer Trajectories with a Constrained Departure, David C. Folta, Natasha Bosanac, Andrew Cox and Kathleen C. Howell (Part II)

AAS 16-286 Performance Characterization of a Landmark Measurement System for ARRM Terrain Relative Navigation, Michael A. Shoemaker, Cinnamon Wright, Andrew J. Liounis, Kenneth M. Getzandanner, John M. Van Eepoel and Keith D. DeWeese (Part IV)

AAS 16-287 Star Centroid on the *F*-Radius Sphere Using von Mises-Fisher Probability Distribution, Daniele Mortari, Márcio A. A. Fialho and Steven A. Lockhart (Part I)

AAS 16-288 Construction of Supersonic Flight Dynamics Test (SFDT-2) Vehicle Monte Carlo Splashdown Footprints for Use in Range Safety and Recovery Operations, William D. Strauss and Mark C. Ivanov (Part II)

AAS 16-289 Space Object Collision Probability via Monte Carlo on the Graphics Processing Unit, Vivek Vittaldev and Ryan P. Russell (Part IV)

AAS 16-290 Fast Autonomous Three-Axis Constrained Attitude Pathfinding and Visualization for Boresight Alignment, Sergei Tanygin (Part II)

AAS 16-291 to -292 Not Assigned

AAS 16-293 Delta-V Assisted Periodic Orbits around Small Bodies, Shota Kikuchi, Yuichi Tsuda and Jun'ichiro Kawaguchi (Part IV)

AAS 16-294 to -297 Not Assigned

AAS 16-298 The Theory of Lattice Flower Formations and its Application to Intensity Correlation Interferometry, Daniele Mortari and David C. Hyland (Part III)

AAS 16-299 Transfers to a Sun-Earth Saddle Point: An Extended Mission Design Option for LISA Pathfinder, Andrew Cox and Kathleen C. Howell (Part I)

AAS 16-300 Stochastic Differential Dynamic Programming for Low-Thrust Trajectory Design with State Uncertainty, Naoya Ozaki, Ryu Funase, Stefano Campagnola and Chit Hong Yam (Part I)

AAS 16-301 SSL Commercial Geosynchronous Spacecraft Orbit Raising Considerations, Gregory Lemieux and Andrew E. Turner (Part III)

AAS 16-302 Fragmentation Event Tracking with the GM-CPHD Filter, Daniel S. Bryant and Brandon A. Jones (Part IV)

AAS 16-303 Space Event Detection via Robust Time Series Forecasting, Pradipto Ghosh (Part IV)

AAS 16-346 Not Assigned

AAS 16-347 Control of High Fidelity Linearized Model for Satellite Formation Flight Using Aerodynamic Drag, M. S. Shouman and A. M. Atallah (Part III)

AAS 16-348 Attitude Determination and Control of ITASAT CubeSat, Valdemir Carrara (Part I)

AAS 16-349 A Comparison Between Gibbs and Herrick-Gibbs Orbit Determination Methods, Arvind Kaushik, Kohei Fujimoto, Kyle T. Alfriend, John E. Hurtado and John L. Junkins (Part III)

AAS 16-350 Autonomous Time-Optimal Spacecraft Rendezvous and Proximity Operations Using Stabilized Continuation, Emily Kollin and Maruthi R. Akella (Part IV)

AAS 16-351 Quantification of the Performance of Numerical Orbit Propagators, Hodei Urrutxua, Javier Roa, Juan Luis Gonzalo, Jesús Peláez and Claudio Bombardelli (Part III)

AAS 16-352 Dynamically Scaled Immersion and Invariance Approach for Spacecraft Attitude Tracking Control, Sungpil Yang and Maruthi R. Akella (Part II)

AAS 16-353 Impact of the Integration Stop-Condition on the Accuracy of Regularized Orbit Formulations, Hodei Urrutxua, Jesús Peláez and Claudio Bombardelli (Part III)

AAS 16-354 Using Shifting Masses to Reject Aerodynamic Perturbations and to Maintain a Stable Attitude in Very Low Earth Orbit, Josep Virgili-Llop, Halis C. Polat and Marcello Romano (Part II)

AAS 16-355 Not Assigned

AAS 16-356 Non-Iterative Approximate Solution to the Angles-Only Initial Relative Orbit Determination Problem in Spherical Coordinates, David K. Geller and T. Alan Lovell (Part IV)

AAS 16-357 Comparison of Orbit Element Sets for Modeling Perturbed Satellite Relative Motion, Kirk W. Johnson, Srinivas R. Vadali and Kyle T. Alfriend (Part III)

AAS 16-358 Effect of Update Frequency on EKF and UKF Performance, Paul J. Frontera, Ronald J. Proulx, Mark Karpenko and I. Michael Ross (Part IV)

AAS 16-359 Mission Design Considerations for Mars Cargo of the Human Spaceflight Architecture Team’s Evolvable Mars Campaign, Waldy K. Sjauw, Melissa L. McGuire and Joshua E. Freeh (Part II)

AAS 16-360 Satellite Constellation Design for the Solve Mission Investigating Diurnal Cycles of Vegetation Phenomena, Luzius Kronig, Sung Wook Paek, Anton Ivanov and Olivier de Weck (Part III)

AAS 16-361 Jupiter Tour of the Jupiter Icy Moon Explorer, Arnaud Boutonnet and Johannes Schoenmaekers (Part II)

AAS 16-362 GTOC8: Results and Methods of PoliMi-UPM, Francesco Topputo, Diogene A. Dei Tos, Daniele Filippetto, Aureliano Rivolta, Mauro Massari, Amedeo Rocchi, Pierluigi Di Lizia, Juan Luis Gonzalo, Hodei Urrutxua, Claudio Bombardelli, Vincenzo Pesce, Andrea Colagrossi and Daniel Pastor Moreno (Part IV)

AAS 16-363 A Note on a Geometrical Method to Solve Spacecraft Formation Flying Control, Aureliano Rivolta, Diogene A. Dei Tos and Daniele Filippetto (Part III)

AAS 16-364 On-Board Orbit Determination Using Sun Sensor and Optical Navigation Camera for Interplanetary Trajectory, Yosuke Kawabata and Yasuhiro Kawakatsu (Part III)

AAS 16-473 Trojan Asteroid Mission Design: Target Selection and Sequencing Optimization, Owen P. Blough, Tyler K. Farrington and Jennifer Hudson (Part II)

AAS 16-474 Boundary Model for Satellite Breakup Debris Clouds, Felix R. Hoots and Brian W. Hansen (Part III)

AAS 16-475 Precomputing Process Noise for Onboard Sequential Filters, Corwin Olson and Ryan P. Russell (Part III)

AAS 16-476 Application of Modified Chebyshev Picard Iteration to Differential Correction for Improved Robustness and Computation Time, Travis Swenson, Robyn Woollands, John Junkins and Martin Lo (Part I)

AAS 16-477 Satellite Navigation in Cis-Lunar Space Using High Definition Television Signals, Ryan E. Handzo, Jeffrey S. Parker, George H. Born, Austin Anderson and Jorge Cervantes (Part III)

AAS 16-478 Formation Flying Concept for Bi-Static SAR Mapping of Titan Surface, Tommaso Guffanti and Michèle Lavagna (Part III)

AAS 16-479 On the Application of Extended Logarithmic Smoothing Technique for Indirect Optimization of Minimum-Fuel Trajectories, Ehsan Taheri, Ilya Kolmanovsky and Ella Atkins (Part I)

AAS 16-480 Not Assigned

AAS 16-481 Parametric Analysis of Low-Thrust Lunar Transfers with Resonant Encounters, Maksim Shirobokov and Sergey Trofimov (Part I)

AAS 16-482 Evidential Reasoning Applied to Single-Object Loss-of-Custody Scenarios for Telescope Tasking, Andris D. Jaunzemis and Marcus J. Holzinger (Part IV)

AAS 16-483 Potential Effects of a Realistic Solar Sail and Comparison to an Ideal Sail, Jules Simo and Colin R. McInnes (Part III)

AAS 16-484 Dynamics of Asteroid 2006 RH120: Pre-Capture and Escape Phases, Brian D. Anderson and Martin W. Lo (Part I)

AAS 16-485 Orion Exploration Mission Entry Interface Target Line, Jeremy R. Rea (Part II)

AAS 16-486 Appropriate Fidelity Electrostatic Force Evaluation Considering a Range of Spacecraft Separations, Joseph Hughes and Hanspeter Schaub (Part III)

AAS 16-487 Not Available (Withdrawn)

AAS 16-488 Earth-Moon Multipurpose Orbiting Infrastructure, Simone Flavio Rafano Carnà, Lorenzo Bucci and Michèle Lavagna (Part II)

AAS 16-489 An Update to the Themis Thermal Gauging Fuel Estimation Process and its Use in a Fuel Imbalance Anomaly, Aaron J. Burgart, Daniel Cosgrove, Jeffrey Marchese and Manfred Bester (Part I)

AAS 16-490 Method for Constellation Design for Earth Periodic Coverage Using Compound Satellite Structures on Orbits with Synchronized Nodal Regression, Yury N. Razoumny (Part III)

AAS 16-491 Multi-Fidelity Model Fusion and Uncertainty Quantification Using High Dimensional Model Representation, Martin Kubicek, Piyush M. Mehta, Edmondo Minisci and Massimiliano Vasile (Part II)

AAS 16-492 An Optimization Based Approach to Correlation of Observations with Uncertainty, Johnny L. Worthy III, Marcus J. Holzinger and Daniel J. Scheeres (Part IV)

AAS 16-493 Commercial CubeSat Technology to Enhance Science: Communications, Space Debris Identification and Moon Surface Reconnaissance Using Lagrangian Cyclers, Pedro J. Llanos and Abdiel Santos (Part II)

AAS 16-494 Initial Results for Preliminary Trajectory Design of Multi-Target Active Debris Removal Missions Using the Atom Solver, Kartik Kumar, Abhishek Agrawal, Enne Hekma and Francesco Topputo (Part II)

AAS 16-495 Nonlinear Analytical Equations of Relative Motion on J_2-Perturbed Eccentric Orbits, Bradley Kuiack and Steve Ulrich (Part IV)

AAS 16-496 Third Order Cartesian Relative Motion Perturbation Solutions for Slightly Eccentric Chief Orbits, Eric A. Butcher, T. Alan Lovell and Andrew Harris (Part III)

AAS 16-497 Adaptive Two-Point Boundary Value Problem Tool for Accurate and Efficient Computation of Perturbed Orbit Transfers, Robyn M. Woollands, Julie L. Read, Austin B. Probe and John L. Junkins (Part III)

AAS 16-498 Development of CubeSat Attitude Determination and Control System with a Hybrid Control Strategy and its Simulator on SO(3), Dae Young Lee, Hyeongjun Park and James W. Cutler (Part II)

AAS 16-499 Dynamics and Control of the Flexible Electrostatic Sail Deployment, JoAnna Fulton and Hanspeter Schaub (Part I)

AAS 16-500 High Geometric Fidelity Modeling of Solar Radiation Pressure Using Graphics Processing Unit, Patrick W. Kenneally and Hanspeter Schaub (Part III)

AAS 16-501 GTOC8: Problem Description and Summary of the Results, Anastassios E. Petropoulos (Part IV)

AAS 16-502 Initial Navigation Analysis for the Europa Multiple Flyby Mission Concept, Sumita Nandi, Julie Kangas, Powtawche Valerino, Brent Buffington, Rodica Ionasescu and Dylan Boone (Part IV)

AAS 16-503 Not Available (Withdrawn)

AAS 16-504 Semi-Analytical Adaptive Guidance Computation Based on Differential Algebra for Autonomous Planetary Landing, Paolo Lunghi, Roberto Armellin, Pierluigi Di Lizia and Michèle Lavagna (Part II)

AAS 16-505 to -506 Not Assigned

AAS 16-507 Coupled Translational and Rotational Dynamics for Precise Constrained Rendezvous and Docking with Periodic Reference Governors, Christopher Petersen and Ilya Kolmanovsky (Part IV)

AAS 16-508 The Effect of Tidal Forces on the Evolution of Minimum Energy Configurations of the Full Three-Body Problem, Edward C. Levine and Christine Hartzell (Part III)

AAS 16-509 Celestial Navigation Device for Future Autonomous Applications, Thomas Fuller, William Nitsch and May-Win Thein (Part IV)

AAS 16-510 Preliminaries of a Space Situational Awareness Ontology, Robert J. Rovetto and T. S. Kelso (Part IV)

AAS 16-511 Repetitive Control Using Real Time Frequency Response Updates for Robustness to Parasitic Poles, Pitcha Prasitmeeboon and Richard W. Longman (Part II)

AAS 16-512 Angles-Only Initial Relative-Orbit Determination via Successive Maneuvers, Laura M. Hebert, Andrew J. Sinclair and T. Alan Lovell (Part I)

AAS 16-513 Not Available (Withdrawn)

AAS 16-514 Resident Space Object Shape Inversion via Adaptive Hamiltonian Markov Chain Monte Carlo, Richard Linares and John L. Crassidis (Part IV)

AAS 16-515 Dynamic Observability Analysis for Attitude, Angular Velocity, Shape, and Surface Parameters, Richard Linares and John L. Crassidis (Part II)

AAS 16-516 Not Available (Withdrawn)

AAS 16-517 Geostationary Satellite Station Keeping Using Drift Counteraction Optimal Control, Robert A. E. Zidek and Ilya V. Kolmanovsky (Part I)

AAS 16-518 Space Object Classification Using Model Driven and Data Driven Methods, Richard Linares and John L. Crassidis (Part IV)

AAS 16-519 Feasibility Regions of Boundary Value Problems of Low-Thrust Trajectories, Chit Hong Yam, Stefano Campagnola, Yasuhiro Kawakatsu and Ming Tony Shing (Part I)

AAS 16-520 Monte Carlo Propagation of Orbital Elements Using Modified Chebyshev Picard Iteration, Julie L. Read, Tarek A. Elgohary, Austin B. Probe and John L. Junkins (Part III)

AAS 16-521 to -522 Not Assigned

AAS 16-523 The Shadow Trajectory Model for Fast Low-Thrust Indirect Optimization, Ricardo L. Restrepo and Ryan P. Russell (Part I)

AAS 16-524 to -525 Not Assigned

AAS 16-526 Hybrid Differential Dynamic Programming with Stochastic Search, Jonathan D. Aziz, Jeffrey S. Parker and Jacob A. Englander (Part I)

AAS 16-527 Real-Time Optimal Control and Target Assignment for Autonomous in-Orbit Satellite Assembly from a Modular Heterogeneous Swarm, Rebecca C. Foust, Soon-Jo Chung and Fred Y. Hadaegh (Part II)

AAS 16-528 Not Assigned

AAS 16-529 Trajectory Characteristics of Spacecraft Propelled by Planet/Asteroid-Based Photonic Laser Propulsion, Fu-Yuen Hsiao (Part II)

AAS 16-530 Improved Maneuver-Free Approach to Angles-Only Navigation for Space Rendezvous, Joshua Sullivan, Adam W. Koenig and Simone D'Amico (Part I)

AAS 16-531 Spherical Coordinate Perturbation Solutions to Relative Motion Equations: Application to Double Transformation Spherical Solution, Eric A. Butcher and T. Alan Lovell (Part III)

AAS 16-532 Cross Fertilization Between Iterative Learning Control and Repetitive Control, Jianzhong Zhu and Richard W. Longman (Part II)

AAS 16-533 Not Assigned

AAS 16-534 Characterization of the Effective Output Magnetic Field of a Tri-Axial Square Helmholtz Cage, Ankit Jain, Erik Kroeker, Vedant, Alexander Ghosh and Patrick Haddox (Part I)

AAS 16-535 Mission Design Trades for a Near Term Pluto Orbiter, Nitin Arora, Anastassios E. Petropoulos and John Elliott (Part II)

AAS 16-536 Not Assigned

AAS 16-537 A Satellite Relative Motion Model Including J_2 and J_3 via Vinti's Intermediary, Ashley D. Biria and Ryan P. Russell (Part III)

AUTHOR INDEX