ASTRODYNAMICS 2018

Front Cover Images:

Artist's illustration of the twin spacecraft of the NASA/German Research Centre for Geosciences (GFZ) Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) mission. GRACE-FO will track the evolution of Earth's water cycle by monitoring changes in the distribution of mass on Earth, providing insights into climate, Earth system processes and the impacts of some human activities.

GRACE-FO continues a successful partnership between NASA and Germany's GFZ, with participation by the German Aerospace Center (DLR). JPL manages the mission for NASA's Science Mission Directorate in Washington. Image Credit: NASA/JPL-Caltech.

ASTRODYNAMICS 2018

Volume 167

ADVANCES IN THE ASTRONAUTICAL SCIENCES

Edited by
Puneet Singla
Ryan M. Weisman
Belinda G. Marchand
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FOREWORD

This volume is the next in a sequence of AAS/AIAA Astrodynamics Specialist Conference 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: Spaceflight Mechanics (published for the AAS annually, but recently changed to every second odd number 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, digital, or in microfiche form. The appendix of the volume lists proceedings available through the American Astronautical Society.

Astrodynamics 2018, Volume 167, Advances in the Astronautical Sciences, consists of four parts totaling about 4,000 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. A chronological index and an author index appear at the end of the main linking file, and are appended to the fourth 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 ASTRODYNAMICS VOLUMES

Astrodynamics 2018 appears as Volume 167, *Advances in the Astronautical Sciences*. This publication presents the complete proceedings of the AAS/AIAA Astrodynamics Specialist Conference 2018.

Astrodynamics 2017, Volume 162, Advances in the Astronautical Sciences, Eds. J.S. Parker et al., 4064p, four parts plus a CD ROM Supplement.

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

AAS/AIAA SPACEFLIGHT MECHANICS VOLUMES

Spaceflight Mechanics 2017, Volume 160, *Advances in the Astronautical Sciences*, Eds. J.W. McMahon et al., 4290p., four parts, plus a CD ROM supplement.

Spaceflight Mechanics 2016, Volume 158, *Advances in the Astronautical Sciences*, Eds. R. Zanetti et al., 4796p., four parts, plus a CD ROM supplement.

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*).

All of these proceedings are available from Univelt, Inc., P.O. Box 28130, San Diego, California 92198 (Web Site: http://www.univelt.com), publishers for the AAS.

Robert H. Jacobs, Series Editor

PREFACE

The 2018 Astrodynamics Specialist Conference was held at the Cliff Lodge in Snowbird, UT from August 19–23, 2018. 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 271 professionals (including 96 students and 12 retirees) 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.

A total of 282 abstracts were submitted for the conference and finally, 225 technical papers were presented in 26 sessions on topics related to space-flight mechanics and astrodynamics. There was one special session on Mission Design for Spacecraft in Near Rectilinear Halo Orbits and one town hall meeting was conducted by Dr. Nathan Strange from the Jet Propulsion Laboratory on the future of astrodynamics research funding. The purpose of this town hall meeting was to seek input from the spaceflight mechanics community for the upcoming decadal survey of NASA's technology roadmaps.

In line with the launch of Explorer 1 and its loss of control due to attitude dynamics and control knowledge, the 2018 Spaceflight Mechanics Meeting suffered an extremely large (and unplanned) number of Attitude Dynamics and Control Session papers being withdrawn giving an overall feeling of poor attitude.

The special events for the conference included the Dirk Brouwer Award Plenary lecture by Dr. Arun K. Misra, from McGill University, on the topic of Fifty Years of Tethered Space Systems. In addition to the plenary talk, the following four new AAS fellows were recognized:

- Dr. Bobby Braun, Dean of the College of Engineering and Applied Science, University of Colorado, Boulder, Colorado.
- Dr. Antonio Elipe, Catedrático (Professor), University of Zaragoza, Spain.
- Dr. Ryan Russell, Associate Professor of Aerospace Engineering, The University of Texas at Austin, Austin, Texas.
- Dr. Puneet Singla, Associate Professor of Aerospace Engineering, The Pennsylvania State University, University Park, Pennsylvania.

The meeting also included a plated dinner on Tuesday evening at the Summit, a guest facility located atop Hidden Peak at 11,000 feet.

The editors extend their gratitude to all the Session Chairs who ensured the smooth organization of all sessions: Nagavenkat Adurthi, Angela Bowes, William Todd Cerven, John Christian, Simone D'Amico, Jacob Darling, Diane Davis, Kyle DeMars, Atri Dutta, Tarek Elgohary, Weston Faber, Roberto Furfaro, Marcus Holzinger, Kathleen Howell, Islam

Hussein, Richard Linares, Bharat Mahajan, Jay McMahon, Jeff Parker, Christopher Roscoe, Aaron Rosengren, John Seago, Andrew Sinclair, Rohan Sood, David Spencer, Nathan Strange, Jeffery Stuart, Kamesh Subbarao, Ehsan Taheri, Mar Vaquero, Ryan Whitley, Matthew Wilkins, Roby Wilson and Waqar Zaidi.

Our gratitude also goes to Maruthi Akella, Kathleen Howell, David Spencer, and Jim Way for their support and assistance in the successful organization of this conference. We also extend our gratitude to the staff of Snowbird resort staff, for their diligence and commitment to excellence both during the organization and execution of this event.

Dr. Puneet Singla
AAS Technical Chair

Dr. Belinda Marchand
AAS General Chair

Dr. Ryan Weisman
AIAA Technical Chair

Dr. Brandon A Jones
AIAA General Chair

CONTENTS

ASTRODYNAMICS

Session Chairs:

Monday Session 1: Jeff Parker, Advanced Space

Co-Chair: Matthew Wilkins, Applied Defense Solutions

Tuesday Session 1: Tarek Elgohary, University of Central Florida

Co-Chair: Aaron J. Rosengren, University of Arizona

Wednesday Session 1: Rohan Sood, University of Alabama

Co-Chair: Nagavenkat Adurthi, Texas A&M University

Thursday Session 3: Atri Dutta, Wichita State University

Co-Chair: Bharat Mahajan, Odyssey Space Research

AAS 18-205

ACTION-ANGLE VARIABLES NEAR DEGENERATE PERIODIC ORBITS

William E. Wiesel*

Classical Floquet theory describes motion near a periodic orbit. However, there is a missing piece in the Floquet solution. A different Jordan normal form allows the decoupling of modal dynamics near the periodic orbit, and not just on the periodic orbit. A new eigenvector solution is offered in the case of repeated eigenvalues. This solution extends the Floquet decomposition to adjacent trajectories, and is fully canonical. This also yields the matrix of frequency partial derivatives, extending the solution's validity. Some numerical examples are offered. [View Full Paper]

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AAS 18-207

DESIGNING LEO CONSTELLATIONS TO MINIMIZE MAX REVISIT TIME

Thomas J. Lang*

For continuous global coverage, a mission designer need only compute the size of the coverage circle for a single satellite and then refer to tables created by various researchers to determine the minimum number (and arrangement) of satellites for his constellation. While allowing coverage gaps or "revisit times" can significantly reduce the constellation size, there has been no correspondingly simple means of finding a constellation which minimizes the maximum revisit time (MRT). The objective of this paper is to provide such a method. Results from this paper show that optimal constellations at all low earth orbit (LEO) altitudes give very nearly the same value of MRT (for a specified coverage circle size), as long as the MRT is measured in revs (i.e., normalized by the orbit period). As part of the current study, a numerical search was performed over "regular" constellations at 3 altitudes spanning the LEO regime. It was found that the MRT curves for these three altitudes basically overlay each other. This means that a mission designer can use the tables of MRT vs. coverage circle size from this paper to find constellations at any LEO altitude to minimize the global MRT. While polar orbits are the focus of this paper, the effects of near polar orbits are also investigated. The MRT reductions by using retrograde inclinations as opposed to polar are usually small, but in some cases can be as much as 4 minutes. The idea is that a mission designer would quickly find a polar constellation that meets his needs and then fine tune it, if desired, using retrograde orbits to obtain slightly lower values of MRT. Illustrative examples are provided.

[View Full Paper]

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AAS 18-209

TRAJECTORY DESIGN LEVERAGING LOW-THRUST, MULTI-BODY EQUILIBRIA AND THEIR MANIFOLDS

Andrew D. Cox,[*] Kathleen C. Howell[†] and David C. Folta[‡]

A key challenge in low-thrust trajectory design is generating preliminary solutions that simultaneously specify the spacecraft position and velocity vectors, as well as the thrust history. To mitigate this difficulty, dynamical structures within a combined low-thrust circular restricted 3-body problem (CR3BP) are investigated as candidate solutions to seed initial low-thrust trajectory designs. The addition of low-thrust to the CR3BP modifies the locations and stability of the equilibria, offering novel geometries for mission applications. Transfers between these novel equilibria are constructed by leveraging the associated stable and unstable manifolds and insights from the low-thrust CR3BP.

[View Full Paper]

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AAS 18-214

A MONOTONIC STARTER FOR SOLVING THE HYPERBOLIC KEPLER EQUATION BY NEWTON'S METHOD

A. Elipe,[*] J. I. Montijano,[†] L. Rández[†] and M. Calvo[†]

This communication deals with the iterative solution of the sine hyperbolic Kepler's equation (SHK): $F_g(S) = S - g \operatorname{arcsinh}(S) - L = 0$. Since this function is monotonic increasing and convex, any starter value S_0 such that $F_g(S_0) > 0$, leads to a Newton's sequence S_j monotic decreasing to the exact solution of SKE equation and therefore has some advantages over non monotonic starters. Because of this, we are able to construct a monotonic starter such that minimizes the computational cost and that guarantees super-convergence (q-convergence) by analyzing the error estimates of Newton's iteration. In contrast with other starters in which the quality is assessed by extensive numerical experiments, here we use theoretical tools to reach super-convergence. [View Full Paper]

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AAS 18-224

FULLY-COUPLED SPHERICAL MODULAR PENDULUM MODEL TO SIMULATE SPACECRAFT PROPELLANT SLOSH

Paolo Cappuccio,[*] Cody Allard[†] and Hanspeter Schaub[‡]

A spacecraft undergoing general translational and rotational motion can be affected by the sloshing of propellant. A spherical pendulum model is used for simulating this phenomenon because it can better represent the sloshing behavior for rotational dynamics in micro-gravity. This paper develops the fully coupled equations of motion of such a system and presents the solution in a form suitable for the back-substitution method. This modular formulation permits the use of as many pendulums as necessary to approximate the actual sloshing behavior. The general formulation makes minimal assumptions for the rigid portion of the spacecraft and is developed in a frame independent manner making the model applicable to wide range of spacecraft configurations. The model is implemented and verified using energy and momentum conservation in the Basilisk astrodynamics software package. The results of a simulation example of a GPS satellite are shown as an application of the model. [View Full Paper]

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AAS 18-233

COMPARISON BETWEEN FIRST AND SECOND-ORDER GAUSS'S VARIATIONAL EQUATIONS UNDER IMPULSIVE CONTROL

Gang Zhang[*] and Daniele Mortari[†]

Due to the insufficient 20 page limit, this paper shows, just as an example, how to derive the 2nd-order Gauss's variational equation of the inclination under impulsive control. The complete derivation of the 2nd-order Gauss's variational equations for all classical and nonsingular orbital elements under impulsive control is done in Ref. [1]. In addition, this paper provides, for an assigned single impulsive velocity variation, the comparison between the orbital elements variations predicted by the 1st-order and 2nd-order with respect to the true Keplerian variations. The gain in accuracy using the 2nd-order over the 1st-order is quantified by numerical Monte Carlo tests. Least-squares estimate of the impulse vector is obtained by inverting the 1st-order and 2nd-order GVEs. The 2nd-order estimation is here proposed for the single-impulse orbital maintenance problem.

[View Full Paper]

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AAS 18-252

PHOBOS ROTATIONAL DYNAMICS

James K. Miller[*] and Gerald R. Hintz[†]

As Phobos orbits Mars, it is subjected to a torque that gives rise to an oscillation about the line connecting the center of Mars with the center of Phobos. This oscillation is referred to as libration and has an amplitude of about one degree. The source of the torque is the variation or gradient of Mars gravity across Phobos. The part of Phobos closer to Mars is accelerated toward Mars more than the part further away. This gradient of the gravity field is what causes tides on Earth and forces the dark side of the Moon to always face away from the Earth whether it is illuminated by the sun or not. The Moon also librates. It was shown on previous missions that a small departure from principal axis rotation or what is called free precession can make determination of the gravity field difficult. An unknown oscillation of a few degrees can cause the orbit determination filter to fail to converge. This is a problem that could complicate navigation in the vicinity of binary asteroids or comets. [View Full Paper]

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AAS 18-261

POWERED AERO-GRAVITY ASSISTED MANEUVERS IN VENUS AND MARS CHANGING THE BANK ANGLE OF THE SPACECRAFT

Jhonathan O. Murcia P.[*] and Antonio F. B. A. Prado[†]

In a three body system, with the Sun as the massive body, a planet as secondary body and a spacecraft as a massless body, the change in the spacecraft trajectory due to a close approach with the planet is known as a gravity-assisted maneuver. If the planet has atmosphere and the pericenter of the spacecraft is lower than the atmospheric limit, the aerodynamic forces affect the gravity-assist, and the new maneuver is known as aero-gravity assisted. Including an instantaneous impulse in the pericenter, it is created the powered aero-gravity-assisted maneuver. The present paper uses this type of maneuver considering Drag, Lift and the bank angle to control the Lift direction. With this maneuver, it is possible to make energy and inclination changes in the trajectory of the spacecraft, which are very expensive maneuvers. A value of L/D = 9.0 is used to represent the maximum value used by waveriders spacecrafts to get maximum effects of Lift. Due to the proximity with the Earth, the presence of planetary atmosphere and applications in previous gravity assisted maneuvers, the planets Venus and Mars are selected to be used in the numerical simulations. A RKF 7/8 integrator with adaptive step is implemented. To observe the influence of Lift and Drag, the ballistics coefficient changes from 0.0 to $5x10^{-7}$ km^2/kg and the impulse at the pericenter is 0.5 km/s. Results show that controlling the Lift directions makes possible to increase or reduce the energy variations of the spacecraft.

[View Full Paper]

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AAS 18-267

THE EFFECT OF ZONAL HARMONICS IN THE CIRCULAR RESTRICTED THREE BODY PROBLEM NEAR THE SECONDARY BODY

Luke Bury and Jay McMahon*

This paper presents the derivation for the Circular Restricted Three Body Problem equations of motion which account for the effects of J_2, J_3, and J_4 of the primary and secondary bodies. Following this derivation, the effects of J_2 of the primary body become the focus, and equations for potential of the system and a modified Jacobi's constant are presented. With these expressions, results are shown for how J_2 shifts the location of the collinear equilibrium points and how it can affect various types of orbits, including some periodic families. [View Full Paper]

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AAS 18-274

IBEX REVISITED: OPERATIONAL RESULTS FOR LONG-TERM CISLUNAR ORBIT PROPAGATION

John Carrico,[*] Lisa Policastri[†] and Stephen Lutz[‡]

In June 2011, the Interstellar Boundary Explorer (IBEX) spacecraft performed maneuvers transferring from its original science orbit to a 3:1 lunar resonant orbit for its extended mission. Prior to the transfer, the IBEX Flight Dynamics Group (FDG) performed analyses to select a precise resonant orbit to meet perigee altitude and eclipse duration requirements. Since then, IBEX has been performing its mission without any need for orbit corrections. The FDG continues to monitor the orbit, comparing the actual orbit and eclipse data with the predictions. In this paper we compare the predictions with the actual values and show the prediction evolution. [View Full Paper]

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AAS 18-288

A SEMI-ANALYTICAL APPROACH TO SATELLITE CONSTELLATION DESIGN FOR REGIONAL COVERAGE

Hang Woon Lee,[*] Koki Ho,[†] Seiichi Shimizu[‡] and Shoji Yoshikawa[‡]

This paper introduces a robust and computationally efficient semi-analytical approach to design regional coverage satellite constellations. By fully utilizing the characteristics of the repeating ground track orbits and multiple access intervals between the target and the satellite, the proposed methods aim to optimally design satellite constellation with the fewest number of satellites possible. Two methods are constructed by applying the circular convolution theorem based on the assumption that the seed satellite access profile and the satellite position vector can be treated as discrete signals. An analysis shows that the While-Loop method is computationally efficient while the Integer Programming method is the most optimal. Various illustrative examples are performed to demonstrate the value provided by the proposed approach. [View Full Paper]

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AAS 18-309

DATA-DRIVEN FRAMEWORK FOR REAL-TIME THERMOSPHERIC DENSITY ESTIMATION

Piyush M. Mehta[*] and Richard Linares[†]

In this paper, we demonstrate a new data-driven framework for real-time neutral density estimation via model-data fusion in quasi-physical ionosphere-thermosphere models. The framework has two main components: (i) the development of a quasi-physical dynamic reduced order model (ROM) that uses a linear approximation of the underlying dynamics and effect of the drivers, and (ii) dynamic calibration of the ROM through estimation of the ROM coefficients that represent the model parameters. We have previously demonstrated the development of a quasi-physical ROM using simulation output from a physical model and assimilation of non-operational density estimates derived from accelerometer measurements along a single orbit. In this paper, we demonstrate the potential of the framework for use with operational measurements. We use simulated GPS-derived orbit ephemerides with 5 minute resolution as measurements. The framework is a first of its kind, simple yet robust and accurate method with high potential for providing real-time operational updates to the state of the upper atmosphere using quasi-physical models with inherent forecasting/predictive capabilities. [View Full Paper]

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AAS 18-321

METHOD OF CHARACTERISTICS BASED NONLINEAR FILTER: APPLICATIONS TO SPACE OBJECT TRACKING

Nagavenkat Adurthi[*] and Manoranjan Majji[†]

This paper deals with the development of a computationally efficient nonlinear filter that implicitly propagates the state probability density function for dynamical systems with no process noise. The proposed method leverages the method of characteristics to propagate probability density values of the state probability density function along the characteristic solutions, thereby avoiding the explicit propagation of the full state probability density function at all time steps. Further, this paper proposes a convex optimization procedure to reconstruct the state probability density function from these characteristic solutions. Numerical examples of capturing the non-Gaussian nature of the uncertainty in the two body problem with uncertain initial conditions is used to illustrate the proposed methods.

[View Full Paper]

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AAS 18-343

DESIGNING A LOW-COST, SMALL-SCALE MARS MISSION WITH ORBIT DETERMINATION TOOL KIT

Lisa Policastri,[*] Jim Woodburn[†] and John Carrico[‡]

Non-typical combinations of observation types and tracking schedules are investigated in support of potential low-cost missions to Mars where a two-way transponder is not available due to cost or space considerations. In the considered configuration, the typical two-way transponder is replaced with a transceiver and a chip scale atomic clock is considered for the frequency reference instead of an Ultra-Stable Oscillator (USO). Various schedules for the collection of one-way Doppler and Delta Differential One-way Range (DDOR) are examined to accommodate the resulting lack of coherent two-way tracking. Resulting orbit accuracies are evaluated in the context of planning and recovery of maneuvers as indicated by the mission plan across the Mars cruise, Mars orbit insertion and Mars science phases of the mission. The Mars 2020 arrival opportunity is used as a baseline case for this research. [View Full Paper]

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AAS 18-344

REFINED MISSION ANALYSIS FOR HERACLES – A ROBOTIC LUNAR SURFACE SAMPLE RETURN MISSION UTILIZING HUMAN INFRASTRUCTURE

Florian Renk,[*] Markus Landgraf[†] and Lorenzo Bucci[‡]

In the frame of the International Space Exploration Coordination Working Group the European Space Agency is participating in the planning of future exploration architectures. The mission concept for the robotic lander mission (Human Enhanced Robotic Architecture and Capability for Lunar Exploration and Science – HERACLES) has matured meanwhile. The mission aims for a human assisted sample return from the lunar surface, while at the same time providing a qualification opportunity for technologies required for a crewed lunar lander. Human spaceflight rating is required for parts of the mission, since the sample return shall not be via a direct return trajectory, but the samples shall be transported via Orion, and thus docking of the robotic lander to the LOP-G will be required. This paper shall provide an update on the current mission design as agreed between the international partners and the associated mission analysis as all the intermediate and final orbits have been selected for the baseline. The implications of the design decision as well as some alternatives that can serve as a backup scenario will be presented as well. The paper will first present the baseline mission sequence and will then focus on aspects of particular interest as e.g. the strong limitation in the launch window design and the rendezvous and docking strategy. [View Full Paper]

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AAS 18-345

COVERAGE OPTIMIZATION FOR SATELLITE CONSTELLATIONS

Alain Lamy*

This paper presents methods for the definition of constellations of satellites in order to optimize coverage and revisit time. The coverage criterion is based on a "longitude-time" map from which a distribution function is derived and a coverage figure of merit deduced. The study is limited to constellations of satellites in circular orbits consisting in one or more planes. The main objective is to find constellations of satellites that maximize the performance index. Results for two main applications are shown: comparison of low and high inclination constellations and extension of an existing constellation for altimetry. Some additional analyses are also provided that enable a better understanding of some of the results. [View Full Paper]

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AAS 18-350

DYNAMICAL EFFECTS OF SOLAR RADIATION PRESSURE ON THE DEFLECTION OF NEAR-EARTH ASTEROIDS

Luis O. Marchi,[*] D. M. Sanchez,[†] F. C. F. Venditti[‡] and A. F. B. A. Prado[§]

This work aims to find an alternative solution to the important problem of deflecting asteroids that are coming too close to Earth, with the risk of collision. This alternative is based on the use of a device with a large area/mass ratio attached by a tether to use solar radiation pressure (SRP) to help to deflect the trajectory of the asteroid. The paper describes the dynamics of the system composed by the asteroid, the tether and the device. The model is then used to study the effects that the tether length and the solar radiation pressure (acting on the surface of the device) exert on the deflection of a larger Potentially Hazardous Asteroid (PHA). As a starting point, the tether is assumed to be inextensible and massless and the motion is described only in the plane of the orbit of the PHA around the Sun. [View Full Paper]

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AAS 18-361

PLANAR ORBIT AND ATTITUDE DYNAMICS OF AN EARTH-ORBITING SOLAR SAIL UNDER J_2 AND ATMOSPHERIC DRAG EFFECTS

Narcís Miguel and Camilla Colombo*

In this paper we study planar orbit and attitude dynamics of an uncontrolled spacecraft taking on-board a deorbiting device such as a drag or solar sail. The dynamics is studied in mean Keplerian elements and restricted to rotations around one of the principal axes of the spacecraft. We consider spacecraft with a simplified version of a solar sail with pyramidal shape to restrict ourselves to planar motion, and we investigate stable or slowly-varying attitudes affected by disturbances due to the Earth oblateness effect, solar radiation pressure, and atmospheric drag, with special emphasis on orbits above 800 km of altitude. A sensitivity analysis on the aperture of the sail is performed. [View Full Paper]

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AAS 18-369

DYNAMICS OF ASYMMETRICAL MOTORIZED MOMENTUM EXCHANGE TETHER BY KEPLER-QUATERNION METHOD

YANG Yong,[*] DU Qiuhua,[†] LI Chao[‡] and QI Naiming[§]

Using the momentum exchange principle, the error dynamics model of the motorized momentum exchange tether (MMET) is assessed by considering structural deviation. The effects of deviations and differences in tethers' lengths and in payloads' masses are investigated. A new Kepler-Quaternion method is studied to build the orbital error dynamic equations and attitude kinematic equations. The numerical simulation results show that the difference in tethers' length and difference in payloads' mass have similar impacts on the chief satellite's orbit of the MMET. Specifically, the tension due to structure bias and tether rotation increasingly affect the chief satellite's orbit. [View Full Paper]

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AAS 18-370

AN ECLIPTIC PERSPECTIVE FOR ANALYTICAL SATELLITE THEORIES

Ioannis Gkolias,[*] Martin Lara[†] and Camilla Colombo[‡]

Traditionally, the forces in analytical theories for Earth satellite orbits are expressed in a coordinate frame which involves the equatorial plane. However, for distant satellites, the Moon and Sun attractions are equally important, and those forces are expressed more conveniently in a frame associated to the ecliptic. In this work, we develop an analytical satellite theory in which all the forces are expressed with respect to the ecliptic plane. The main advantage of the method is that, after the averaging process, all time-dependent terms disappear from the formulation yielding a model suitable for preliminary orbit design. [View Full Paper]

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AAS 18-373

DESIGN OF A FLEXIBLE, SCALABLE, AND EXTENSIBLE CLOUD-BASED MULTI-MISSION FLIGHT DYNAMICS SYSTEM

Rebecca Besser,[*] Russell DeHart,[†] Haisam Ido,[‡] Ryan Jim,[§] Joseph Kaminsky,[**] Craig Roberts,[††] Jennifer Sager,[‡‡] Noah Williams,[§§] John Zarek,[***] Eduardo Gurgel Do Amaral Valente[†††] and Dale Fink[‡‡‡]

In October 2017, navigation operations for the ACE and Wind spacecraft operated by the Space Science Mission Operations Project at the NASA Goddard Space Flight Center transitioned to the Navigation as a Service (NaaS) flight dynamics system. NaaS uses the Amazon Web Services GovCloud and the virtual multi-mission environment as the high-reliability, cost-effective core architecture. The NaaS design produces a repeatable and reusable process which lowers overhead to analysts by automating: the collection of elements necessary to create work-spaces, the execution of the flight dynamics engine, and the delivery of products to customers. It also allows operator-in-the-loop troubleshooting of flight dynamics analysis. [View Full Paper]

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AAS 18-374

NAVIGATION AND MANEUVER REQUIREMENTS DETERMINATION FOR ELLIPTICAL RENDEZVOUS OPERATION

Kai Jin,[*] David Geller[†] and Jianjun Luo[‡]

A novel navigation and maneuver requirements determination approach for elliptical rendezvous operation is developed in this paper. This approach can quickly determine the required navigation and maneuver performance that can meet trajectory dispersion requirements with the lowest sensor and actuator cost. It combines linear covariance analysis with convex optimization to describe and solve this problem. First, the trajectory dispersion of the closed-loop guidance, navigation, and control (GN&C) system with navigation error and maneuver execution error is modeled using linear covariance analysis theory. Using the trajectory dispersion as the optimization constraint, the navigation and maneuver requirements determination problem is formulated as a second-order cone programming (SOCP) problem and solved, based on Kronecker product theory. In order to apply this approach on a perturbed elliptical orbit rendezvous mission, a new state transition matrix is calculated to model the relative motion of two spacecraft in arbitrarily eccentric orbits perturbed by J_2 harmonic, aerodynamic drag. Finally, a series of simulations are carried out, showing that the proposed navigation and maneuver requirements determination approach works well. [View Full Paper]

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AAS 18-380

STUDYING THE MOTION OF A SPACECRAFT ORBITING AN ASTEROID MODELED AS AN ASYMMETRIC MASS DIPOLE

Leandro F. Brejão,[*] Leonardo B. T. Santos,[†]
Diogo M. Sanchez[‡] and Antonio F. B. A. Prado[§]

In this study, the dynamics of a space vehicle in the vicinity of a binary system of asteroids is analyzed by modeling one of the primaries as a rotating mass dipole considered to be in a spin-orbit resonance. Different mass distributions for the binary and for the dipole are considered, as well as different dimensional configurations. Then, the influence of such characteristics on the location of the equilibrium points of the system is studied. The zero velocity curves of the system are also plotted, identifying the regions of forbidden and allowed motion for a spacecraft travelling near the system. Finally, several maps are made showing the lifetimes of orbits as a function of their initial conditions, where the end of the life of an orbit is defined as a collision with any of the bodies or an ejection from the system. [View Full Paper]

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AAS 18-389

ON THE EVOLUTION OF ORBITS ABOUT ACTIVE COMETS

Mark J. Moretto* **and Jay McMahon†**

Spacecraft and large particles orbiting an active comet are perturbed by gas drag from the coma. These gases expand radially at about 0.5 *km/s*, much faster than orbital velocities that are on the order of meters per second. The coma has complex gas distributions and is difficult to model. Accelerations from gas drag can be on the same order of gravity and are currently poorly understood. We present semi-analytical solutions for the evolution of the Keplerian orbital elements of a spacecraft orbiting a comet. Implications for trajectory design, operations, and natural particle dynamics about the comet are shown.

[View Full Paper]

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AAS 18-396

SEARCHING FOR ORBITS AROUND EQUILIBRIUM POINTS IN A BINARY ASTEROID SYSTEM MODELED AS A MASS DIPOLE

L. B. T. Santos,[*] P. A. Sousa-Silva,[†] D. M. Sanchez[‡] and A. F. B. A. Prado[§]

The objective of the present work is to search for orbits around the equilibrium points L_1 and L_2 of the restricted three-body synchronous problem (RTBSP). From the equations of motion of a binary system of asteroids, where one of the asteroids is modeled as a rotating mass dipole, it was possible to determine the initial conditions for Lyapunov orbits. The study was carried out by modifying the mass ratio of the system and the size of the dipole mass in rotation. By linearizing the equations of motion, it is possible to obtain the eigenvectors and eigenvalues, and, with these values, it was possible to determine the initial estimates of periodic orbits around the equilibrium points using Newton's method. Then, a family of orbits was built around the equilibrium points L_1 and L_2.

[View Full Paper]

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AAS 18-400

MULTI-SPHERE METHOD FOR FLEXIBLE CONDUCTING SPACE OBJECTS: MODELING AND EXPERIMENTS

Jordan Maxwell,[*] Kieran Wilson,[*] Mahdi Ghanei[†] and Hanspeter Schaub[‡]

In the last two decades, concepts have been developed to harness electrostatic forces and torques to enable new categories of missions, from formation flying to inflating membrane structures or detumbling and reorbiting debris touchlessly. The need for faster-than-realtime modeling of the electrostatic forces and torques in these missions has led to the development of the Multi-Sphere Method (MSM) in which the electrostatic field generated by a charged body is approximated through the use of a series of optimally placed and sized conducting spheres. While the prior work assumed the charged body is rigid, this paper extends the use of MSM to flexible shapes. The effectiveness of the flexible MSM approach is shown using an analytical matching with a line deforming into a circle. However, the core underlying assumption of the shape surface being a conductor remains. To explore how well this flexible shape model allows for charge membrane deflections to be modeled, a thin aluminum coated mylar strip is exposed to a constant electric field in a vacuum chamber. The results indicated that with a given field and high strip potentials the deflections are modeled well. However, the experiments also illustrate that the dielectric mylar material causes significant dynamic response changes. While the flexible MSM approach is a good method to approximate the electrostatic forces and torques on a general shape, the limiting case of extremely thin mylar sheets illustrate that additional physical phenomena must be modeled to predict the motion of such objects.

[View Full Paper]

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AAS 18-404

BOUNDED MOTIONS NEAR RESONANT ORBITS IN THE EARTH-MOON AND SUN-EARTH SYSTEMS

Natasha Bosanac*

Bounded trajectories near orbital resonances contribute to an underlying dynamical structure that governs motion within a multi-body system. When the dynamics in this system are modeled using a circular restricted three-body problem, boundedness is exhibited by both periodic and quasi-periodic solutions. To date, periodic orbits have been the focus of most investigations. However, recent advances in computational methods enable direct recovery and analysis of the invariant tori associated with families of quasi-periodic orbits. These techniques are employed to compute planar and symmetric quasi-periodic trajectories in various interior and exterior resonant orbit families within the Sun-Earth and Earth-Moon systems. Characterization of these complex dynamical structures significantly expands the design space for mission orbit selection and trajectory construction.

[View Full Paper]

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AAS 18-408

TRANSITING EXOPLANET SURVEY SATELLITE (TESS) FLIGHT DYNAMICS COMMISSIONING RESULTS AND EXPERIENCES

Joel J. K. Parker,[*] Ryan L. Lebois,[†] Stephen Lutz,[†] Craig Nickel,[†] Kevin Ferrant[‡] and Adam Michaels[‡]

The Transiting Exoplanet Survey Satellite (TESS) will perform the first-ever spaceborne all-sky exoplanet transit survey and is the first primary-mission application of a lunar-resonant orbit. Launched on April 18, 2018, TESS completed a two-month commissioning phase consisting of three phasing loops followed by a lunar flyby and a final maneuver to achieve resonance. During the science orbit, no further station-keeping maneuvers are planned or required. NASA Goddard Space Flight Center is performing flight dynamics operations for the mission. This paper covers the design, implementation, and results from TESS commissioning, including the projected performance of the final science orbit. [View Full Paper]

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AAS 18-413

AN INVESTIGATION OF NATURAL DYNAMICAL PROCESSES ON ASTEROID SURFACES USING A COMBINED ASTEROID SURFACE-BOULDERS MODEL

Daniel N. Brack[*] and Jay W. McMahon[†]

A new asteroid model is presented to investigate the interaction between the asteroid's rotational dynamics and the state of boulders on its surface. The model considers boulder motion on the surface of the asteroid as well as boulder launch, orbit, crash and escape in two ways. First, there can be a momentum transfer during launch and crash of boulders, and second when a boulder moves the inertia tensor of the system changes. Both of these will result in a change to the angular velocity. If a boulder launches and escapes the system, an effective ΔV is applied to the asteroid velocity. Surface moving boulders tend to reach the equator and launch from it or rest near it. The resulting orbits are of low inclination and a chaotic trajectory leading to crash events. [View Full Paper]

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AAS 18-425

SENSOR TASKING FOR SATELLITE TRACKING UTILIZING OBSERVABILITY MEASURES

Mitchel T. McDonald[*] and Kamesh Subbarao[†]

This paper presents a new observability measure based sensor tasking method for satellite tracking. The tasking is performed by first computing the Hellinger Distance between ground/space based sensors and space objects and then using this metric for selecting the sensors that maximize observability. The object's state estimates are obtained using non-linear estimation techniques. The Extended Kalman Filter and Unscented Kalman Filter are compared within this framework. Representative numerical simulations are performed to evaluate the efficacy of the new tasking approach. The proposed tasking approach is also compared with some baseline approaches. [View Full Paper]

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AAS 18-426

MEAN VALUES IN ELLIPTIC MOTION: AVERAGING THE LEGENDRE POLYNOMIALS

Aaron J. Rosengren,[*] Jeremy R. Correa[*] and Daniel J. Scheeres[†]

Being one of the oldest and most developed topics of investigation in celestial mechanics, averaging provides a particularly effective method for the approximate evaluation of the dynamics of a system. We present here a systematic approach for computing the mean values of general functions encountered in elliptic motion. We show that all orbital averages occurring in perturbed Keplerian motion (assuming non-commensurate orbital frequencies) reduce to averages of certain powers of the orbit radius; thereby revealing the fundamental significance and profundity of Hansen's coefficients. This method is applied to averaging the Legendre expansion of various gravitational potentials.

[View Full Paper]

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AAS 18-435

A HIGH ORDER FILTER FOR ESTIMATION OF NONLINEAR DYNAMIC SYSTEMS

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In this paper, a high order filter is presented for estimation of nonlinear dynamic systems. The proposed filter computes higher order moment update equations in a Jacobian free manner and a computationally attractive manner. Compared to the conventional filters such as the Extended Kalman Filter (EKF) and Unscented Kalman Filter (UKF), the proposed filter captures desired order of statistical moments by making use of the higher order state transition matrices developed in our previous works, providing more accurate estimates through sparse measurements. The connection between the conventional high order method, the higher order state transition matrices and the proposed filter is discussed. Orbit estimation problem is considered to demonstrate the numerical efficiency and accuracy of the proposed filter. [View Full Paper]

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AAS 18-455

RELATIVE EQUATIONS OF MOTION USING A NEW SET OF ORBITAL ELEMENTS

Pardhasai Chadalavada[*] and Atri Dutta[†]

In this paper, we consider the relative equations of spacecraft motion in terms of a new set of orbital elements that includes the components of the angular momentum in the inertial reference frame, the components of the eccentricity vector in a suitably chosen non-inertial reference frame, and a true-anomaly-like angle determining the location of the spacecraft. We derive a detailed mathematical formulation of the relative dynamics using orbital element differences in terms of the new state parameters. Using numerical simulations, we compare the formulation with Hill-Clohessey-Wiltshire equations of relative motion. [View Full Paper]

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AAS 18-456

ON THE SOLUTION TO EVERY LAMBERT PROBLEM

Ryan P. Russell*

Lambert's Problem is the two-point boundary value problem for Keplerian dynamics. The parameter and solution space is surveyed for both the zero- and multi-rev problems, including a detailed look at the stress cases that typically plague Lambert solvers. The problem domain, independent of formulation, is shown to be rectangular for each revolution case, making the elusive initial guess and the solution itself amenable for interpolation. Biquintic splines are implemented to achieve continuous derivatives and quick evaluation. Resulting functions may be used directly as low-resolution solutions or used with a single update iteration without safeguards. A concise, improved vercosine formulation of the Lambert Problem is presented and the interpolation scheme is applied for up to 100 revolutions. The domain considered includes all practically conceivable flight times, and every possible geometry except a small region near the only physical singularity of the problem: the equal terminal vector case. The solutions are archived and benchmarked for accuracy, memory footprint and speed. The result using the single, unguarded update step is globally accurate to near machine precision over the full domain, including the most extreme scenarios. Depending on desired resolution, coefficient files vary in size from ~3 to 65 MB for each revolution case. Evaluation runtimes vary from ~2 to 6 times faster than the industry benchmark Gooding algorithm. [View Full Paper]

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AAS 18-460

QUASI-HOVERING FORMATIONS IN ELLIPTICAL ORBIT

Huan Chen,[*] Chao Han,[†] Yinrui Rao[‡] and Jianfeng Yin[§]

This paper proposes a kind of quasi-hovering formation by forcing the deputy satellite revisiting the same point with impulses. The revisiting formation solution, geometrical properties regarding time, the geometric design method and the maintenance control strategy are investigated in detail. In addition, the optimal control model of quasi-hovering formation is established and simplified to make it easier to solve with dynamic programming algorithm. Finally, numerical examples are conducted to compare the formation maintenance fuel cost of the revisiting formation, the optimal quasi-hovering formation and the strict hovering formation. [View Full Paper]

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AAS 18-474

FIRST ORDER APPROXIMATION OF THE EFFECTS OF SOLAR RADIATION PRESSURE ON RELATIVE MOTION USING A LINEARIZED REPRESENTATION OF RELATIVE ORBITAL ELEMENTS

Hermann Kaptui Sipowa[*] and Jay McMahon[†]

A linearized equation for relative orbital elements is derived. The presented model allowed for the reproduction of the relative position of the deputy using a unit-sphere projection approach. The performance of the linearized model is compared to the truth relative Cartesian coordinates using the Cannonball model and the Fate Plate model. The linearized solution is accurate to about 1% for similar spacecraft. However, it struggles to capture the fast changing dynamics of the deputy in the simulations where the two satellites are different. [View Full Paper]

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AAS 18-486

SUPERSONIC RETROPROPULSION ON ROBOTIC MARS LANDERS: SELECTED DESIGN TRADES*

Aron A. Wolf,† Connor Noyes,† William Strauss,† Joel Benito,† Marcus Lobbia,‡ John McCann,§ Barry Nakazono, Zachary R. Putnam,†† and Christopher G. Lorenz‡‡**

Many concepts for future robotic Mars lander missions require landing heavier payloads than those landed to date. Mars lander architectures to date have relied on a parachute to help slow the lander; however, the effectiveness of a parachute in the thin Martian atmosphere is diminished with heavier payloads unless the diameter of the parachute is increased or it is deployed at a higher Mach number, both of which are significant technical challenges. In addition, the parachute can be successfully deployed only within a specific Mach number and dynamic pressure range. Targeting the entry trajectory to hit this "Mach-Q box" imposes constraints on the entry ballistic coefficient, limiting it to ~ 150-200 kg/m^2. Eliminating the parachute from the design requires descent engine ignition at supersonic speeds (Supersonic Retropropulsion, or SRP). SRP increases the propellant requirement, but also allows entry ballistic coefficients of ~600 kg/m^2 or more, with the consequence of significantly increased entry mass and landed payload mass.

[View Full Paper]

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* The decision to implement the SRL mission will not be finalized until NASA's completion of the National Environmental Policy Act (NEPA) process. This document is being made available for information purposes only.

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AAS 18-487

MORPHING HYPERSONIC WAVERIDER FOR MARS ENTRY

Jesse R. Maxwell*

The primary contemporary challenge for planetary entry is the landed payload surviving the intense heating and deceleration during atmospheric entry. Mars exploration to date has included ballistic and lifting capsules, but no high-lift entry vehicles. The Equilibrium Glide approximation for the trajectory of a lifting entry vehicle suggests that the key to minimizing entry heating and deceleration is to increase the entry vehicle size relative to its mass and increase its lift coefficient. More detailed analysis of entry physics suggests that the lift-to-drag ratio is also of high significance for determining the severity of heating and deceleration. The highest-lift and highest lift-to-drag vehicles known in the high-speed regimes of entry vehicles are *hypersonic waveriders*, a class of vehicles constructed using a design flow field and knowledge of high-speed aerodynamics and possessing the distinct characteristic of an attached shock all along their leading edges. While classically designed for a specific, single Mach number, prior work has demonstrated the ability of specific lower surface distortions to enable high performance across a wide Mach number range, known as "morphing waveriders." This concept has been evaluated for its potential use in entry vehicles for Earth's atmosphere and demonstrated to outperform conventional lifting capsules and the NASA Space Shuttle. The present work continues this entry vehicle exploration with the use of morphing waveriders applied for entry into Mars' atmosphere. The simple vehicle, aerodynamics, and entry dynamics models are presented and compared to the entry of the Mars Science Laboratory (MSL) capsule with good agreement. Next, a comparison is made between the MSL capsule and a morphing waverider for interplanetary transport entry conditions, where the waverider is demonstrated to produce a trajectory with more benign heating and deceleration than a conventional lifting capsule. [View Full Paper]

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PROXIMITY MISSIONS AND FORMATION FLYING

Session Chairs:

Monday Session 2: David B. Spencer, The Pennsylvania State University

Co-Chair: Waqar Zaidi, Applied Defense Solutions

Tuesday Session 5: Andrew J. Sinclair, Air Force Research Laboratory

Co-Chair: Jay McMahon, CCAR (Colorado Center for Astrodynamics Research)

The following papers were not available for publication:

AAS 18-281 Paper Withdrawn

AAS 18-284 Paper Withdrawn

AAS 18-342 Paper Withdrawn

AAS 18-452 Paper Withdrawn

AAS 18-478 Paper Withdrawn

AAS 18-212

COLLOCATION OF GEOSTATIONARY SATELLITES IN WHEEL CLUSTER FORMATION

Chia-Chun Chao*

The concept of a wheel cluster formation in a single orbit plane has been demonstrated to be fuel efficient in initial deployment and formation-keeping. This paper further demonstrates through numerical simulations how the concept can be applied to the collocation of several geostationary satellites. Both east/west and north/south stationkeeping with a tight control box of ±0.1 deg are simulated with sun-pointing constraint. Two control methods are explored. The first method assumes ground control of the sub-satellites, while the second method employs the auto-feedback controller with onboard GPS measurements. The number of collocated GEO satellites can be 10 or more depending on the accuracy of position determination and onboard propulsion system. A proposed procedure of initial deployment from the center satellite is outlined. [View Full Paper]

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AAS 18-218

LINEARIZED RELATIVE ORBITAL MOTION MODEL ABOUT AN OBLATE BODY WITHOUT AVERAGING

Ethan R. Burnett,[*] Eric A. Butcher,[†] Andrew J. Sinclair[‡] and T. Alan Lovell[‡]

A new linearized differential equation model and solution for spacecraft relative motion about an oblate body is obtained without averaging the perturbing acceleration, and presented for the case of near-zero chief orbit eccentricity. The model is stand-alone and does not require integration of the chief orbit, while the time-explicit solution depends only on initial chief orbital elements, time since epoch and node crossing, and the deputy's initial conditions in the chief Hill frame. The resulting model outperforms previous models obtained via averaging, and has a similar error to the GA-STM for zero initial chief orbit eccentricity. [View Full Paper]

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AAS 18-219

WHEEL CLUSTER FORMATION FOR HEO SATELLITES — A FEASIBILITY STUDY

Chia-Chun Chao*

The concept of a wheel cluster formation in a single orbit plane has been demonstrated to be orbit dynamically stable, and fuel efficient in initial deployment and formation-keeping. This paper provides an in-depth feasibility study to further demonstrate, through numerical simulations, how the concept can be applied to highly elliptical orbit (HEO) satellites. In this study, a cluster of 10 closely separated sub-satellites are deployed and controlled at a Tundra orbit, a Molniya orbit and a geosynchronous transfer orbit (GTO). A proposed procedure of initial deployment from the center satellite is outlined. The method of adjusting initial semi-major axis to maintain long-term cluster formation stability for satellites with same area-to-mass ratio is illustrated. Alternatively, formation-keeping propellant is estimated for spacecraft with different area-to-mass ratios.

[View Full Paper]

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AAS 18-223

TRAJECTORY OPTIMIZATION FOR RENDEZVOUS WITH BEARING-ONLY TRACKING

Xiaoyu Chu,[*] Kyle T. Alfriend,[†] Jingrui Zhang[‡] and Yao Zhang[§]

In this paper a bearing-only tracking system for spacecraft rendezvous is proposed. The observability of the system is analyzed and the trajectory optimization algorithms to enhance the observability of the spacecraft rendezvous are presented. Firstly, the relative dynamic model and measurement model are established, and the necessary and sufficient condition for the observability when maneuvering is quantitatively determined using the pseudo linear method. Then, a Kalman filter is used to obtain the optimal estimation of the states according to the observation data. The relevant parameters in the filtering process are optimized to generate the trajectory with maximum observability. Two optimization algorithms are presented, including minimizing the filter covariance matrix trace and maximizing the Fisher information matrix determinant. Numerical results show that the combination optimization of the observability and fuel consumption can generate an optimal control trajectory with high tracking precision. [View Full Paper]

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AAS 18-228

METHODS FOR PASSIVE OPTICAL DETECTION AND RELATIVE NAVIGATION FOR RENDEZVOUS WITH A NON-COOPERATIVE OBJECT AT MARS*

Alan M. Didion,† Austin K. Nicholas,‡ Joseph E. Riedel,§ Robert J. Haw and Ryan C. Woolley††**

Long-range passive optical detection of an orbiting inert sphere by a robotic Mars orbiter is investigated and trades are described in terms of detectability via reflected visible light in the presence of orbit uncertainty, gravitational perturbations, and camera electronics noise. A new approximate equation for signal-to-noise ratio (SNR) is developed to include most relevant camera imperfections, diffraction, and stray light from the Mars limb as relevant to this scenario. Using this method, a notional camera suite is designed to meet detection, navigation, and redundancy requirements for an example mission scenario. Results from a simulation tool demonstrate the long-range initial detection strategy in the presence of perturbations from various sources. Navigation analysis shows that the information gathered using passive optical detection is sufficient to begin orbit matching. Finally, applicability of this sensor suite is examined relative to later phases.

[View Full Paper]

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AAS 18-231

ALGORITHMS FOR SMALL SATELLITE FORMATION INITIALIZATION

Robert B. LaRue[*] and Kirk W. Johnson[†]

This paper presents a general algorithm for relative motion maneuvering that allows any number of impulses to be defined. The algorithm can accommodate a wide variety of relative motion models that are currently in the literature. A method is provided for dispersing satellites such that the relative velocity between them is negated. Trends between the transfer time and formation initialization ΔV are examined. The equations of motion for the spacecraft account for the full nonlinear dynamics, as well as J_2 and aerodynamic drag perturbations. [View Full Paper]

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AAS 18-278

A MINIMAL PARAMETERIZATION ON SIX D.O.F. RELATIVE ORBITAL MOTION PROBLEM USING DUAL LIE ALGEBRA

Daniel Condurache*

This main goal of this research is the development of a new approach of minimal parameterization to the full-body relative orbital motion problem. Using the isomorphism between the Lie group of the rigid displacements and Lie group of the orthogonal dual tensors, a solution of the problem is given. The results are applied for giving a representation theorem of the six degrees of freedom relative orbital motion problem. Using the Euler dual vector, the higher-order Rodrigues dual vector or Davenport-Euler dual angles the minimal dimensional representations of this problem is obtained. The novelty of the method over existing solutions is discussed and the main advantages are revealed.

[View Full Paper]

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AAS 18-312

STATE-DEPENDENT RICCATI EQUATION CONTROL FOR SPACECRAFT FORMATION FLYING IN THE CIRCULAR RESTRICTED THREE-BODY PROBLEM

Michael Tannous,[*] Giovanni Franzini[†] and Mario Innocenti[‡]

The use of the state-dependent Riccati equation (SDRE) technique for formation flying control in the circular restricted three-body problem is investigated in this paper. First, the relative dynamics of a leader-follower formation is described by computing the difference between the equations of motion associated to the two spacecraft. Then, a pseudo-linear form of the relative motion equations is identified in order to implement the SDRE control technique. The effectiveness of the controller is proved by the high accuracy and the limited control usage achieved during the numerical simulations, set up considering the New Worlds Observer mission scenario. [View Full Paper]

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AAS 18-322

SPACECRAFT RENDEZVOUS GUIDANCE IN CLUTTERED ENVIRONMENTS VIA ARTIFICIAL POTENTIAL FUNCTIONS AND REINFORCEMENT LEARNING

Brian Gaudet,[*] Richard Linares[†] and Roberto Furfaro[‡]

The primary contribution of this work is to use Artificial Potential Functions (APF) for generating trajectories to be used as initial guesses for General Pseudospectral Optimal Control (or GPOPS). This work demonstrates dramatic speed up for GPOPS solution times, giving an average trajectory generation time of around 6 seconds. With this level of performance, the trajectory generation could occur on board the spacecraft based off of its current state estimate. In the type of scenarios that this algorithm is designed for (rendezvous, orbital transfer), this work can execute in near-real-time. This worked also improves the trajectory tracking controller performance, achieving continuous thrust fuel efficiency equal to the GPOPS optimal solution, and pulsed thrust fuel efficiency about 25% worse than the GPOPS optimal solution. [View Full Paper]

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AAS 18-326

A SEMI-ANALYTICAL APPROACH TO CHARACTERIZE THE RELATIVE MOTION IN THE VICINITY OF PHOBOS

Davide Conte[*] and David B. Spencer[†]

This paper discusses a semi-analytical approach that can be used to approximate the relative motion of spacecraft around nominal periodic Distant Retrograde Orbits (DROs) in the vicinity of Mars' largest moon, Phobos. Numerical analysis reveals that in the Circular Restricted Three-Body Problem (CR3BP) rotating reference frame, Mars-Phobos DROs can be represented analytically in a moderately accurate way by two terms of their Fourier series representations due to the fact that the mass of Phobos is much smaller than the mass of Mars. Additionally, assuming that the relative distance between spacecraft is sufficiently small, the equations of motions can be further simplified and semi-analytically solved to obtain an accurate representation of the relative motion in the vicinity of Phobos. It is found that the equations exhibit a secular behavior, which can be accurately described by the Hill-Clohessy-Wiltshire (HCW) equations, and a short-term cyclic behavior which is attributed to the gravitational attraction of Phobos that the HCW equations cannot represent. [View Full Paper]

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AAS 18-339

ARC-LENGTH SOLVER METHODOLOGY FOR RELATIVE ORBIT DETERMINATION MEASUREMENT EQUATIONS

Brett Newman,[*] T. Alan Lovell,[†] Geoffrey Rose[‡] and Duc Nguyen[§]

Numerical solution of an algebraic formulation of the Keplerian circular relative motion initial orbit determination problem is investigated using iterative nonlinear arc-length solver methodology. A series of azimuth-elevation angular measurements locating the deputy satellite with respect to the chief satellite are coupled through observation geometry with an approximate analytic second order three-dimensional time dependent solution for relative motion. The motion expressions are based on the quadratic Volterra series having terms of linear, quadratic, and bilinear combinations of the deputy initial conditions and chief orbital elements. The resulting set of nonlinear measurement equations are numerically solved for the six unknown deputy initial conditions using the arc-length method. A finite set of multiple solutions exist in this problem and the arc-length method provided a reliable, accurate, and systematic technique for generating these solution sets. The arc-length method computes a continuous family of solutions based on the continuation parameter, which is included as an unknown variable. The degree of freedom added to the iterative methodology by not specifying the continuation parameter is a key ingredient to providing robust solver behavior compared to point solver techniques. From this continuous solution family, specific solutions corresponding to a continuation parameter value of zero are extracted. Additional logic is required to identify from this set the actual deputy orbit. The method was successfully applied to a three-dimensional case without measurement or process error. Results matched previous attempts at solving the measurement equations using other techniques, and avoided concerns related to start value selection, convergence to trivial or undesired solutions, divergence to infinite valued solutions, and numerical ill-conditioning, at the expense of added computation to construct the continued solution family. The method was also adapted to support deterministic error analysis in the orbit determination application. [View Full Paper]

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AAS 18-384

INCREMENTAL STATES FOR PRECISE ON-ORBIT RELATIVE KNOWLEDGE IN FORMATION FLIGHT

Martin Cacan,[*] Andrew Harris,[†] Jack Aldrich,[*]
David Bayard[*] and Carl Seubert[*]

High precision and close proximity formation flight is an enabling technology for future space missions and requires an on-board relative navigation capability that is accurate to the mm-level and robust to formation parameters. Common estimation techniques linearize the entire formation about one spacecraft's position, resulting in degraded accuracy due to linearization errors when separation distances become large. Additionally, methods which decouple absolute and relative state estimates usually require ad-hoc methods to incorporate the estimates together. This work discusses an alternative "incremental" formulation of the relative navigation problem which is invariant to formation size, robust to coupling between absolute and relative dynamics, and can undergo similarity transformations to smoothly incorporate either absolute or relative information without numerical issues. A specific example of this architecture is presented in the context of formation navigation using Carrier-Differential Global Positioning System measurements, and is compared to a traditional leader-linearized filter. In the presence of accurate measurements, the incremental architecture is shown to reduce linearization errors and mean estimate errors by up to three orders of magnitude without the incorporation of new sensor information.

[View Full Paper]

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AAS 18-390

SAFE SPACECRAFT RENDEZVOUS WITH CONSTRAINED MODEL PREDICTIVE CONTROL

Ali Tevfik Büyükkoçak[*] and Ozan Tekinalp[†]

Rendezvous and docking problem of a pair of low Earth orbit spacecraft is ad-dressed. Equations for the nonlinear orbital relative motion of spacecraft are de-rived and a simulation code for this motion is developed. For the control algorithm, linearized Hill-Clohessy-Wiltshire (HCW) equations are used in chaser-target spacecraft configuration. All authority is given to the chaser spacecraft, and the target is kept passive. The HCW equations are linearized assuming a circular orbit. Model Predictive Control (MPC) strategy is applied with safety constraints including debris avoidance and Line of Sight constraint. This includes the avoidance of a relatively moving debris with an unbounded motion. Simulation results are given and discussed. A parametric study is also performed to obtain the proper prediction horizon as well as weighting matrices to be used in the simulations. [View Full Paper]

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AAS 18-420

REAL-TIME ANGULAR VELOCITY ESTIMATION OF NON-COOPERATIVE SPACE OBJECTS USING CAMERA MEASUREMENTS

Marcelino M. de Almeida,[*] Renato Zanetti,[†] Daniele Mortari[‡] and Maruthi Akella[§]

This paper presents an algorithm for angular velocity estimation of a non-cooperative space object using camera measurements. We consider that the non-cooperative space target is one whose inertia properties and actuation torques are not known. The relative pose of such space object with respect to the camera can be obtained using Simultaneous Localization and Mapping (SLAM) methods. In this paper, we specifically adopt the ORB-SLAM package, which has already been validated in prior research as a successful tool for SLAM applications in space missions. Using the relative pose between the target and the camera, the angular velocity can be obtained through attitude kinematics. However, the lack of a reliable propagation model for the angular velocity constrains the use of traditional Kalman Filter based methods, which typically require some knowledge of the inertia matrix and any perturbing torques governing the rotational dynamics of the non-cooperative space object. Instead, our work is based on the Discrete Adaptive Angular Velocity Estimator (DAAVE) algorithm to estimate for the target's spin axis, and use this as prior information for a modified version of the Multiplicative Extended Kalman Filter (MEKF) formulation. This work introduces both the DAAVE and the modified MEKF algorithms, and presents the performance of the angular velocity estimator using a camera-target simulator. In our simulator, we are able to use the 3D model of a target of interest, which can be configured to tumble with any desired angular rate, while being visually captured with a camera. The simulation results demonstrate that the algorithm pipeline engaging ORB-SLAM, DAAVE, and the modified MEKF, is successful in adequately tracking the angular velocity of targets in multiple tumbling configurations. [View Full Paper]

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AAS 18-444

DEMONSTRATION OF A PROPELLANTLESS SPACECRAFT HOPPING MANEUVER ON A PLANAR AIR BEARING TEST BED

Andrew R. Bradstreet,[*] Josep Virgili-Llop[†] and Marcello Romano[‡]

During on-orbit servicing or exploration of small planetary bodies, robotic spacecraft may need to move between different locations on the surface of their target object. Hopping is an alternative mobility approach where spacecraft use their robotic arms to jump between two locations. A hopping maneuver is composed of an initial push followed by a free-flying coast and an eventual soft-landing on the destination. The experimental demonstration of a propellantless hopping maneuver is presented here. This demonstration has been conducted on a planar air bearing test bed, where a test vehicle, equipped with two robotic manipulators, successfully executed a hopping maneuver between the two extremes of the test bed. The vehicle's robotic manipulators were used to execute the push and soft-landing phases. During the free-flying coast, the vehicle's state was only controlled by an onboard reaction wheel. The demonstrated hopping maneuver is therefore fully propellantless. The robotic vehicle and the low friction environment provided by the test bed results in a high dynamic fidelity, otherwise difficult to achieve with numerical simulations. The test set up, the maneuver formulation, the control laws, and the results of the experimental campaign are presented in this paper. [View Full Paper]

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AAS 18-472

PRECISION CONTROL OF MICROSATELLITE SWARMS USING PLASMONIC FORCE PROPULSION

Pavel Galchenko[*] and Henry Pernicka[†]

Scientific mission concepts using swarm formations require micronewton levels of thrust to enable precision formation flying and spacecraft pointing. Plasmonic force propulsion can provide these levels of thrust to the microsatellite platform to enable these advanced missions. Three case studies are used to evaluate the performance of a swarm composed of microsatellites, each equipped with plasmonic thrusters. Control techniques are evaluated and adapted to provide robust and precise control under system disturbances, model uncertainties, and noise. Results show that relative position and pointing can be achieved to meet scientific objectives for a range of swarm precision formation missions.

[View Full Paper]

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TRAJECTORY DESIGN AND OPTIMIZATION

Session Chairs:

Monday Session 3: Roby Wilson, Jet Propulsion Laboratory

Tuesday Session 2: Nathan Strange, Jet Propulsion Laboratory / California Institute of Technology

Co-Chair: Angela Bowes, NASA Langley Research Center

Tuesday Session 7: Roby Wilson, Jet Propulsion Laboratory

Co-Chair: Jeff Parker, Advanced Space

Wednesday Session 3: Tarek Elgohary, University of Central Florida

Thursday Session 1: Richard Linares, University of Minnesota

Co-Chair: Ehsan Taheri, Texas A&M University

The following papers were not available for publication:

AAS 18-395 Paper Withdrawn

AAS 18-454 Paper Withdrawn

AAS 18-475 Paper Withdrawn

AAS 18-204

LOW-THRUST TRANSFER NOMOGRAMS

Salvatore Alfano*

A nomogram (or nomograph) is a graphical representation of three or more pieces of data; knowledge of two of those values visually leads to the other(s). Typically, a sharp pencil and keen eye will produce results within 5% of an exact numerical solution. Nomograms predate personal computing devices and hand-held electronic calculators by almost 100 years. It wasn't until the mid-1980s that operators and engineers had access to personal computers; prior to this time mainframe computations or hand calculations were the only means to arrive at precise answers. Such calculations were used to produce nomograms for those that did not have access to such computational devices. Thus, prior to the mid-1980s many operators and engineers relied on nomograms to perform what would now be considered back-of-the-envelope computations. Presented here is the construction of some useful nomograms regarding minimum-time, continuous low-thrust, circle-to-circle, orbit transfers in addition to nomograms relating miss distance to off-cycle thrust time as well as to maximum probability. The nomogram relating miss distance to maximum probability and its associated standard deviation is not limited to low-thrust transfers and can be used for any collision avoidance maneuver planning. The nomograms are useful for pre-mission planning and determining if further numerical processing is even worth the bother. Their main advantages are that no software or licenses are required, nor even understanding of the underlying fundamentals. All that is needed is a straight edge, a sharp pencil, and good eyesight. In a matter of seconds one can arrive at proximate answers, making them very convenient for initial assessments.

[View Full Paper]

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AAS 18-211

NUMERICAL CHALLENGES IN CASSINI MANEUVER OPERATIONS

Mar Vaquero[*] and Yungsun Hahn

Launched in 1997 to observe Saturn and its system, Cassini successfully entered Saturn orbit in 2004 and impacted the planet on September 15, 2017 after 22 orbits each skimming over Saturn's cloud tops. The Cassini mission represents the most complex gravity-assist trajectory ever flown. As such, the Flight Path Control Team encountered many difficulties along the way, resulting in a continuously evolving maneuver process. In this paper, we focus on the challenges presented by the well-known singularities in the transfer problem and the unexpected numerical instabilities in state propagations through flybys, maneuver algorithm convergence issues, and orbital element targeting difficulties.

[View Full Paper]

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AAS 18-215

OPTIMAL NONLINEAR FEEDBACK WITH FEEDFORWARD CONTROL OF HIGH SPEED AEROSPACE VEHICLES USING A SPATIAL STATISTICAL APPROACH*

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The control of dynamical systems in the presence of uncertainty and disturbances must include state feedback for acceptable performance. However, the real-time optimal control of aerospace vehicles is challenging because of the computational time required to generate an *ab initio* optimal trajectory at every time step starting from the current state. Thus practical control systems assume that the actual trajectory lies in the neighborhood of the nominal optimal trajectory, and generate control perturbations using feedback gains determined using the nominal trajectory. Alternative methods implement optimal feedback controllers using control interpolation over a pre-computed extremal field, i.e. a family of open-loop optimal trajectories. Nevertheless, optimal feedback (FB) controllers can show reduced performance and accuracy in systems subject to significant disturbances. If such disturbances can be measured in real-time, this information can be fed forward to the controller for higher performance due to a more complete knowledge of the system environment. This work presents a methodology for the implementation of optimal nonlinear feedback+feedforward (FB+FF) controllers using kriging regression on extremal fields. This work also shows the implementation of FB+FF controllers on multiphase systems, i.e. trajectories with different dynamics on distinct phases. The proposed method is illustrated in the real-time optimal control of a high speed aerospace vehicle in the presence of realistic wind conditions. [View Full Paper]

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AAS 18-243

DESIGN OF INTERPLANETARY TRAJECTORIES WITH MULTIPLE SYNERGETIC GRAVITATIONAL ASSIST MANEUVERS VIA PARTICLE SWARM OPTIMIZATION

Matthew J. Shaw[*] and Robert G. Melton[†]

The design capacity for synergetic gravity assists (powered flyby's) changes possible types of optimal interplanetary trajectories. The application of Particle Swarm Optimization (PSO) is used to determine optimal mission trajectories from Earth to planets of interest, via synergetic gravity assist maneuvers. In order to verify the design results from PSO, past missions are re-examined from a new design perspective. Test results are obtained for Voyager 1, Voyager 2, and Cassini. The results closely resemble those of actual mission data, providing support for the new design method involving PSO and synergetic gravitational assists. The computation of these solutions offers the significant benefit of costing one to two minutes of wall-clock time with standard desktop or laptop computing systems. In addition to these past missions, the work then extends the design method to a newly proposed multiple gravity-assist (MGA) mission from Earth to Saturn that could take place within the next few years. The best solutions from PSO for the MGA routes are on the order of one half to one third the propellant cost as compared to the direct routes for the launch and arrival dates chosen. [View Full Paper]

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AAS 18-246

ENHANCED STATIONKEEPING MANEUVER CONTROL TECHNIQUE FOR DELTA-V COST REDUCTION IN THE KOREA PATHFINDER LUNAR ORBITER

Diane C. Davis,[*] Jae-ik Park,[†] Sujin Choi,[‡] Ryan Whitley,[§] John Carrico,[**] Dong-Young Rew[††] and Seok-Weon Choi[‡‡]

This paper proposes an enhanced control technique for stationkeeping maneuvers to reduce Δv costs for the Korea Pathfinder Lunar Orbiter (KPLO). A scheduled circularization control technique exploits patterns in the evolution of the line of apsides and eccentricity to achieve a significant reduction in station-keeping Δv costs based on spacecraft requirements. The technique is compared against previous algorithms implemented for maneuver operations of the Lunar Prospector and Lunar Reconnaissance Orbiter (LRO) missions in the USA and KAGUYA in Japan. Through Monte Carlo analysis, the efficacy and robustness of the proposed method are verified, and the technique is shown to meet the operational requirements of KPLO. [View Full Paper]

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AAS 18-250

MMS EXTENDED MISSION DESIGN: EVALUATION OF A LUNAR GRAVITY ASSIST OPTION

Trevor Williams,[*] Dominic Godine,[†] Eric Palmer,[†] Ishaan Patel,[†] Neil Ottenstein,[†] Luke Winternitz[‡] and Steve Petrinec[§]

This paper describes maneuvers that were recently considered for a later extended mission phase for the Magnetospheric Multiscale (MMS) mission. These are apogee-raises to set up a lunar gravity assist, which in turn raises perigee for enhanced magnetopause science collection, followed by apogee-lowering to inject into a 3:1 lunar resonance orbit. Since a lunar encounter is only achievable when the MMS apogee vector lies approximately in the lunar orbit plane, the possible dates are mid-2021 or early 2027. This study was made feasible by the fact that MMS is consuming fuel for formation maintenance at a far slower rate than expected pre-flight, and completed the prime mission with a significant amount of fuel remaining. [View Full Paper]

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AAS 18-251

2018 MARS INSIGHT MISSION DESIGN AND NAVIGATION OVERVIEW

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Originally scheduled for a launch in the 2016 Earth to Mars opportunity, NASA's Interior Exploration using Seismic Investigations, Geodesy, and Heat Transport (InSight) mission will launch the next lander to Mars in May-June 2018 arriving to the Red Planet in November 2018. 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.

[View Full Paper]

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AAS 18-259

EVALUATION OF OPTIMAL CONTROL TECHNIQUES USED IN SPACECRAFT MANEUVER PLANNING

Christopher P. Lawler*

An analysis is presented to compare the optimal control techniques used in a new maneuver planning tool developed at the US Naval Research Laboratory (NRL) with that of System Toolkit's (STK) Astrogator module. Each software tool solves for the same trajectory optimization problem in order to compare the use of the Numerical Algorithm Group's (NAG) E04UF algorithm to established STK optimizer profiles. The trajectory problem is the direct transfer of a spacecraft from one pre-defined orbit to another using two finite burn maneuvers. The initial estimate to the optimal control problem is given by the solution to the same problem using impulsive burn maneuvers. STK's Differential Corrector and the Sparse Nonlinear Optimizer (SNOPT) algorithm are compared to E04UF in solving for the feasible and optimal solutions using both impulsive and finite burn maneuvers. The result provided by E04UF in solving for the optimal solution using impulsive burns, in comparison to the result produced by Astrogator, shows that it can be used effectively to solve trajectory optimization problems. Additionally, for the given problem formulation, only the E04UF algorithm successfully converged to an optimal solution for the finite burn case. [View Full Paper]

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AAS 18-262

TRAJECTORY ANALYSIS OF A SPACECRAFT MAKING A THREE-DIMENSIONAL POWERED SWING-BY MANEUVER

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The present paper studies the problem of orbital maneuvers performed combining the passage of a spacecraft by a celestial body with an impulse applied to the spacecraft during the close approach. The motion of the spacecraft is assumed to be in the three-dimensional space, thus allowing plane change. This type of maneuver can also send the spacecraft to a point far from the orbit or to end in capture or collision of the spacecraft by the celestial body. The effects of the variations in the orbital plane, energy and the angular momentum of the spacecraft are presented. [View Full Paper]

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AAS 18-264

EXPLORATION OF THREE-DIMENSIONAL ORBIT BIFURCATIONS IN THE CRTBP USING CELL MAPPING

Dayung Koh,[*] Rodney L. Anderson[†] and Ivan Bermejo-Moreno[‡]

The natural nonlinear dynamical behavior with periodic motions around Europa has been studied using cell mapping. This study is especially focused on spatial periodic orbits and bifurcation phenomena. The proposed method is generic for various classes of problems including non-autonomous systems and unknown types of periodic solutions. It also provides a way to compute bifurcation diagrams that connect the different orbit types and produce a framework from which to obtain a more complete understanding of the orbit family options in this system. The result contains several periodic orbit families around Europa and bifurcation studies. [View Full Paper]

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AAS 18-269

A CONVEX OPTIMIZATION APPROACH TO MARS ENTRY TRAJECTORY UPDATING

Connor D. Noyes[*] and Kenneth D. Mease[†]

A convex optimization method is proposed for updating an existing Mars entry trajectory. The original trajectory and the updated trajectory may take any form and are not subject to a low-order parametrization. Due to the use of an existing trajectory, the approach does not require multiple iterations to produce a valid solution. Each update produces a neighboring trajectory that repairs constraint violations while retaining characteristics of the original trajectory. Online trajectory planning is beneficial in trajectory tracking approaches, and is the basis for predictor-corrector methods. Trajectory updating allows the vehicle to compensate for uncertainties beyond what can be handled by tracking alone. Simulations are conducted using dispersions in entry conditions, atmospheric modeling, and aerodynamics. The trajectory updates rapidly provide feasible trajectories, and a simple guidance approach demonstrates the effectiveness of repeated trajectory updates. [View Full Paper]

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AAS 18-271

ARCUS MISSION DESIGN: STABLE LUNAR-RESONANT HIGH EARTH ORBIT FOR X-RAY ASTRONOMY

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The *Arcus* mission, proposed for NASA's 2016 Astrophysics Medium Explorer (MIDEX) announcement of opportunity, will use X-ray spectroscopy to detect previously unaccounted quantities of normal matter in the Universe. The *Arcus* mission design uses 4:1 lunar resonance to provide a stable orbit for visibility of widely-dispersed targets, in a low background radiation environment, above the Van Allen belts for the minimum two-year science mission. Additional advantages of 4:1 resonance are long term stability without maintenance maneuvers, eclipses under 4.5 hours, perigee radius approximately 12 Re for data download, and streamlined operational cadence with approximately 1 week orbit period. [View Full Paper]

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AAS 18-276

OPTIMAL TRAJECTORIES FOR A DUAL-SPACECRAFT OUTER PLANET MISSION

Hongwei Yang,[*] Wei You,[†] Shuang Li[‡] and Xiuqiang Jiang[§]

A hypothetical future dual-spacecraft mission for visiting Jupiter and Uranus is considered in this paper. The constrained impulsive trajectory optimization method using the particle swarm optimization algorithm is proposed for the design trajectory of the mission. In trajectory optimization, Venus-Earth-Earth-Jupiter gravity assists are employed. For low-thrust case, an indirect method is employed for trajectory optimization based on the impulsive-thrust trajectories. A technique for solving hybrid-thrust trajectories is also presented. Analyses on the mission fuel consumption are conducted based on optimized trajectories. The obtained results are expected to provide reference for future missions.

[View Full Paper]

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AAS 18-277

MISSION ANALYSIS FOR AN ESA CONTRIBUTION TO THE MARS SAMPLE RETURN CAMPAIGN

Eric Joffre,[*] Uwe Derz,[†] Marie-Claire Perkinson,[‡] Jakob Huesing,[§] Friederike Beyer[**] and Jose-Manuel Sanchez Perez[††]

Bi-lateral discussions between NASA and the European Space Agency identified the orbiter element as a promising European-led contribution to a future international Mars Sample Return campaign. Airbus recently completed the Mars Sample Return Architecture Assessment Study on behalf of ESA, with the objective to identify and quantify candidate mission architectures. The paper describes the mission analysis that has been conducted to support preliminary system design, launch mass estimation and mission timeline for the architectures investigated. It includes the optimisation of interplanetary transfers, Mars operations including aerobraking and rendezvous, up to Earth re-entry conditions. [View Full Paper]

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AAS 18-282

THE THEORY OF CONNECTIONS APPLIED TO PERTURBED LAMBERT'S PROBLEM

Hunter Johnston[*] and Daniele Mortari[†]

Lambert's problem remains important in celestial mechanics for application such as rendezvous, targeting, guidance, and orbit determination and has many robust algorithms for solving this type of problem using Kepler's equation of motion. Solutions to the unperturbed case have been studied extensively and are leverage and built upon by developing an algorithm that allows for the solution of the perturbed Lambert problem by the addition of *all* perturbations at once. By doing this, both analytical and numerical perturbation models to be handled in a unified manner. Since at its core, Lambert's problem is simply a two point boundary value problem for the differential equation of motion, extension of the *Theory of Connections* (ToC) for this case is immediate. In this paper, a new solution to the perturbed Lambert Problem is developed using the *Theory of Connection* (ToC) where first Lambert's problem is solved for the unperturbed case, then this solution is adjusted for *all* incorporated perturbations simultaneously utilizing a *constrained expression*. From this, a solution is produced with sub-meter accuracy. [View Full Paper]

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AAS 18-293

TRAJECTORY DESIGN FOR THE KOREA PATHFINDER LUNAR ORBITER (KPLO)

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The Korea Pathfinder Lunar Orbiter (KPLO) will be the first spacecraft for the Korean lunar exploration program. KPLO will fly in a low 100 km mean altitude lunar polar orbit. KPLO will utilize a 3.5 phasing loop transfer trajectory. This paper will describe several trade-off studies of critical parameters to minimize the Delta-V such as phasing loop option, trans-lunar inclination, 1st apogee altitude, SEM (Satellite-Earth-Moon) angle and periselene altitude for lunar orbit insertion. After lunar orbit insertion, KPLO will be placed into a mission orbit. These parameters were studied over a month-long launch period in December 2020 and the results are given. As a result, 3.5 loops with first apogee altitude of a 320,000 km provides minimum Delta-V. Low initial inclination, low SEM angle and low captured periselene altitude of LOI1 shows better performance.

[View Full Paper]

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AAS 18-296

STATISTICAL APPROACHES TO INCREASE EFFICIENCY OF LARGE-SCALE MONTE-CARLO SIMULATIONS

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Numerical astrodynamics simulations are regularly characterized by a large input space and complex, nonlinear input-output relationships. Monte Carlo runs of these simulations are typically time-consuming and numerically costly. In this paper the Design and Analysis of Computer Experiments (DACE) approach is adapted to astrodynamics simulations to improve runtimes and increase information gain. Two case studies are presented: a satellite detumbling simulation using the BASILISK software, and orbit trajectory simulations in the IBEX-extended mission. The space-filling and meta-modelling techniques of DACE are shown to provide significant improvements for astrodynamics simulations in speed of sensitivity analysis, determination of outliers and identifying extreme output cases not found by standard simulation and sampling methods. [View Full Paper]

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AAS 18-310

TWO-BODY ORBITAL BOUNDARY VALUE PROBLEMS IN REGULARIZED COORDINATES

Bharat Mahajan[*] and Srinivas R. Vadali[†]

Lambert's problem is widely used in preliminary design and optimization of interplanetary as well as planetocentric missions. For preliminary design, it is often necessary to obtain feasible trajectories that satisfy the mission constraints. These solutions can be used for low-fidelity trade studies and as initial guesses for high-fidelity numerical optimization. The classic Lambert's problem only allows for position and transfer time constraints. In this work, various two-body orbital boundary value problems with constraints on velocities, flight path angle, Δv, final radius, transfer angle, etc. are studied and their exact solutions in universal form are derived via the KS-transformation. All of the solutions are regular and completely analytic if the energy of the transfer orbit is known a priori, otherwise they reduce to solving a single transcendental equation with well-defined bounds on the roots. The formulation presented in the paper results in a single constraint in each case for solving a class of boundary value problems commonly encountered in trajectory design problems. [View Full Paper]

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AAS 18-314

TRAJECTORY DESIGN FOR A SOLAR-SAIL MISSION TO ASTEROID 2016 HO_3

Jeannette Heiligers,[*] Juan M. Fernandez,[†]
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This paper proposes the use of solar-sail technology currently under development at NASA Langley Research Center for a CubeSat rendezvous mission with asteroid 2016 HO_3, a quasi-satellite of Earth. Time-optimal trajectories are sought for within a 2022 – 2023 launch window, starting from an assumed launcher ejection condition in the Earth-Moon system. The optimal control problem is solved through a particular implementation of a direct pseudo-spectral method for which initial guesses are generated through a relatively simple and straightforward genetic algorithm search on the optimal launch date and sail attitude. The results show that the trajectories take 2.16 – 4.21 years to complete, depending on the assumed solar-sail reflectance model and solar-sail technology. To assess the performance of solar-sail propulsion for this mission, the trajectory is also designed assuming the use of near-term solar electric propulsion. The resulting fuel-optimal trajectories take longer to complete than the solar-sail trajectories and require a propellant consumption that exceeds the expected propellant capacity onboard the CubeSat. This comparison demonstrates the superior performance of solar-sail technology for this mission.

[View Full Paper]

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AAS 18-324

CONCEPT OF OPERATIONS FOR EARTH-MOON DEPARTURES TO MARS-PHOBOS DISTANT RETROGRADE ORBIT ARRIVALS

Davide Conte[*] and David B. Spencer[†]

This paper focuses on the trajectory design for missions destined to explore Mars and/or Phobos departing from Low Earth Orbit (LEO) and arriving into a Mars-Phobos Distant Retrograde Orbit (DRO). Lunar DROs are also briefly explored as an alternative departure location. A Mars-Phobos DRO is a relatively stable environment which would make both the surfaces of Mars and Phobos available for a reasonable propellant expenditure. This paper presents the methodology used to compute LEO to Mars-Phobos DRO trajectories and results regarding required C_3 at launch, v_∞ at arrival, Time-of-Flight (*TOF*), and total ΔV for various Mars-Phobos DROs using full ephemeris planetary data. The results show that propellant-optimal trajectories from LEO to a specified Mars-Phobos DRO could be used as a staging location between Mars and Phobos. Assuming that refueling is available at the targeted DRO, LEO to Low Mars Orbits (LMO) trajectories would have higher total ΔV due to the additional stop at the Mars-Phobos DRO. However, the aforementioned trajectories would have lower Initial Mass in LEO (IMLEO) and thus a lower gear ratio thanks to the added "pit stop" located at the given DRO. This results in a lower overall spacecraft dry mass that needs to be launched into space from Earth's surface. [View Full Paper]

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AAS 18-325

TRAJECTORY DESIGN FOR LEO TO LUNAR HALO ORBITS USING MANIFOLD THEORY AND FIREWORKS OPTIMIZATION

Davide Conte,[*] Guanwei He,[*] David B. Spencer[†] and Robert G. Melton[†]

In this paper a simple and efficient way of computing impulsive maneuver transfers from a user-defined Low Earth Orbit (LEO) to a desired lunar halo orbit around the Earth-Moon Lagrange point 2 (EML2) utilizing a heuristic optimization method is presented. The dynamical framework utilized is the Circular Restricted Three-Body Problem (CR3BP). Sample LEO to lunar halo trajectories along with their required ΔV costs and Time-of-Flight (*TOF*) are provided and compared to known numerical techniques to assert the validity of the proposed method. The obtained results are close in both ΔV and *TOF* to what the existing literature reports. [View Full Paper]

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AAS 18-332

FRAMEWORK FOR OPTIMIZING MANY-REVOLUTION LOW-THRUST TRANSFERS*

Zubin P. Olikara†

This work presents a general-purpose approach to directly optimize many-revolution low-thrust transfers around solar system bodies. Control parameterization combined with numerical averaging allows complete trajectories to be generated using a small number (tens) of control variables. A collocation discretization enables robust convergence while providing flexibility for a wide variety of constraints. The scheme is developed for both minimum-time and minimum-fuel (bang-bang) transfers and illustrated using a variety of test cases. Computational performance is competitive with indirect techniques while also being notably insensitive to initial guess. [View Full Paper]

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AAS 18-337

EVENT-DRIVEN SPACE LOGISTICS NETWORK OPTIMIZATION FOR CISLUNAR SUPPLY CHAIN DESIGN WITH HIGH-THRUST AND LOW-THRUST PROPULSION TECHNOLOGIES

Bindu B. Jagannatha[*] and Koki Ho[†]

Various high-thrust and low-thrust propulsion technologies have been developed to sustain future space exploration activities; however, designing and optimizing a multi-mission campaign with both propulsion options is generally computationally challenging due to the coupling of network logistics design and space transportation costs. To tackle this challenge, this paper develops a novel event-driven space logistics network approach with mixed-integer linear programming methods and precomputed transfer cost models for campaign-level space mission design. The specific case of optimally designing a cislunar propellant resupply chain is considered for the purposes of supporting lunar surface access. The results are compared with an existing stochastic combinatorial formulation. The newly developed approach provides superior results in terms of cost, as well as utilization of vehicle fleet. [View Full Paper]

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AAS 18-341

SOLAR ORBITER 2020 FEBRUARY MISSION PROFILE

José M. Sánchez Pérez,[*] Waldemar Martens[*] and Gábor I. Varga[*]

ESA's Solar Orbiter mission, with NASA participation, will investigate the physical processes of the inner heliosphere and return unprecedented observations of the Sun polar regions. The mission success depends on achieving Sun distances down to 0.28 AU and heliocentric inclinations of 33 deg by the end of the 10-year mission, along with providing enough downlink opportunities to optimize the science data return. Following programmatic delays the mission is now scheduled to launch in February 2020. Key elements of the mission design are a short cruise including two Venus and an Earth gravity assist and a science phase including a series of resonant Venus gravity assists. A complete trajectory description and correction maneuver schedule are shown.

[View Full Paper]

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AAS 18-349

TRACKING CONTROL OF SPACECRAFT ATTITUDE AND POSITION ON TIME DEPENDENT TRAJECTORIES USING DUAL QUATERNIONS

Ali Tevfik Büyükkoçak[*] and Ozan Tekinalp[†]

A spacecraft attitude and position control algorithm that uses dual quaternions for parametrization is proposed. Error dual quaternion and its derivative are obtained from the desired attitude and position information which are the trajectories of time dependent functions. This position and orientation (pose) formulation is used in a Lyapunov based nonlinear feedback control law that includes derivative of desired attitude and position. Simulation results show that desired attitude and position trajectories are successfully tracked by the new algorithm. [View Full Paper]

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AAS 18-364

LOW-THRUST STATION-KEEPING FOR AN ELLIPTICAL POLAR LUNAR ORBIT

Alexander J. Mazarr[*] and David C. Folta[†]

The Lunar IceCube CubeSat mission, a partnership between NASA's Goddard Space Flight Center and Morehead State University, is set to launch on Exploration Mission-1. The primary science objective is to observe volatiles and water ice near the lunar equator, requiring a tightly controlled elliptical polar orbit. In order to achieve and maintain the required orbit parameters, a low thrust Busek BIT-3 ion propulsion system provides the only maneuver capability available. This paper discusses perturbations of the specific lunar orbit and operational low-thrust station-keeping concepts that extend the life of the mission while maintaining required orbit parameters. [View Full Paper]

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AAS 18-385

STATE VECTOR REPRESENTATIONS FOR LOW-THRUST TRAJECTORY OPTIMIZATION

John L. Junkins[*] and Ehsan Taheri[†]

Coordinate choices have significant consequences in the analytical and computational approaches to solve celestial mechanics problems. The present study focuses on the impact of various coordinate representations of the dynamics on the solution of the ensuing state/costate two-point boundary-value problems that arise when solving the indirect optimal control necessary conditions. Minimum fuel trajectory designs are considered for a geocentric spiral from GTO to GEO. Eight different coordinate/element sets are investigated. Specifically, two different sets of orbit elements are considered: Equinoctial elements and a six element set consisting of the angular momentum vector and the eccentricity vector. Furthermore, four hybrid coordinate sets associated with an osculating triad defined by the instantaneous position and velocity vectors that consist of a mixture of slow and fast variables are introduced and studied. Reliability and efficiency of convergence to the known optimal solution are studied statistically against the Cartesian and spherical coordinates, which constitute eight element/coordinate sets; the results are interesting and of significant practical utility. [View Full Paper]

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AAS 18-392

AEROPROPCAPTURE: APPLYING PROPULSION TO AEROCAPTURE MANEUVERS

Eiji Shibata*

Chemical propulsion and aerocapture are the main methods used to place a spacecraft into orbit for interplanetary missions. Yet, orbital insertion maneuvers are dependent on the incoming velocity, while aerocapture has low targeting capabilities at lower entry velocities. Aeropropcapture (APC) is a combination of the two methods by using propulsion in the atmosphere as a control. The capability of APC is first evaluated by comparing trajectories while varying entry velocity, ballistic coefficient, post-capture apoapses, and thrust-to-weight ratios (T/W). Equivalent lift-to-drag ratios (L/D) in an aerocapture trajectory are then found for a given entry T/W in an APC trajectory. The required propellant for both chemical propulsion and APC are then compared. For low hyperbolic velocities, APC has the potential to have better targeting capabilities than that of aerocapture while still requiring less propellant than a propulsive burn. [View Full Paper]

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AAS 18-397

OPTIMAL LOW-THRUST TRAJECTORY CORRECTION WITH NEURAL NETWORKS

Nathan L. Parrish[*] and Daniel J. Scheeres[†]

Although electric propulsion technologies give spacecraft a leap forward in maneuverability over time relative to chemical propulsion, the greater lifetime delta-v comes at the expense of thrust. The traditional paradigm of large, impulsive maneuvers with later clean-up is not relevant to low-thrust trajectories. In highly sensitive dynamical environments such as the Earth-Moon system, frequent ground contacts are required to maintain low-thrust spacecraft in a tight control box. Here we introduce neural networks as a way to map position and velocity error to an updated low-thrust optimal control policy. Promising results are shown for interplanetary and CRTBP force models. [View Full Paper]

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AAS 18-398

LOW-THRUST GTO-TO-GEO TRAJECTORY OPTIMIZATION AND TRACKING

Uroš Kalabić,[*] Avishai Weiss[†] and Piyush Grover[†]

In this work, we consider the problem of low-thrust GTO-to-GEO osculating trajectory optimization and tracking. We exploit analytical solutions available in the averaged minimum-energy planar optimal control problem, and use homotopy methods to obtain fuel- and time-optimal osculating trajectories using direct numerical optimal control tool GPOPS-II. We employ an attitude controller for tracking the thrust vector profile obtained from the optimal trajectories, while maintaining desired solar panel alignment. We simulate the operation of our controller numerically using MATLAB and the high-fidelity Systems Tool Kit (STK) software, and show satisfactory tracking performance of the controller. [View Full Paper]

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AAS 18-399

A UNIFIED APPROACH TO OPTIMIZATION OF LOW-THRUST AND IMPULSIVE ORBIT MANEUVERS

Ehsan Taheri[*] and John L. Junkins[†]

This paper builds upon a recently introduced concept of *switching surfaces* and performs an in-depth analysis of such switching surfaces for an interplanetary mission from the Earth to the Mars. Indirect method of optimal control theory along with Lawden's primer vector theory are essential to the method and are used to discuss a unified systematic means to study continuous low-thrust and impulsive trajectories. An interplanetary rendezvous-type maneuver from the Earth to the Mars is considered and its associated switching surface is analyzed. A bifurcation is observed in the switching surface, which in general, trigger the creation of new thrust arcs. In general, switching surfaces' topology provide new tools for mission designers and enables insights to perform useful trade-offs for sizing vehicles, propulsion systems. [View Full Paper]

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AAS 18-401

A NOVEL MULTI-SPACECRAFT INTERPLANETARY GLOBAL TRAJECTORY OPTIMIZATION TRANSCRIPTION

Sean W. Napier*† and Jay W. McMahon‡

As the frontier of space exploration continues to advance, so does the design complexity of future interplanetary missions. This increasing complexity includes a class of designs known as *Distributed Spacecraft Missions*; missions where multiple spacecraft coordinate to perform shared objectives. Current approaches for global trajectory optimization of these Multi-Vehicle Missions (MVMs) are prone to shortcomings, including laborious iterative design, considerable human-in-the-loop effort, treatment of the multi-vehicle problem as multiple, separate trajectory optimization subproblems, and poor handling of coordination objectives and constraints. This leads to suboptimal solutions where the whole is less than the sum of its parts. There are only a handful of software platforms in existence capable of fully-automated, rapid, interplanetary global trajectory optimization, including the Gravity Assisted Low-thrust Local Optimization Program (GALLOP), and the Evolutionary Mission Trajectory Generator (EMTG). However, none of these tools is capable of performing such tasks for MVM designs. We present a fully-automated technique which frames interplanetary MVMs as Multi-Objective, *Multi-Agent* Hybrid Optimal Control Problems (MOMA HOCP). First, the basic functionality of this technique is validated on the single-vehicle problem of reproducing the Cassini interplanetary cruise. The technique is then applied to explore the possibility of a dual-manifest mission to the Ice Giants, Uranus, and Neptune. A single trajectory with flybys of both planets has been shown to be infeasible with only a single spacecraft anytime between 2020 and 2070.

[View Full Paper]

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AAS 18-407

AUTONOMOUS OPTICAL NAVIGATION USING NANOSATELLITE-CLASS INSTRUMENTS: A SENSOR DESIGN CASE STUDY

Harry Zhang[*] and John Enright[†]

This paper looks at optimizing the sensor configuration for small star trackers for orbit determination. Using our previously developed navigation filter, we conduct a set of tradeoff studies investigating the effects that various parameters have on the system. Sensor placement and field of view sizing are parameters we consider. Our results show that for attitude constrained cases, sensor placement can restore lost performance and reduce error. Results also indicate smaller fields of view have an effect on improving convergence time. Through these trials we demonstrate the utility of our framework to evaluate changes to the mission and satellite design. [View Full Paper]

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AAS 18-411

INTERPLANETARY TRAJECTORY DESIGN USING A RECURRENT NEURAL NETWORK AND GENETIC ALGORITHM: PRELIMINARY RESULTS

Paul A. Witsberger[*] and James M. Longuski[†]

A low-thrust gravity-assist trajectory design tool is proposed that uses a recurrent neural network (RNN) to create a spacecraft steering strategy and is trained using an evolutionary algorithm. This strategy extends the concepts of genetic reinforcement learning and evolutionary neurocontrol, which both use a feedforward neural network (FNN). The effectiveness of using dynamic backpropagation to form an initial guess for the global optimizer is also considered. In the cases studied here, the process to gather enough training data to train a generalizable neural network was found to be tedious, and the time to train an RNN was longer than the time to train an FNN while offering no notable improvement in quality of solutions. An RNN took around twice the amount of time to converge compared to the FNN for the cases considered, reaching up to 45 minutes for simple cases and over 15 hours for complicated trajectories. Both the RNN and FNN are not competitive with existing optimizers for simple cases. [View Full Paper]

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AAS 18-423

MARS ION AND SPUTTERING ESCAPE NETWORK (MISEN) MISSION CONCEPT

Jeffrey S. Parker,[*] Nathan Parrish,[†] Rob Lillis,[‡] Shannon Curry,[§] Dave Curtis,[**] Janet Luhmann,[††] Jordi Puig-Suari,[‡‡] Christopher Russell[§§] and David Brain[***]

The Mars Ion and Sputtering Escape Network (MISEN) is a mission concept developed through the Planetary Science Deep Space SmallSat (PSDS3) program supported by NASA's Science Mission Directorate. MISEN includes three small satellites deployed as secondary payloads aboard a primary mission destined for Mars, the Moon, or another orbit of similar launch energy. The three satellites each use solar electric propulsion (SEP) to transfer to Mars, rendezvous with Mars, and descend to three different orbits. Once there, they conduct a joint investigation characterizing ion and sputtering escape mechanisms in the Martian atmosphere. This paper describes the mission design challenges and solutions, illustrating the viability of achieving multiple different orbits about Mars as a secondary payload aboard many viable launches using SEP. [View Full Paper]

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AAS 18-431

ANALYTIC EXPRESSIONS FOR DERIVATIVES FROM SERIES SOLUTIONS TO THE THREE BODY PROBLEM

Nathan Strange*

This paper presents a notation system to facilitate to solution of differential equations via Taylor series expansions and applies it to solve the circular restricted three body problem. Unlike previous Taylor series methods in the astrodynamics literature, computer algebra solvers are not used. Instead the notation system allows one to solve a system of differential equations analytically "by hand" without resorting to computer algebra software. This method produces recurrence relations explicitly in terms of a sequence of derivatives of the state with respect to time for the coefficients of Taylor Series solutions that can be evaluated numerically or manipulated further to investigate properties of the solution. For example, additional derivatives with respect to other parameters may also be found, including those that describe the dependence of the solution on initial conditions.

[View Full Paper]

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AAS 18-434

ORBITAL MAINTENANCE FOR THE WIDE FIELD INFRARED SURVEY TELESCOPE: THE EFFECTS OF SOLAR RADIATION PRESSURE AND NAVIGATION ACCURACIES ON STATIONKEEPING

Ariadna Farres,[*] Cassandra Webster,[†] Jennifer Donaldson[‡] and Dave Folta[§]

The Wide-Field Infrared Survey Telescope (WFIRST), a NASA observatory designed to investigate dark energy and astrophysics, is planned for a launch in 2025 to orbit the Sun-Earth L2 (SEL2) Libration Point. Due to the instability of the SEL2 environment, WFIRST must perform maneuvers to remain in its mission orbit. This paper investigates how different error sources affect the resulting stationkeeping Δv for WFIRST. We study how Solar Radiation Pressure (SRP) modeling affects WFIRST's orbital motion and stability, and how SRP combined with Orbit Determination (OD) errors drive the stationkeeping maneuver magnitudes. Our goal is to determine the best way to model WFIRST's SRP so that we minimize its impact on total stationkeeping Δv required over the mission lifetime. [View Full Paper]

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AAS 18-436

TRANSFER FROM TLI TO LUNAR POLAR ORBIT VIA BALLISTIC LUNAR CAPTURE

Anthony L. Genova[*] [†] and Brian Kaplinger[‡]

The presented trajectory design connects a trans-lunar injection (TLI) trajectory to lunar polar orbit via ballistic lunar capture. The TLI is assumed to originate from NASA Kennedy Space Center with solutions presented for a full 360 degree sweep of the Moon-Earth-Sun angle. The design is compatible with small spacecraft equipped with propulsion systems that lack sufficient thrust to enter lunar orbit from a traditional lunar orbit transfer such as the LunaH-Map cubesat (~1 mN thrust capability) which is planning to share a ride on a TLI trajectory with EM-1 on SLS. [View Full Paper]

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AAS 18-442

ROBUST TRAJECTORY OPTIMIZATION FOR MARS ATMOSPHERIC ENTRY BASED ON UNCERTAINTY PROPAGATION

Xiuqiang Jiang[*] and Shuang Li[†]

A robust optimization procedure of Mars atmospheric entry trajectory under uncertainty is newly developed in this paper. Uncertainty propagation due to both initial state and dynamical parameters are taken into account. In the proposed robust design framework, the original robust trajectory optimization problem is transformed into an equivalent deterministic one in the expanded higher-dimensional state space by polynomial chaos expansion at first. Quantification of the stochastic cost, and boundary and path constraints in terms of polynomial chaos expansion is formulated. Then, *hp*-adaptive pseudospectral method is adopted to solve the equivalent optimal control problem numerically. Finally, the effectiveness of the proposed procedure is verified through final altitude maximization problem. And the obtained optimal trajectory is evidently more robust to uncertainties compared to traditional deterministic optimization and reliability-based optimization. [View Full Paper]

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AAS 18-445

UNCERTAINTY QUANTIFICATION FOR MARS ATMOSPHERIC ENTRY USING MODIFIED GENERALIZED POLYNOMIAL CHAOS

Xiuqiang Jiang,[*] Shuang Li[†] and Roberto Furfaro[‡]

This paper presents a novel computational approach for quantifying the propagation of the uncertainties in the state trajectories of low-lift Mars entry vehicle. The unique contribution of this work is twofold: one is considering the change of stochastic characteristics due to the high nonlinearity of Mars entry dynamics to improve propagation accuracy, and the other is suppressing the increase of equation dimension in long-term integration to enhance computational efficiency. Generalized polynomial chaos is modified accordingly through conducting spectral decomposition and random space decomposition adaptively. In this framework, stochastic dynamics is modeled and transformed into equivalent deterministic dynamics in higher-dimensional space and is updated adaptively when the statistic characteristic of system state changes greatly. The random space is decomposed adaptively when the relative error in variance becomes larger than the predefined threshold. In each random sub-domain, the updated generalized polynomial chaos is employed. We demonstrate that the proposed method is able to quantify propagation of uncertainty effectively in Mars atmospheric entry dynamics, with a better accuracy level than generalized polynomial chaos and much more computational efficiency than Monte-Carlo simulations. Meanwhile, the influences and the evolution profiles of the initial and parametric uncertainties during Mars entry are revealed through parametric studies. [View Full Paper]

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AAS 18-447

RAAN-AGNOSTIC 3-BURN DEPARTURE METHODOLOGY FOR DEEP SPACE MISSIONS FROM LEO DEPOTS

Michel Loucks,[*] Jonathan Goff,[†] John Carrico[‡] and Brian Hardy[§]

The authors continue investigation of a 3-burn departure approach that enables deep space missions to depart from a LEO depot even if the depot orbital plane is not optimally aligned with the desired departure asymptote. In this paper, a methodology will be described for targeting specific departure trajectories from a LEO depot whose orbit's RAAN is not optimized for the given mission, and the concept will be illustrated by showing how multiple interplanetary missions can realistically be launched, in a short time-period, from a single LEO depot. [View Full Paper]

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AAS 18-457

CONCEPTUAL DESIGN AND AEROCAPTURE ANALYSIS FOR A CREW TRANSFER VEHICLE FOR AN EARTH-MARS CYCLER

Larissa Balestrero Machado,[*] Markus Wilde,[†] Brian D. Kaplinger[‡] and Robert W. Moses[§]

This paper presents the results of a conceptual design and aerocapture analysis for a Crew Transfer Vehicle to/from an Earth-Mars Cycler. The Crew Transfer Vehicle is designed to reduce propellant demand by using a combination of propulsive and aerodynamic braking for insertion into a low Mars orbit. The requirements for propulsive and aerodynamic braking are given by the hyperbolic excess arrival speed at Mars, thus driving the overall design requirements for the vehicle. The paper describes a first-principle simulation model for aerocapture at Mars and discusses the applicability of aerocapture for S1L1 Cycler flight opportunities. Furthermore, the paper outlines a parametric design model for the Crew Transfer Vehicle and presents concepts for the integration of aerocapture within a sustainable cycler architecture. [View Full Paper]

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AAS 18-462

ELLIPTICAL ORBIT PROXIMITY OPERATIONS DIFFERENTIAL GAMES*

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Differential games are formulated and solved for an inspector satellite operating nearby a resident space object (RSO) in an elliptical orbit. For each differential game, the goal of the inspector satellite is to minimize the time to achieve an inspection goal, while the goal of the RSO is to delay that condition as long as possible. Thus, it is assumed that the RSO can maneuver, and that both the inspector satellite and the RSO use a constant, steerable thruster (e.g. an electric engine) during each game. The following games are formulated and solved via an indirect heuristic method, where each game corresponds to an inspection goal of the inspector satellite: a) intercept; b) rendezvous; c) obtain Sun vector; d) match energy; e) obtain Sun vector and match energy; and f) match energy and remain in close proximity during the ensuing orbit. The open-loop strategies obtained for these games represent worst-case scenarios, and may inform requirements for future satellites as well as be actual open-loop strategies for a given scenario. [View Full Paper]

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AAS 18-467

A PIECEWISE-CONSTANT SUNDMAN TRANSFORMATION FOR SPACECRAFT TRAJECTORY OPTIMIZATION

David Ottesen[*] and Ryan P. Russell[†]

A piecewise-constant Sundman transformation is introduced for a spacecraft trajectory discretized into many segments. The piecewise-constant Sundman transformation is a function that automatically produces the time of flight for the boundary value problem between the terminal states of each segment implicitly enforcing position continuity along the trajectory. The piecewise-constant Sundman transformation is based on the classic differential Sundman transformation to provide an efficient discretization in two-body dynamics that enables the use of fast Lambert solvers for all conics. The efficient discretization naturally avoids the singularity of equal terminal positions of the Lambert problem while conveniently modeling approximate low thrust. For three sets of examples, the need for and utility of the piecewise-constant Sundman transformation is demonstrated using the terminal positions as decision variables to embed the boundary value problem inside a direct, gradient-based spacecraft trajectory optimization algorithm. The three demonstrations cover the desirability of different fast boundary value problem solvers, the usefulness of different forms of the piecewise-constant Sundman transformation, and a comparison between the piecewise-constant and differential Sundman transformation that uses a shooting method as the embedded boundary value problem solver. [View Full Paper]

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AAS 18-489

AN ANALYTICAL 3D SHAPE-BASED ALGORITHM BASED ON ORBITS INTERPOLATION FOR MULTI-REVOLUTIONS LOW-THRUST TRAJECTORY OPTIMIZATION WITH ECLIPSES AND PERTURBATIONS

J. Prinetto[*] and M. Lavagna[†]

A novel 3-dimensional shape based algorithm is proposed in order to extend the domain of analytical solutions to planeto-centric mission scenarios, in which hundreds or thousands of revolutions are required. Due to the strong physical meaning of the shape the method outputs a trajectory close to the real optimal solution. Practical mission constraints are easily formalized, such as maximum thrust threshold and eclipses; moreover, relevant perturbations effects can be considered; free and fixed time of flight are manageable as well. The approach is almost completely analytic, beneficial to significantly lower the computational load, well suited for complex mission scenarios near optimal solutions fast detection.

[View Full Paper]

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ORBITAL DEBRIS

Session Chairs:

Monday Session 8: John H. Seago, ERC

Co-Chair: William Todd Cerven, The Aerospace Corporation

AAS 18-338

PRACTICAL SURVEY STRATEGIES FOR GEO FROM A SINGLE GROUND BASED OBSERVATORY

Akhter Mahmud Nafi[*] and David Geller[†]

Space debris poses an increasing risk for the geosynchronous orbit (GEO) satellites. Further, space debris is increasing and at least two breakups have been reported in this regime. Thus it is important to have the capability to detect GEO objects and update the GEO catalog on a regular basis to ensure the safety of high-value assets in this congested orbit regime. It is also important to develop and evaluate ground-based optical survey designs to help achieve these objectives. The GEO resident space object environment and the observation properties of GEO RSO orbits from an Earth-based observatory are studied thoroughly. Based on this information, efficient and practical surveys will be designed for USU's Space Situational Awareness Telescope for Astrodynamics Research (USU-STAR).

[View Full Paper]

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AAS 18-352

CHARACTERIZING THE REENTRY PREDICTION UNCERTAINTY OF TIANGONG-1

Eric A. Eiler[*] and Andrew J. Abraham[†]

In March 2016, the Tiangong-1 (TG-1) Chinese space station ended its telemetry communication and became uncontrolled space debris. This large space object, with an orbit that never rose above 400 km, was initially predicted to reenter between late 2017 and mid-2018 with a significant reentry prediction uncertainty that spanned several months. Between March 2017 and the April 2018 reentry, a study was conducted to better evaluate the uncertainty in reentry prediction of TG-1 and found that the traditional ±20% of the time-to-go rule-of-thumb was insufficient to accurately capture this uncertainty. Here, a process is described to better characterize the uncertainty for the reentry. [View Full Paper]

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AAS 18-372

TARGETING REGIONS OF CHAOS IN THE GNSS REGIME

Marielle M. Pellegrino[*] and Daniel J. Scheeres[†]

This paper seeks to utilize solar radiation pressure in the form of a solar sail to reach regions of chaos proximate to GNSS satellite orbits for debris mitigation purposes. These regions are caused by luni-solar resonances and are defined by the semimajor axis, eccentricity, and inclination. The semimajor axis is defined by the orbit the satellite is in, (GPS, Galileo, GLONASS, and Beidou) but the eccentricity and inclination will need to change from the initial orbit. This paper explores the minimum sail characteristics needed to achieve these orbits. [View Full Paper]

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AAS 18-376

DISPOSAL DESIGN FOR GEOSYNCHRONOUS SATELLITES REVISITED

Ioannis Gkolias[*] and Camilla Colombo[†]

The orbits at geosynchronous altitude provide a valuable natural resource for the human kind. In the absence of atmospheric drag, human intervention is needed to keep the region clean of space debris. Current post-mission disposal guidelines deal efficiently with the geostationary low-inclination, low-eccentricity satellites but fail to efficiently regulate the whole geosynchronous region. In this work, we revisit the problem of geosynchronous disposal orbits, trying to identify all possible mechanisms for designing effective disposal strategies. Massive numerical simulations are coupled with optimization techniques and semi-analytical modelling to achieve this goal. [View Full Paper]

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AAS 18-382

FREQUENCIES OF OSCILLATIONS OF A SPACE TETHER TOWING SPACE DEBRIS

Richa Saynak* **and Arun K. Misra†**

One of the potential applications of tethers in space in the near term is the towing of space debris for its disposal. These systems are expected to have a nominal configuration inclined to the local vertical (possibly almost near horizontal) and subjected to a thrust for orbital transfer. The frequencies of libration, as well as of elastic longitudinal and transverse oscillations of these systems are obtained in this paper for various parameters. It is noted that these frequencies can be very different from those of the conventional tethered satellites systems in vertical configuration. [View Full Paper]

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AAS 18-394

LONG SHORT-TERM MEMORY NEURAL NETWORKS FOR THE PREDICTION OF LOCALIZED ATMOSPHERIC DENSITY FOR ORBIT DETERMINATION

Kyri E. Barton[*] and Craig A. McLaughlin[†]

Modeling of atmospheric drag is among the most important aspects in determining the dynamics of a satellite in low Earth orbit (LEO). Variations in the local atmospheric density present the largest source of uncertainty in drag modeling as complex thermo- and magnetospheric coupling mechanisms have yet to be robustly modeled. As drag directly affects the motion of the satellite, the ability to predict density with very high accuracy becomes critical as the corresponding perturbation error becomes larger with orbit propagation. The objective of this research is to provide an alternative method for calibrating local atmospheric density using neural networks to be used in existing atmospheric models for orbit determination of low Earth orbit satellites. Implementing these densities improves the accuracy of satellite drag calculations, thereby improving orbit determination, orbit forecasting, satellite life-cycle analysis, and also contributes to a better understanding of the nature of atmospheric density in the thermosphere and exosphere. This research examines Long Short-Term Memory neural network architectures as they apply to predicting local atmospheric density along the orbits of the Challenging Minisatellite Payload (CHAMP) and Gravity Recovery and Climate Experiment (GRACE-A) satellites, and the contributions to their respective estimated orbits. Comparisons with the accelerometer data over the future specified time horizon reveals more accurate density estimation and prediction using the presented neural networks than the existing empirical atmospheric models.

[View Full Paper]

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AAS 18-418

UNCERTAINTY IN DRAG COEFFICIENT MODELING AND THE EFFECTS ON DENSITY ESTIMATION

Craig A. McLaughlin,[*] Alex Sizemore[†] and Piyush M. Mehta[‡]

Various satellite drag coefficient theories are examined to better characterize the uncertainties of drag coefficients used in orbit analysis. The drag coefficient theories for spherical satellites are applied to the Atmospheric Neutral Density Experiment (ANDE) series of satellites. The different drag coefficients are then used in an orbit estimation process that also estimates atmospheric neutral density along the satellite orbit. The effects on density estimation of the different theories are quantified. [View Full Paper]

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AAS 18-430

ANALYSIS OF A THRESHOLD ON LONG-TERM ORBITAL COLLISION PROBABILITY

Alan B. Jenkin,[*] John P. McVey[†] and Glenn E. Peterson[‡]

U.S. standards on limiting orbital debris contain a threshold that is not to be exceeded of 0.001 on long-term collision probability between mission orbital objects and background orbital objects larger than 10 cm. An analysis was performed to determine how often this threshold could be exceeded by future launched vehicles if they comply with recommended end-of-life disposal practice in U.S. and international debris mitigation guidelines. The analysis used a model of the future Earth orbital population generated with the Aerospace Debris Environment Projection Tool suite. The model of future launch traffic is based on past historical launches and does not include proposed future large constellations or an expected large increase in number of CubeSats. Collision probabilities were determined for a set of future launched objects. These collision probabilities were processed to generate products such as histograms, cumulative density functions, and chi-plots. These products were used to determine the percentage of objects contained by the threshold and the variation in sum of collision probabilities for the set of objects processed as the threshold is varied. It is recommended that the study be repeated as expected changes in launch traffic develop. [View Full Paper]

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AAS 18-438

UNCERTAINTY QUANTIFICATION USING NON-INTRUSIVE GENERALIZED POLYNOMIAL CHAOS EXPANSION FOR ORBITAL DEBRIS STUDIES

Rajnish Bhusal[*] and Kamesh Subbarao[†]

This paper demonstrates the use of generalized polynomial chaos expansion for propagation of uncertainties present in various dynamical models. The idea behind generalized polynomial chaos is to express the random solutions to stochastic differential equations as orthogonal polynomials of input random variables. In this paper, a sampling based non-intrusive approach using pseudospectral stochastic collocation is employed to obtain the coefficients required for the generalized polynomial chaos expansion. Pseudospectral stochastic collocation uses nodes and weights generated by a numerical quadrature technique and its convergence explicitly depends on the efficiency of the quadrature technique employed. This paper illustrates the efficacy of various recently developed quadrature techniques within the generalized polynomial chaos expansion framework. Furthermore, this paper also provides an approach for propagation of uncertainties, governed by different probability distribution functions in a stochastic dynamical system. Results are presented for the uncertainty propagation in a second order oscillator system with uncertain system parameters and initial conditions, and orbital motion of a 2U CubeSat subject to initial condition and atmospheric drag uncertainties. [View Full Paper]

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SPACE SITUATIONAL AWARENESS

Session Chairs:

Monday Session 4: Christopher Roscoe, Applied Defense Solutions

Co-Chair: Kyle DeMars, Missouri University of Science and Technology

Tuesday Session 4: Islam Hussein, Applied Defense Solutions

Co-Chair: Rohan Sood, University of Alabama

Wednesday Session 5: Marcus Holzinger, University of Colorado Boulder

Co-Chair: Jeffrey Stuart, Jet Propulsion Laboratory

Thursday Session 2: Islam Hussein, Applied Defense Solutions

Co-Chair: Jacob Darling, Air Force Research Laboratory

The following paper was not available for publication:

AAS 18-450 Paper Withdrawn

AAS 18-213

EFFICIENT COLLISION PROBABILITY FOR NONLINEAR COVARIANCE*

William T. Cerven† and Felix R. Hoots‡

The location of a satellite in space is typically described by an element set or state vector at some epoch time and the location uncertainty is described by a covariance. The probability density function is usually assumed to be Gaussian. Nonlinearities can introduce significant errors in the propagation of the covariance and have been a topic of several recent papers. We have developed a method to remove most of the nonlinearities and provide accurate propagation of the uncertainty estimate for 30 days or more. This paper demonstrates how the resulting covariance can be used to compute an accurate probability of collision.

[View Full Paper]

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AAS 18-216

SYSTEMATIC EXPLORATION OF SOLAR GRAVITY DRIVEN ORBITAL TRANSFERS IN THE MARTIAN SYSTEM USING ARTIFICIAL NEURAL NETWORKS

Stijn De Smet,[*] Daniel J. Scheeres[†] and Jeffrey S. Parker[‡]

Current solar electric propulsion and launch vehicle technology allow sending multiple spacecraft to Mars simultaneously. For capture orbits with very high apoareion, the solar gravity perturbations deploy the spacecraft in vastly different areocentric orbits. This application requires knowledge of possible transfers and an efficient way to identify them; a well-defined and easily accessed database of solutions. First, a method is developed to identify the required initial orbital elements and timing to target a final orbit, for a dynamical model ignoring the Martian eccentricity. This method can be applied to any planetary system with low heliocentric eccentricity. Second, the effect of Mars' eccentricity and the corresponding time-dependence of solar distance are analyzed. This analysis requires a much larger number of numerical integrations. The research is therefore limited to placing bounds on the solution space. Third, this paper determines the way artificial neural networks can reduce this number by order(s) of magnitude while maintaining sufficient accuracy to enable preliminary transfer design. The neural networks enable the design of transfers between a low, near-polar orbit to Phobos in an approximation of the eccentric model.

[View Full Paper]

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AAS 18-220

THE EFFECT OF DIFFERENTIAL COLOR REFRACTION ON SHORT-ARC ESTIMATION OF THE AREA-TO-MASS RATIO OF GEOSTATIONARY OBJECTS USING GROUND-BASED TELESCOPES*

Roman Geykhman† ‡ and Kerri Cahoy‡

Ground-based telescopes collect the majority of astrometric observations of geosynchronous satellites and debris. Earth's atmosphere subjects this data to systematic bias from differential color refraction (DCR). Advancements in star catalog accuracy leave DCR as the dominant bias source in ground-based astrometry. We analyze the effect of DCR bias on short-arc orbit estimation. DCR resolves into a biased estimate of solar radiation pressure area-to-mass ratio (AMR). This imposes a growing error floor of tens of meters per day in resulting orbit predictions, thereby lowering the time horizon on the prediction of appulses of geosynchronous satellites with natural guide stars. We present empirical measurements of DCR bias in observations of GLONASS satellites, simulations and measurements of the effect of DCR bias on geosynchronous satellite orbit estimates, describe a spectroscopic instrument for real-time DCR compensation and present preliminary data.

[View Full Paper]

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AAS 18-235

SPACE DEBRIS FIELD REMOVAL USING TETHER MOMENTUM EXCHANGE

Zachary D. Asher,[*] Steven Tragesser,[†] Christian Kneubel,[‡] Jennifer Hudson,[*] Thomas H. Bradley[§] and Ilya Kolmanovsky[**]

Space debris threatens operation in space, requires perpetual tracking costs, and adds complexity to mission design and planning. To combat these issues, researchers have investigated numerous debris field removal techniques including sequential debris object removal using a single spacecraft. But, the analyses developed so far typically require high power, large amounts of propellant, and/or long mission times. This research argues feasibility of a low propellant and fast sequential debris object removal technique using a single spacecraft by demonstrating removal of two real debris fields consisting of 10 debris objects each. Several assumptions are utilized to investigate feasibility which include in plane debris and spacecraft alignment, a massless rigid inelastic tether, 20kg debris masses, and successful intermediate maneuvers such as capture, spin-up, tether extension, and tether reeling. Sequential debris object removal occurs first using a capture phase, then a tethered system orbit phase, followed by a debris removal phase. Capture and removal occurs by controlling tether lengths and spin rates only, thus eliminating the need for any spacecraft positioning maneuvers. The results show that each debris field is removed using tether lengths less than what has already been deployed in space, the required spacecraft and system spin rates are on the order of milliradians, and the mission times are approximately 100 days for the first set and 150 days for the second set when removed in order. Overall this research demonstrates that tether momentum exchange may overcome the drawbacks of other proposed methods of debris field removal. [View Full Paper]

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AAS 18-244

HIGH FIDELITY COLLISION PROBABILITIES ESTIMATED USING BRUTE FORCE MONTE CARLO SIMULATIONS

Doyle T. Hall,[*] Stephen J. Casali,[*] Lauren C. Johnson,[*] Brent B. Skrehart[*] and Luis G. Baars[*]

The NASA Conjunction Assessment Risk Analysis team has implemented new software to estimate the probability of collision (P_c) for Earth-orbiting satellites. The algorithm employs a "brute force Monte Carlo" (BFMC) method which differs from most other methods because it uses orbital states and covariances propagated from their orbit determination epoch times using the full set of the Astrodynamics Support Workstation's higher order theory models, including the High Accuracy Satellite Drag Model. This paper describes the BFMC algorithm, presents comparisons of BFMC P_c estimates to those calculated using other methods, and discusses the implications for conjunction risk assessment.

[View Full Paper]

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AAS 18-249

SMALLSAT NAVIGATION VIA THE DEEP SPACE NETWORK: INNER SOLAR SYSTEM MISSIONS*

Jeffrey R. Stuart† and Lincoln J. Wood‡

The space industry has seen an explosion in the number of operational SmallSats in Earth orbit, with a natural interest in extending SmallSat capabilities outside of low Earth orbit. As with larger missions, near-term deep-space SmallSats will rely on the Deep Space Network or similar facilities. Given the predicted growth in the number of deep space missions, effective use of DSN resources will be more critical than ever. Our investigation provides an initial survey of expected inner Solar System navigation performance for DSN radiometric data types, from two-way Doppler and ranging to one-way equivalents, including delta differential one-way range and alternative tracking strategies. [View Full Paper]

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AAS 18-260

LOW-EARTH ORBIT DETERMINATION BASED ON ATMOSPHERIC DRAG MEASUREMENTS

Rui Zhang,[*] Fei Xu,[†] Chao Han[‡] and Xiucong Sun[§]

An autonomous low-Earth orbit determination method based on measurements of atmospheric drag is proposed, with use of a high-precision tri-axis accelerometer as well as a star sensor. A set of equations is formulated to determine current position and velocity of the spacecraft using drag measurements of at least four epochs. Magnitude of the drag acceleration vectors is not used in the proposed method in order to avoid orbit determination error due to the uncertainty of the Earth atmosphere model. Analytical initial values of position and velocity which is used to solve the orbit determination equations numerically is provided under the assumption of circular orbit. Numerical simulations are performed which show good performance of the novel orbit determination method. This method is useful for the navigation of low-Earth-orbiting spacecraft in the environments where there is no global navigation satellite system. [View Full Paper]

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AAS 18-268

Q-LEARNING ALGORITHM FOR PATH-PLANNING TO MANEUVER THROUGH A SATELLITE CLUSTER

Xiaoyu Chu,[*] Kyle T. Alfriend,[†] Jingrui Zhang[‡] and Yao Zhang[§]

In this paper, a path planning method for maneuvering through a satellite cluster using Q-learning is presented. An on-orbit servicing spacecraft is supposed to rendezvous with the failed central satellite of a formation and avoid collisions with the other satellites. The dynamic model of the satellite cluster is first established by Lawden equations. Then the theory of Q-learning is introduced and the reward shaping is specified to guide the learning system quickly to success. Furthermore, combining Q-learning with deep neural networks, deep Q-network (DQN) is employed when the dimension of the problem is enormous. Finally, the rendezvous mission is simulated in 2D and 3D scenarios separately to demonstrate the effectiveness of the proposed method. [View Full Paper]

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AAS 18-272

EFFECT OF CROSS-CORRELATION OF ORBITAL ERROR ON PROBABILITY OF COLLISION DETERMINATION

Stephen J. Casali,[*] Doyle T. Hall,[*] Daniel R. Snow,[*] M. D. Hejduk,[†] Lauren C. Johnson,[*] Brent B. Skrehart[*] and Luis G. Baars[*]

This paper discusses the effect of global model error on probability of collision (Pc) determination. Modifications to the Pc formulation for cross-correlation of orbital error in prediction are developed and assessed for recent conjunctions. While specific geometries can be identified or constructed to produce significant change in Pc for the modified formulation, it is of operational interest to quantify the relative occurrence of such cases for satellite conjunction risk assessment. Such analysis is feasible per data collections in place over the past year. [View Full Paper]

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AAS 18-292

ATMOSPHERIC MASS DENSITY CALIBRATION AND ITS APPLICATION IN LEO OBJECT ORBIT PREDICTION USING ANGULAR DATA FROM A SMALL-TELESCOPE ARRAY

Junyu Chen,[*] Jizhang Sang,[†] Zhenwei Li[‡] and Chengzhi Liu[§]

This paper presents results of atmospheric mass density calibration and its effect on the orbit determination and prediction (OD and OP) accuracy of LEO objects using angular data collected by a small-telescope array. The array consists of 8 telescopes each having a 15cm aperture and a field of view of 14°x 14°. It is designed to cover the north space region of the observing station. More than 1000 LEO objects can be observed each night, but many have only one or two passes of data in a 3-day time span. In such sparse data circumstances, the OD and OP performance can be enhanced by the calibration of density models. Choosing less than 20 objects in the height region from 380 to 600km as calibration objects, and applying the HASDM method and atmospheric density model coefficient (ADMC) modification method using the tracking data of these objects, the density is calibrated before being used in the OD and OP of LEO objects. It is found that, the 7-day OP errors are reduced by about 50% when the calibrated density is used in the orbit predictions of the objects in the calibration region, and the OP errors for the objects outside the calibration region are reduced by about 30%. [View Full Paper]

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AAS 18-327

GENERALIZATION CAPABILITY OF MACHINE LEARNING APPROACH AMONG DIFFERENT SATELLITES: VALIDATED USING TLE DATA

Hao Peng[*] and Xiaoli Bai[†]

A recently proposed machine learning (ML) approach is further investigated in this paper. The generalization capability from historical data to future predictions has been validated in previous studies. This paper demonstrates recent results on validating a more difficult generalization capability: training the ML models with a set of resident space objects (RSOs) and applying them to a different RSO. The design of learning and target variables is consistent with previous studies. The new results show that this challenging generalization task is actually very promising. For all the seven tested RSOs, orbit prediction errors of some components can be significantly reduced, regardless of variations of training and testing data size. Additionally, by choosing only closely relevant RSOs to provide the training data, we show that the performance can be further improved. [View Full Paper]

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AAS 18-328

OBTAIN CONFIDENCE INTERVAL FOR THE MACHINE LEARNING APPROACH TO IMPROVE ORBIT PREDICTION ACCURACY

Hao Peng[*] and Xiaoli Bai[†]

A machine learning (ML) approach has been recently proposed to improve orbit prediction accuracy of resident space objects through learning from historical data. Previous results have shown that the ML approach can successfully improve the point estimation accuracy. This paper extends the ML approach by introducing the Gaussian process regression (GPR) method to generate uncertainty information about the point estimate. Numerical results demonstrate that GPR can effectively improve the orbit prediction accuracy and the generated uncertainty boundaries can cover the majority of the testing data. Additionally, effects of the number of the basis function used by the GPR and the orbital measurement noise are explored. Results reveal that properly designed and trained GPRs have stable performance for all experiment cases. [View Full Paper]

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AAS 18-336

STREAK DETECTION AND CHARACTERIZATION IN GROUND-BASED OPTICAL OBSERVATIONS OF SPACE OBJECTS

N. Houtz[*] and C. Frueh[†]

Objects in Earth orbit move relative to the background stars, causing them to create streaks in sidereally-tracked images or images tracking other objects with a different relative velocity with long exposure times. For the purpose of detecting and characterizing new or previously lost objects, the algorithms that detect such streaks cannot restrict their search by making assumptions about the objects' relative motions, that is, the streaks' properties. Many interesting objects appear faint in observations, especially when their light is spread over many pixels. Detecting and characterizing streaks of unknown parameters is challenging to do in a computationally efficient manner, since simple detection methods are not adequate to identify faint streaks with low signal-to-noise ratios. We present a method of streak detection and characterization for real-time analysis of telescope images that uses computationally-efficient thresholding for identifying streaks and objects, but incorporates a more advanced mathematical streak model to accurately characterize streaks with a maximum-likelihood method. [View Full Paper]

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AAS 18-347

BLAST POINT DETERMINATION FOR SPACE OBJECT FRAGMENTATION EVENTS*

W. R. Faber,† Waqar Zaidi‡ and Paul W. Schumacher, Jr.§

The rush to obtain space real estate has created an increase in planned satellite launches and with it an increase in potential fragmentation events. These events generate debris fragments that threaten the usability of space. Providing timely, accurate, and statistically significant Space Situational Awareness (SSA) data is crucial to protect space assets and operations. Determining the point of initial breakup, the blast point, is valuable in characterizing and modeling the event. A standard approximation of the blast point is to propagate the mean orbits of well-tracked debris fragments, backward in time, to the time of closest approach. At this time, fragment positions are averaged to determine the blast point location. The errors in this approach arise from the uncertainty in debris fragment state and the uncertainty in the time of the fragmentation event. Accounting for these uncertainties can increase blast point estimation accuracies. In this paper, the authors discuss the complexities involved in this approximation and discuss methods used to determine the blast point. Parameters such as the number of tracked debris fragments and the uncertainty in both time and fragment state are used to develop an understanding of method sensitivities. The authors present multiple approaches for blast point determination that take advantage of fragment state uncertainty. These techniques are tested using GEO fragmentation events simulated according to NASA's standard breakup model. [View Full Paper]

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AAS 18-355

DYNAMIC SENSOR STEERING FOR TARGET SEARCH FOR SPACE SITUATIONAL AWARENESS

Mihir Patel,[*] Andrew J. Sinclair,[†] Hoong Chieh Yeong,[*] Ryne Beeson[*] and Koki Ho[‡]

This paper proposes a set of particle clustering-based sensor steering algorithms to search for a target among a large set of candidate orbits in the context of space situational awareness(SSA). The challenge of such an initial target problem is that the uncertainty region of the target is much larger than the sensor's FOV and that the sensor is not perfect. Existing initial target search methods use particle-based methods to represent the uncertainties and evaluate each particle to determine the sensor pointing at every time step. The proposed algorithms improve the traditional particle-based algorithms by clustering the particles so that we only need to evaluate the cluster centroids to determine the sensor pointing instead of evaluating all particles. Simulations show that this approach can save the computational cost of particle-based methods significantly while achieving a similar initial target search performance compared to the traditional methods. The proposed methods are expected to improve the real-time performance of initial target search. [View Full Paper]

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AAS 18-357

ANALYSIS AND DESIGN OF COLLISION AVOIDANCE MANEUVERS FOR PASSIVE DE-ORBITING MISSIONS

Juan Luis Gonzalo,[*] Camilla Colombo[†] and Pierluigi Di Lizia[‡]

Collision avoidance maneuvers (CAMs) for passive de-orbiting missions using sails are studied, maneuvering either the sail or the incoming object. Analytical expressions for the CAM are obtained leveraging the proximal motion equations, maximizing the total or b-plane-contained deviation, or minimizing collision probability. When the sail performs the CAM, different attitude-related strategies are investigated. Representative test cases are proposed using data from ESA's MASTER tool or conjunction data messages. The required amount of propellant or sail maneuverability as function of lead time is traded-off, and the evolution in time of the covariance matrix is investigated. [View Full Paper]

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AAS 18-377

PHYSICALLY-CONSTRAINED INVERSE OPTIMAL CONTROL FOR SATELLITE MANEUVER DETECTION

Richard Linares[*] and Joseph B. Raquepas[†]

This paper develops an approach to determine the behavior of Space Objects (SOs) using Inverse Optimal Control (IOC) theory. The proposed method determines the control objective function that each SO is using for control utilizing IOC theory, thereby determining the behavior of the SOs. The approach discussed in this work can be used to analyze maneuvering SOs from observational data. The contribution of this work is to formulate the behavior estimation problem using IOC theory. The IOC problem is solved using the Pontryagin's minimum principle which results in a convex optimization problem. Three simulation test cases are shown, the first two cases study the behavior estimation problem for a using the relative motion equations, while the third case studies the behavior estimation problem for continuous thrust orbit raising maneuver. Additionally, a general approach for modeling the SO reward function using Extreme Learning Machines (ELM) is discussed. The simulation example demonstrate that the control objective function can be recovered using the proposed method. [View Full Paper]

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AAS 18-381

EARLY TRAJECTORY ESTIMATE OF PROXIMATE OBJECTS WITH AN OPTICAL FENCE

Liam M. Healy, Scott Kindl, Christopher R. Binz, Christoph Englert and Andrew Nicholas*

An on-board optical fence using a light sheet and camera provides angles-only relative orbital knowledge of objects in its vicinity and can be used to make early estimates of the relative orbit, before anything else is known about it. The dwell time that the secondary spends in the vicinity of the sensor host with the light sheet perpendicular to the direction of motion can be estimated from three detections, that is, crossings of the sheet. With two parallel and closely spaced sheets, the complete two-dimensional relative motion in the host's orbital plane can be determined. [View Full Paper]

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AAS 18-393

POLYNOMIAL CHAOS CONFINED TO THE UNIT CIRCLE

Christine L. Schmid[*] and Kyle J. DeMars[†]

Polynomial chaos expresses a probability density function (pdf) as a linear combination of basis polynomials. If the density and basis polynomials are over the same field, any set of basis polynomials can describe the pdf; however, the most logical choice of polynomials is the family that is orthogonal with respect to the pdf. This problem is well-studied over the field of real numbers, but has yet to be extended to the field of complex numbers. This extension would make polynomial chaos a feasible choice for representing angular random variables, which are confined to the complex unit circle. A method of performing polynomial chaos expansions on angular random variables is developed using the Szegö polynomials as the orthogonal basis. This expansion provides an alternate method for propagating a circular pdf that does not require a distribution assumption. The accuracy of the expansion, and its ability to propagate a pdf, is tested by comparing the first two raw moments estimated using polynomial chaos against the analytic values. [View Full Paper]

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AAS 18-403

MULTIPLE SET FILTERING USING PROBABILITY HYPOTHESIS DENSITIES

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

Emerging tools derived from finite set statistics model candidate targets as a random finite set (RFS) and use Bayesian inference to produce estimates of the RFS given collected data. This work aims to extend that concept to estimating multiple RFSs simultaneously such that targets belonging to different state spaces may be tracked in the same framework. The new filter utilizes the probability hypothesis densities of the RFS to approximate the joint multitarget Bayes filter of the sets. Expressions for the time and measurement update steps are derived, and modifications are made to enable practical implementation. Numerical studies are presented to illustrate the performance of the filter and it is compared to a representative analog of an existing filter found in related literature. [View Full Paper]

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AAS 18-415

UNCERTAINTIES IN THE CONJUNCTION RISK ASSESSMENT OF THE CYGNSS CONSTELLATION

Charles D. Bussy-Virat[*] and Aaron J. Ridley[†]

Conjunction analysis is particularly challenging at altitudes below ~1,000 km, where drag is the largest perturbing force. Atmospheric density forecast errors result in important uncertainties in the probability of collision. The Spacecraft Orbital Characterization Kit is an orbit propagator that models errors in the forecast of solar drivers to generate probability distribution functions of the probability of collision. The algorithm is applied to investigate the effects of density uncertainties on a particular conjunction of a CYGNSS spacecraft, which triggered a collision avoidance maneuver in November 2017. Results show variations in the probability of collision of several orders of magnitude, depending on the epoch. A comparison to the approach implemented by the Department of Defense shows that their method bounds the effects of atmospheric density uncertainties, although with a tendency to overestimate them. [View Full Paper]

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AAS 18-427

LEARNING CAPABILITIES OF NEURAL NETWORKS AND KEPLERIAN DYNAMICS

Damien Guého,[*] Puneet Singla[†] and Robert G. Melton[‡]

Machine learning (ML) tools, especially deep neural networks (DNNs) have garnered significant attention in the last decade; however, it is not clear whether ML tools can learn the inherent characteristics of dynamical model (such as conservation laws) from the training data set. This paper considers the effectiveness of DNNs in learning dynamical system models by considering the Keplerian two-body problem. Training a DNN with data from a single revolution produces poor performance when predicting motion on subsequent revolutions. By incorporating deviations from constancy of angular momentum and total energy into the loss function for the DNN, predictive performance improves significantly. Further improvements appear when a richer training data set (generated from a number of orbits with different in orbital element values) is employed. [View Full Paper]

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AAS 18-428

HIGHER ORDER POLYNOMIAL SERIES EXPANSION FOR UNCERTAIN LAMBERT PROBLEM

Zach Hall[*] and Puneet Singla[†]

In this paper, the Uncertain Lambert Problem is solved using higher order polynomial series instead of the conventional first order one used in linear analysis. Coefficients of the polynomial series are computed in a Jacobian free manner, providing a computationally tractable approach. This polynomial series is exploited to compute the density function for the Lambert solution given the probability density function for initial and final position vector. Non product quadrature method known as the Conjugate Unscented Transformation (CUT) approach is used to construct coefficients of polynomial series by solving a minimal number of Lambert problems through the intelligent sampling of the uncertain initial and final position vector space. Numerical simulation results are presented to validate the proposed approach. [View Full Paper]

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AAS 18-439

ASSESSING MEASURES TO RELIABLY PREDICT COLLISIONS IN THE PRESENCE OF UNCERTAINTY

A. Burton,[*] M. Zielinksi,[†] C. Frueh,[‡] A. Mashiku[§] and N. Memarsadeghi[**]

It is essential for operational satellites to have accurate collision warnings, which are usually based on the projected probability of collision. Exact determination of the probability of collision is challenging. One challenge is that the precise expression can only be determined using computationally expensive Monte Carlo simulation, populating both objects' uncertainties and propagating all particles forward in time. This is not feasible for large object catalogues. One common simplification is to use two-dimensional projections in a relative space. However, those approximations are often inaccurate even under the assumption of perfect Gaussian uncertainties. This paper explores a computationally fast method to approximate the probability of collision based on the Mahalanobis distance. The result is validated by comparison with the Monte Carlo results. [View Full Paper]

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AAS 18-440

MULTI-TARGET TRACKING AND CONJUNCTION ASSESSMENT FOR LARGE CONSTELLATIONS*

Nicholas Ravago† and Brandon A. Jones‡

Multiple proposals for the deployment of constellations of hundreds or thousands of satellites represent a major increase in the scale of space object operations. Part of those operations involve space object tracking, conjunction assessment (CA), and risk analysis. This paper presents work to evaluate if current methods are sufficient to accurately track large constellations and assess collision risk. The Labeled Multi-Bernoulli (LMB) filter is used to track a simulated large constellation over a period of time using data generated from a set of ground-based sensors. After this period, a risk analysis is performed to identify future close approaches and flag high-risk events. The LMB tracked all objects accurately to within meters, and the proceeding risk analysis was generally able to identify positive collision events while raising a manageable number of false alarms. The results of the risk analysis were sensitive to the quality of the estimate catalog, and further analysis should consider how more accurate uncertainty propagation methods may affect the qualities of the filter and risk analysis. [View Full Paper]

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AAS 18-441

A LIGHT CURVE INVERSION SCHEME FOR ARTIFICIAL OBJECTS

Siwei Fan[*] and Carolin Frueh[†]

While the orbit of a space object is referred to as its first degree of characterization usually done through orbit determination, the second degree of characterization involves revealing information like the object shape and its materials. For non-resolved objects, resolved imaging which reveals details is not available. However, it is possible to obtain information from the brightness measurement obtained. Since only a one-dimensional quantity is measured, the problem is often under-determined for space objects with complex geometry. Current methods for such inversion problem mostly consider perfect data. In this paper, the measurement noise effect is investigated. Two artificial objects are constructed and put in orbit for measurement simulation. In a Monte Carlo Approach, measurement errors are then sampled in measurement to obtain Extended Gaussian Images, where the final shape results can be retrieved through Minkowski Inversion. As a result, the shape inversion result and the effect of noise on the inversion result are highly dependent on the specific light curve, and observation scenario. The added noise can be beneficial to overcome the inaccuracy due to the iterative inversion process. [View Full Paper]

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AAS 18-443

INFORMATION METRICS FOR OBSERVATION-TO-TRACK ASSOCIATION*

Michael Mercurio,† Eamonn J. Moyer,* Matthew P. Wilkins,* and Paul W. Schumacher Jr.‡

The classical data association problem, also known as observation-to-track association, is of particular importance in astrodynamics. Filtering frame works allow for the fusion of dynamic state predictions with imperfect observations to obtain updated ephemeris estimates. Due to the agnostic measurement update step, knowledge of the true observation-to-track associations must be known a-priori. This research proposes the use of information-based metrics as a discriminator for ambiguous observation-to-track associations. Metrics such as Mutual Information and various Information Divergence measures will be investigated for applicability to the classical observation-to-track association problem.

[View Full Paper]

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AAS 18-446

CONJUNCTION ANALYSIS AND PROBABILITY OF COLLISION USING RELATIVE ORBITAL ELEMENTS

Christopher T. Shelton[*] and John L. Junkins[†]

The probability of collision problem can be broken down into two main parts. The propagation stage, during which the initial conditions and distributions are propagated through then on linear equations of motion. And the integration stage, where the probability of collision integral is evaluated. It is well known that the equations of motion governing the time evolution of orbital elements are more linear than the Cartesian equations of motion, and therefore make an excellent choice for propagating the distributions in time. Unfortunately, all existing semi-analytical methods for computing the probability of collision require that this distribution in orbital element space be mapped into Cartesian coordinates for the evaluation of the probability of collision integral. In this paper a set of relative orbital elements are presented along with conditions for collision between two spherical bodies in the relative orbital element space. Formulating the probability of collision problem in this coordinate system is shown to make the problem more linear as well as reduce computational burden. This new method is then used to compute the probability of collision and is compared, using the CRATER collision risk assessment tool, to results from the Cartesian formulation of the probability of collision integral and Monte Carlo results on a number of test cases. [View Full Paper]

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AAS 18-451

MULTIPLE HYPOTHESIS TRACKING AND JOINT PROBABILISTIC DATA ASSOCIATION FILTERS FOR MULTIPLE SPACE OBJECT TRACKING

Utkarsh R. Mishra,[*] Nagavenkat Adurthi,[†] Manoranjan Majji[‡] and Puneet Singla[§]

In this paper we study the problem of data association where multiple measurements have to be associated to multiple targets. Specifically, we review and compare the performance of the Joint Probabilistic Data Association (JPDA) Filter and the Multiple Hypothesis Tracking (MHT) Filter in associating measurements with Resident Space Objects (RSO).

[View Full Paper]

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AAS 18-453

LEO SSA AT THE SPOT FACILITY

Morgan Yost[*] and Andrew Zizzi[†]

Lockheed Martin's Space Object Tracking (SpOT) facility consists of three 1meter telescopes in the Santa Cruz Mountains of California. The telescope mounts are capable of slewing fast enough to rate-track Low Earth Orbit (LEO) satellites, and have enough sensitivity to detect dim objects in Geosynchronous Earth Orbit (GEO).

During 2018, the SpOT facility has been operating predominantly as an autonomous Space Situational Awareness (SSA) system. This paper presents a summary of the data captured in the autonomous operational campaign. The imagery content is further analyzed with the use of a Multiple Hypothesis Tracker (MHT) that was able to identify signals and characterize them as stars, objects, or noise.

SpOT observed over 3,600 satellite passes between February and August of 2018. Of the 1,300 imagery sets collected on rocket bodies with similar characteristics, the MHT identified 350 stars and 2048 satellite tracks with a type I error rate less than 0.1%.

[View Full Paper]

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AAS 18-459

SPACECRAFT MANEUVER DETECTION USING OPTIMAL CONTROL THEORY AND EQUATIONS OF RELATIVE MOTION

Atri Dutta* **and Joseph B. Raquepas†**

In this paper, we investigate the spacecraft maneuver detection problem by considering an optimal control formulation, in which we minimize the control effort subject to the Hill-Clohessy-Wiltshire equations of relative motion. The control effort is measured by the L_p norm of the control variables. Necessary conditions of optimality are investigated to analytically compare the performance of L_1 and L_2 norms. Both deterministic and stochastic formulations for the optimal control problem are considered. Using numerical simulations, we compare the performance of the proposed formulations in determining high- and low-thrust maneuvers. [View Full Paper]

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AAS 18-461

PARALLEL MARKOV CHAIN MONTE CARLO FOR SENSOR SCHEDULING

Dilshad Raihan,[*] Weston Faber,[†] Suman Chakravorty[‡] and Islam Hussein[§]

In this paper, we present a novel parallel Markov Chain Monte Carlo(MCMC) based solution to the sensor scheduling problem. In the context of space situational awareness, the objective of sensor scheduling is to maximize the information gain from observing a large number of space based targets using a limited number of sensors. The parallel MCMC approach is a sampling based optimization approach that can explore the space of configurations efficiently and quickly. We consider a scheduling scenario that involves a single sensor and multiple targets. The parallel MCMC method is used to obtain the look directions of a ground based sensor that maximizes the information gain over a receding horizon. The effectiveness of the new method is demonstrated through a simulation study.

[View Full Paper]

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AAS 18-468

ANGLES-ONLY NAVIGATION FOR AUTONOMOUS ON-ORBIT SPACE SITUATIONAL AWARENESS APPLICATIONS

Joshua Sullivan,[*] T. Alan Lovell[†] and Simone D'Amico[‡]

This paper addresses the design and validation of a prototype angles-only estimation architecture for on-orbit space situational awareness applications. The proposed navigation approach addresses the main challenges and limitations in the current literature, which generally stem from poor handling of the inherent observability constraints, heavy reliance on prior orbit information, and excessive use of maneuvering to reconcile the unknown range information. The relative orbital element representation is leveraged to decouple the state into weakly and strongly observable components, and to parameterize the relative motion dynamics in slowly time-varying coordinates. Using these features, a novel batch relative orbit estimation algorithm is developed which uses bearing angle trends over at least one orbital period to estimate the state without any prior orbit knowledge. This solution can be further refined using a sequential unscented Kalman filter which exploits nonlinearities in the system dynamics and measurements to disambiguate the unique relative orbit estimate. In particular, a new approach for angles-only filter state propagation based on numerical integration of the Gauss Variational Equations is compared with a filter class using linear state updates. This delineation enables a strategic filter design process to be taken which considers estimation accuracy, efficiency and robustness. Long-term filter stability is compared between maneuver-free and maneuver-inclusive navigation scenarios, and it is shown that sparse control profiles are sufficient to hasten and stabilize the estimation convergence. All algorithms are verified in high-fidelity software-based and hardware-in-the-loop simulation. [View Full Paper]

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AAS 18-471

AN OPTIMIZATION FORMULATION OF INFORMATION THEORETIC SENSOR TASKING

Matthew J. Gualdoni[*] and Kyle J. DeMars[†]

The process of tracking and maintaining estimates for the numerous space objects in orbit about the Earth is a complex and highly demanding problem, as it requires robust state estimates in the presence of sparse data. As the number of space objects greatly outweigh the number of available sensors, a sensor tasking policy is necessary to properly utilize the available sensor resources. This work takes a common approach to the problem of sensor tasking, namely utilizing the first moment of the Kullback-Leibler divergence, and extends its use to consider entire measurement sets through the use of a reference time. The resulting method is applied in both the single-target and multitarget domains, and compared to more conventional approaches to illustrate its viability. [View Full Paper]

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AAS 18-477

LASER RANGING TO UNKNOWN OBJECTS FOR INITIAL ORBIT DETERMINATION, A FEASIBILITY STUDY

Mark L. Psiaki*

Satellite laser ranging to objects without corner-cube retro-reflectors is explored as a means of providing range and range-rate data for use in initial orbit determination. The goal of this work is to couple laser range data with optically derived angular data and eliminate the need for radar. Laser ranges eliminate the initial indeterminacy that exists when angular observations are used alone. This study employs analysis and truth-model simulation to investigate the feasibility of using a laser to track range. It considers the effects of laser energy per pulse, pulse rate, $1/r^4$ path loss, optical telescope diameter, radar cross section of the object, atmospheric losses, and noise photons. The study develops signal processing algorithms that can successfully determine orbit when 20-40 true returned photons and 1200-1300 noise photons arrive during a tracking window. These algorithms include initial clustering calculations that distinguish between true and noise photons. They culminate with an optimal estimation algorithm that explicitly accounts for noise/clutter photons. One example case considers a LEO object with a radar cross-section of 0.5m^2 at a distance of 1170 km. The laser transmission/reception telescope has a diameter of 0.2 m, and the laser transmits 100 pulses per second at 0.25 Joules per pulse. Despite receiving a mere 18 true photon returns during a 20 sec tracking interval, the system is able to determine orbit to a 7 m position accuracy and a 0.3 m/sec velocity accuracy. [View Full Paper]

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ATTITUDE DYNAMICS AND CONTROL

Session Chairs:

Monday Session 5: Andrew J. Sinclair, Air Force Research Laboratory

Co-Chair: Jay McMahon, CCAR (Colorado Center for Astrodynamics Research)

Tuesday Session 3: Kamesh Subbarao, University of Texas at Arlington

Co-Chair: Christopher Roscoe, Applied Defense Solutions

Wednesday Session 6: Atri Dutta, Wichita State University

Co-Chair: Weston Faber, Applied Defense Solutions

The following papers were not available for publication:

AAS 18-275 Paper Withdrawn

AAS 18-294 Paper Withdrawn

AAS 18-464 Paper Withdrawn

AAS 18-466 Paper Withdrawn

AAS 18-479 Paper Withdrawn

AAS 18-222

CHANGE OF INERTIA TENSOR DUE TO A SEVERED RADIAL BOOM FOR SPINNING SPACECRAFT

Joseph E. Sedlak[*] and Babak Vint[†]

Many spinning spacecraft have long, flexible, radial booms to carry science instrumentation. These radial booms often have low mass but contribute significantly to the spacecraft moment of inertia due to their length. There are historical cases where radial booms have been severed or have failed to deploy. This paper presents models for the center of mass (CM) and inertia tensor that account for variable boom geometry and investigates how the CM and inertia tensor change when a radial boom is severed.

The CM and inertia tensor models presented here will be included in the Attitude Ground System (AGS) for the Magnetospheric Multiscale (MMS) mission. This work prepares the AGS to provide uninterrupted support in the event of a radial boom anomaly. These models will improve the AGS computations for spin-axis precession prediction, Kalman filter propagation for the definitive attitude, and mass property generation needed for the onboard control system. As an additional application, a method is developed for approximating the location on the boom where the break occurred based on the new models and readily observable attitude parameters. [View Full Paper]

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AAS 18-301

ORBIT AND ATTITUDE OBSERVABILITY USING ACCELEROMETER MEASUREMENTS

David K. Geller[*] and Rachit Bhatia[†]

Under the ideal assumptions of a point mass gravity model and zero non-gravitational accelerations, it is shown that an onboard gravity model and measurements from an accelerometer-based gradiometer consisting of three 3-axis onboard accelerometers can provide simultaneous orbital and attitude observability. Orbital and attitude navigation based on traditional dead-reckoning is not considered. Instead, gravity field gradients from onboard accelerometer measurements are correlated to onboard gravity maps, and used to conduct spacecraft orbital position, velocity and attitude observability analysis. The analysis is extended to higher order gravity models, where it is shown that measurements from just one 3-axis accelerometer can provide orbital and attitude observability under ideal circumstances. When non gravitational accelerations due to external forces are considered, the importance of having at least two accelerometers is demonstrated. Important issues such as vehicle rotation, uncertainties in vehicle center-of-mass location, uncertainties in accelerometer location, and accelerometer misalignment, bias, and noise are recognized as future areas of research. [View Full Paper]

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AAS 18-302

BILINEARIZED MODEL-BASED DISCRETE-TIME ITERATIVE LEARNING CONTROL FOR NONLINEAR SYSTEMS

Bing Song[*], Minh Q. Phan[†] and Richard W. Longman[‡]

Iterative learning control (ILC) learns to track a pre-defined maneuver with high accuracy through practice. It aims to approach the hardware reproducibility error level, beyond the accuracy of the system model used in the learning process. ILC can be used in spacecraft fine pointing sensors doing repeated scanning maneuvers. This paper improves upon linearized model-based ILC for nonlinear systems by using a Carleman bilinearized model instead. By capturing more nonlinear dynamics, a bilinearized model is a considerable improvement over the linearized model. This results in a faster convergence. To limit the learning inside of the neighborhood along the reference for linearization/bilinearization, a homotopy of the desired trajectory is used. Numerical examples show this bilinearized model based ILC algorithm converges substantially faster and does so in a manner closer to monotonic by comparison to ILC through linearization. [View Full Paper]

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AAS 18-303

DATA-DRIVEN MODEL-FREE ITERATIVE LEARNING CONTROL USING REINFORCEMENT LEARNING

Bing Song,[*] Minh Q. Phan[†] and Richard W. Longman[‡]

Iterative learning control (ILC) learns to track a pre-defined maneuver with high accuracy by repetitions in practice. It can be applied to repeated scanning maneuvers with fine pointing equipment in spacecraft. An ILC learning law usually necessitates an a priori model. To remove this constraint, an off-policy reinforcement learning (RL) method is applied in the trial domain to design an ILC learning law based on data. To improve sampling efficiency and avoid dangerous learning behavior, multiplicative randomness in the learning law is used for exploration. This multiplicative randomness helps one maintain the learning process within a stable region. The algorithm developed starts with the simple model free learning that adjusts the command to the control system by the error that needs to be corrected in the previous run. The RL process uses batches of randomized ILC updates to create an improved state-action value function corresponding to a cost-to-go function. Then the cost-to-go function is used to update the ILC learning matrix. RL updates of the ILC learning matrix can be stopped at some point, and if the error starts to increase we can restart updating. This can be seen as the first step to bridge ILC and RL for data-driven learning algorithms. [View Full Paper]

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AAS 18-305

DEVELOPMENT OF TRANSIENT BASIS FUNCTIONS TO IMPROVE BASIS FUNCTION ITERATIVE LEARNING CONTROL

Bowen Wang,[*] Richard W. Longman[†] and Minh Q. Phan[‡]

Iterative Learning Control (ILC) considers systems which repeatedly perform some desired trajectory. After each run, the command is updated based on the previous recorded error, aiming to converge to zero error. Spacecraft applications include vibration isolation of sensors performing precision scanning maneuvers. For long trajectories or with fast sample rates, the ILC computation and memory needs can be substantial. This can be reduced using basis functions spanning the most important error components, and asking these components to converge to zero. Benefits include: (1) Reduced computation, (2) Eliminating the need for a zero-phase low-filter for robustification, (3) Automatic stabilization of the often unstable inverse problem, (4) And possibly faster learning. The ILC problem asks for zero tracking error every time step in a finite time problem. One expects this to include transients. This paper develops ILC making use of matched input-output basis functions for fast learning, and develops a new kind of matched basis function designed to quickly eliminate error components related to transients. This can further reduce computation by producing a reduced error for the same number of basis functions employed, and can also help with tracking of the finite time signal when the desired trajectory is largely within the system settling time. Since transients are not part of the forced response, the new kind of basis functions developed here are matching initial conditions to transients. It is shown that if the desired finite time trajectory has smooth transition of all derivatives at the start of the trajectory, these new basis functions are not needed. The conditions under which they are needed are analyzed, and methods are developed to ensure feasibility of the learning process in such cases. [View Full Paper]

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AAS 18-313

ON NOVEL APPOINTED-TIME INERTIA-FREE ADAPTIVE ATTITUDE CONTROL OF SPACECRAFT

Caisheng Wei,[*] Jianjun Luo[†] and Kai Jin[‡]

This paper investigates a novel fixed-time attitude control scheme for a rigid spacecraft with unknown inertial properties and external disturbance. First, a new prescribed performance function is developed, based on which an adaptive inertia-free controller is constructed to guarantee the fixed-time convergence. Compared with the existing finite-time/fixed-time attitude controllers based on sliding mode control technique, the primary advantage is the fractional power state or output feedback is not used, while the arbitrarily appointed-time convergence and steady-state tracking accuracy can be simultaneously guaranteed. Finally, a group of illustrative examples are employed to validate the effectiveness of the proposed control scheme. [View Full Paper]

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AAS 18-315

THE EXTREME BEHAVIOR OF THE SIMPLEST FORM OF ITERATIVE LEARNING CONTROL

Morgan T. Walker,[*] Xiaoqiang Ji[†] and Richard W. Longman[‡]

Iterative learning control (ILC) can be applied to any feedback control system that repeatedly performs the same task, allowing it to improve its tracking performance each run or iteration. It has applications in spacecraft for repeated scanning maneuvers, producing much higher precision motion from software modifications instead of hardware. ILC in its simplest form says: If the output was 2 units too low at a certain time in the last run, add 2 units to the command in the next run. This is sometimes referred to as P type ILC as defined by Arimoto. Many are not aware of the extreme behavior that this ILC can exhibit. We consider it entertaining and enlightening. This paper makes a more detailed examination of this behavior than has previously appeared. This discussion highlights the distinctions and interplay between the contributions in the development of a new field, of mathematical analysis, simulation, and experiment. Included are demonstrations of mathematical analysis indicating convergence to zero error, while simulations produce exponential overflow on the computer – and both are correct. In spite of such behavior, this model free approach to ILC can be very effective in the world if one asks for zero tracking error only up to a certain frequency. [View Full Paper]

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AAS 18-316

DEVELOPMENT AND LABORATORY EXPERIMENTATION OF A MAGNETORQUER CONTROL SYSTEM FOR CUBESAT USING A THREE-AXIS SIMULATOR

Guglielmo Cervettini,[*] Hyeongjun Park,[†] Dae Young Lee,[‡] Stefano Pastorelli[§] and Marcello Romano[**]

For a small spacecraft requiring high pointing accuracy and slewing agility, ground-based test beds are strongly demanded to test and validate hardware subsystems and guidance, navigation, and control algorithms. In this paper, a magnetorquer system is developed and integrated with an existing three-axis spacecraft test bed using a spherical air bearing. The design and developing procedure of the magnetorquer system is presented in detail. Ground testing scenarios to validate the performance of the developed magnetorquer system are then introduced. To generate enough torque from the magnetorquer system, the Helmholtz coil system of the test bed provides an augmented magnetic field. Using B-dot control to detumble the small satellite simulator, the experimental results are compared with those of the numerical simulations. The comparison demonstrates the capability and effectiveness of the magnetorquer system for ground-based tests. [View Full Paper]

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AAS 18-331

A HYBRID OPTIMAL CONTROL METHOD FOR TIME-OPTIMAL SLEWING MANEUVERS OF FLEXIBLE SPACECRAFT

Sandeep K. Singh,[*] Ehsan Taheri[†] and John L. Junkins[‡]

The problem of time-optimal, rest-to-rest slewing of a flexible spacecraft through a large angle is studied. These maneuvers are known to have bang-bang control profiles, which lead to undesirable excitation of higher frequency vibrations. It is common to approximate the dynamics using the assumed modes method; and formulate and solve the resulting optimal control problem using both direct and indirect methods. In order to improve solution convergence and attenuate the effects of undesired vibrations, torque smoothing is applied through a novel hyperbolic tangent smoothing. Application of control smoothing is demonstrated within the indirect formulation. Results of the two approaches are compared along with discussions on the advantages of smoothing, truncation of the discretized model and development of a hybrid optimal control method. [View Full Paper]

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AAS 18-333

EQUILIBRIA ASSOCIATED WITH THE ATTITUDE DYNAMICS OF A RIGID BODY IN KEPLERIAN MOTION

Roshan T. Eapen,[*] Manoranjan Majji[†] and Kyle T. Alfriend[‡]

This paper investigates then on linear attitude dynamics of a rigid body in a Keplerian orbit. We show that the use of Classical Rodrigues Parameters for the attitude motion of the rigid body subject to gravity-gradient torques enables us to characterize the rotational motion about its mass center. The stability of oscillations is investigated using inertia as a parameter and it is shown that large oscillations are induced due to the energy exchange between the pitching and roll-yaw motion of the rigid body. Furthermore, the effect of moments of inertia on the attitude motion is studied under the framework of a higher order approximation of the gravity-gradient potential. [View Full Paper]

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AAS 18-334

GOOD PERFORMANCE ABOVE A FEEDBACK CONTROL SYSTEM BANDWIDTH USING A PARTIAL INVERSE MODEL POSSIBLY IMPROVED BY ILC

Tianyi Zhang[*] and Richard W. Longman[†]

A common requirement specified to a feedback control system designer is the needed bandwidth. When using typical feedback control laws, such as proportional, integral, proportional plus derivative, etc. it can easily happen that the bandwidth requirement is not achievable for any choice of control gains. Several ways of seeing the bandwidth limitation the designer faces are presented. To address this situation, a method is offered of achieving the performance of a feedback system associated with a bandwidth higher than the actual feedback system's bandwidth. A partial system inverse is generated. Given a desired tracking maneuver, one first uses the inverse to compute a command and then applies it to the system. Bandwidth is based on steady state frequency response. It is converted here to a finite-time frequency response behavior to use in creating the partial inverse model. Bandwidth specification does not ask for high accuracy tracking within the bandwidth, but if it is needed, a method is also presented to start with the partial inverse and use Iterative Learning Control concepts to improve the tracking accuracy by correcting for model error in the partial inverse model. [View Full Paper]

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AAS 18-346

OBSERVER-BASED ATTITUDE CONTROL WITH MEASUREMENT UNCERTAINTIES

Haichao Gui[*] and Qingqing Dang[†]

The robust spacecraft attitude tracking is addressed with uncertainties in state estimates, inertia matrices, and disturbances. Instead of designing new control laws, this paper considers the simple yet classical quaternion controller consisting of a proportional-derivative feedback plus some feed forward (PD+). First, the closed-loop stability is analyzed when attitude and velocity estimates are algebraically extracted from direct sensor measurements. By a sequential Lyapunov technique, a convergent sequence of analytical, successively tighter upper bounds on the steady-state tracking error is derived from known bounds of measurement errors and modeling uncertainties. Moreover, a numerical algorithm is constructed to obtain less conservative performance bound predictions. These results are then extended to the case when state estimates are generated from any stand-alone observers yielding uniformly ultimately bounded estimation errors. Given known ultimate bounds on the estimation errors, the same algorithm can be used to derive bounds on the ultimate tracking error. Our analyses not only establish a separation principle between the quaternion PD+ controller and a broad class of observers but facilitate gain selection given steady-state performance bounds. Numerical examples demonstrate the utility of the proposed theory. [View Full Paper]

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AAS 18-359

OPTIMAL MOTION PLANNING IN ATTITUDE MANEUVER USING NON-HOLONOMIC TURNS FOR A TRANSFORMABLE SPACECRAFT

Kaoru Ohashi,[*] Toshihiro Chujo[†] and Junichiro Kawaguchi[‡]

As an innovative spacecraft system, a transformable spacecraft is being studied by the authors. One of the most innovative points of the spacecraft is that it is capable of non-holonomic turns for attitude maneuver. By the combination of the turns, the spacecraft can change its attitude largely without using fuel or external forces/torques. In this paper, we first show that it is possible to achieve any kinds of attitude with slight error in principle using a simple model, although it may not be optimal. After that, a method for optimal motion planning using genetic algorithm is proposed. [View Full Paper]

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AAS 18-367

DISTURBANCE-BASED HIGH-ORDER SLIDING MODE OBSERVER-BASED CONTROL FOR SPACECRAFT HIGH ACCURACY POINTING

Divya Bhatia[*] and Peter Hecker[†]

In this paper a disturbance-based high-order sliding mode observer-based control is applied to solve the challenging spacecraft attitude control problem, which involves simultaneously tackling nonlinearities of system motion equations, providing robustness towards unexpected external disturbances, mass inertia uncertainty and varying initial conditions. This controller enables rest-to-rest (regulation) large-angle slews exhibiting global stability all the while meeting high accuracy pointing for a space-telescopic mission named Infrared Astronomy Satellite Swarm Interferometer (IRASSI). This control is based on an extended sliding mode observer that utilizes multi-input multi-output sliding-mode disturbance observer to reconstruct the disturbances on-line. It precludes the inherent chattering problem in classical first-order sliding mode control (SMC) and provides better accuracy compared to the classical SMC as validated in the simulations. [View Full Paper]

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AAS 18-387

ATTITUDE DETERMINATION OF ROTATING SPACECRAFT USING LIGHT CURVE MEASUREMENTS FROM MULTIPLE OBSERVATION SITES

Arun J. Bernard[*] and David K. Geller[†]

In recent years the ability to determine the attitude of a spacecraft using light curve measurements from an electro-optical sensor, or telescope, has been a topic of great interest. The focus of this paper is to investigate the effects on the accuracy of the attitude estimate when light curve measurements from multiple observation sites are combined. Simulations using a variety of different shape models and attitude dynamics are used to assess two different attitude estimation algorithms. Attitude estimation is performed using a bootstrap particle filter and a multiplicative extended Kalman filter. A comparison of these estimation methods is presented. [View Full Paper]

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AAS 18-422

REORIENTATION OF RIGID SPACECRAFT USING ONBOARD CONVEX OPTIMIZATION

Josep Virgili-Llop,[*] Alanna Sharp[†] and Marcello Romano[‡]

A guidance algorithm for constrained attitude reorientation maneuvers suitable for onboard implementation and real-time use is here presented. Using a sequential convex programming approach, the proposed algorithm is able to find locally optimal solutions by sequentially solving inner-convex approximations of the original guidance problem. The proposed sequential convex programming procedure is recursively feasible and strictly descending as long as the first convex problem in the sequence is feasible. The convergent and recursively feasible properties, along with the deterministic convergence properties of convex optimization, allows the algorithm to solve constrained attitude reorientation maneuvers in real-time on embedded computing platforms. To substantiate this claim, the results of an implementation on two embedded computers are presented. The solutions obtained by the proposed algorithm are compared to the solutions obtained with pseudospectral methods and particles warm optimization. This comparison shows that the proposed approach produces near-optimal solutions with a low computational footprint. [View Full Paper]

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AAS 18-449

COVARIANCE MATCHING FILTER FOR IMU ERROR ESTIMATION

Rahul Moghe,[*] Renato Zanetti[†] and Maruthi Akella[‡]

In this paper, anon-line adaptive accelerometer calibration algorithm is presented. The accelerometer is corrupted with an exponentially correlated random bias and white Gaussian noise. Assuming the availability of noisy position and velocity measurements, the estimates of position, velocity, bias as well as the accelerometer's noise characteristics are estimated. These results are made possible through the application of use a covariance matching adaptive filter recently established by the authors. Numerical simulations are performed to evaluate the performance of the proposed calibration algorithm and its effectiveness subject to noisy accelerometer measurements. [View Full Paper]

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AAS 18-469

ROBUST-OPTIMAL RULE-BASED ATTITUDE CONTROL OF SPACECRAFT WITH A PARTIALLY-FILLED FUEL TANK

Lilit Mazmanyan[*] and Mohammad A. Ayoubi[†]

We present a robust-optimal fuzzy controller to stabilize the attitude of the spacecraft with a partially-filled fuel tank. First, the nonlinear equations of motion of spacecraft containing a liquid fuel store are presented briefly and approximated by the Takagi-Sugeno (T-S) fuzzy model. Next, the robust-optimal controller is designed with the parallel distributed compensation control technique. The problem of designing robust-optimal controller based on the T-S fuzzy model with quadratic cost function and actuator amplitude constraint is cast in the form of linear matrix inequalities. In the end, the performance of the proposed robust-optimal fuzzy controller is compared with fuzzy PDC and PID controllers.

[View Full Paper]

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AAS 18-480

ATTITUDE CONTROL OF SPINNING SOLAR SAILS BASED ON MODAL ANALYSIS

Yuki Takao,[*] Shota Kikuchi,[†] Osamu Mori[‡] and Jun'ichiro Kawaguchi[§]

Attitude dynamics and control of spinning solar sails are investigated considering the flexibility of sail membranes. Attitude maneuver of solar sails is, in many cases, performed using thrusters. In most studies, the attitude motion is analyzed assuming that the spacecraft is a rigid disk. However, the sail membrane deforms during attitude maneuver due to flexibility. This may cause coupled vibration between the spacecraft main body and sail membrane. This study presents an analysis model of spinning solar sail attitude dynamics considering sail deformation, based on modal analysis. [View Full Paper]

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ORBIT DETERMINATION

Session Chairs:

Tuesday Session 6: Nagavenkat Adurthi, Texas A&M University

Co-Chair: Matthew Wilkins, Applied Defense Solutions

AAS 18-202

GENERATING REALISTIC SENSOR OBSERVATIONS FOR OD ANALYSIS

David A. Vallado*

Satellite mission design requires simulating realistic observations to determine the expected accuracy of the orbit determination. Generating observations for satellites is complicated because actual observations are affected by many factors, including operational limitations. Target satellite catalogs must be accurate. Sensor access must be realistic and include additional constraints of scanning, range, lighting, frequency, elevation, cadence, observation scheduling, and sensor limitations. A generic architecture is developed to interact with a variety of simulation tools. Examples are provided using STK and ODTK for satellites observed from the AFSPC SSN, optical, transponder, and SLR networks. [View Full Paper]

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AAS 18-365

ORBIT ESTIMATION STRATEGY FOR LOW EARTH ORBIT AND GEOSTATIONARY SATELLITES

Abdulkadir Köker[*] and Ozan Tekinalp[†]

In this paper, an orbit determination strategy that uses non-recursive batch filter, and unscented Kalman filter methods is presented and utilized for satellite orbit determination. For the orbit determination system, the range, azimuth, and elevation angles of the satellite measured from ground tracking stations are used for observations. An efficient filter initialization algorithm using the Gibbs method is also proposed to provide an initial state estimate. The non-recursive batch filter is applied to improve initial conditions and to provide initial covariance. Finally, the unscented Kalman filter is used for recursive nonlinear estimation of the states of an Earth-orbiting satellite. The effect of measurement noise and observation duration on orbit determination accuracy is also investigated, and presented.

[View Full Paper]

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AAS 18-366

DEFINING AND PROPAGATING UNCERTAINTY ON REGULARIZED MANIFOLDS*

Lorraine M. Weis,† Michael Mercurio,† Christopher W. T. Roscoe,† Matthew P. Wilkins† and Paul W. Schumacher, Jr.‡

Converting orbital dynamics problems to regularized coordinate systems has a number of advantages. Historically, the main motivation for regularization was the significantly improved numerical accuracy given limited computation resources. With modern computation and numerical integration algorithms, a major benefit is the ability to analytically propagate uncertainty, and better understand the effects of perturbations on the character of uncertainty. By choosing a transform to a well behaved set of manifolds, we can extract meaningful metrics and quantify the behavior of density currents within the probability distribution. This work will define a probability density function in regularized coordinates that allows for analytical propagation, and compare results back to the physical space and time coordinates. [View Full Paper]

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AAS 18-386

SEQUENTIAL ORBIT ESTIMATION AND PREDICTION USING MODIFIED EQUINOCTIAL ELEMENTS*

Waqar H. Zaidi,† Michael Mercurio,‡ Wes Faber§ and Paul W. Schumacher, Jr.**

Traditional Bayesian estimation involves characterizing a posterior probability density function (PDF) by fusing obtained measurement data with dynamic state predictions. The seminal Kalman Filter provides a sequential predict-then-update paradigm in which the first and second moments of the posterior PDF are computed as new measurements arrive. In the context of spacecraft orbit estimation, when expressed in Cartesian space, the uncertainty in the orbital state evolves in a non-Gaussian fashion. Modified Equinoctial Elements (MEE) describe a nonsingular state space in which the uncertainty in the orbital state can be well-characterized by a Gaussian density function for extended periods of time. Capitalizing on this behavior, an end-to-end estimation framework is derived, whereby the recursive Bayesian prediction and update equations are expressed directly in MEE space. The results of the proposed approach are compared with a congruent application in Cartesian space. Furthermore, the observability in both MEE and Cartesian coordinate systems is examined to give validity to the proposed estimation analysis. The underlying goal of this paper is to initialize the framework to completely perform estimation, prediction, and collision risk assessment using equinoctial elements. [View Full Paper]

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AAS 18-391

USING TRIANGULATION IN OPTICAL ORBIT DETERMINATION

Arun J. Bernard,[*] Akhter Mahmud Nafi[†] and David K. Geller[‡]

There are many different methods that are currently employed to determine the orbit of a resident space object using angles measurements from an electro-optical sensor. The research presented in this paper focuses on orbit determination using simultaneous angle measurements from two separate observatories. These angle measurements are combined with the known observer locations to obtain a position vector of the satellite using basic trigonometry. This triangulation approach is investigated to determine its feasibility in initially determining the orbit of an object. The accuracy of this method with respect to timing, measurement errors, and observatory location is investigated. [View Full Paper]

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AAS 18-410

INITIAL ORBIT DETERMINATION WITH VELOCITY VECTORS AND ANGLES

Courtney L. Hollenberg[*] and John A. Christian[†]

Classical methods of initial orbit determination (IOD) from Earth-bound observations are well established. Although traditional methods utilize range, position, and angle measurements, advancements in measurement techniques and sensor technologies have motivated a new class of IOD problems that utilize different parameters. Specifically, x-ray pulsar navigation (XNAV) allows for significantly more accurate measurements of an object's velocity vector than its position in the absence of an a-priori state estimate. A new method for initial orbit determination using only two velocity vectors (e.g. from XNAV) combined with their respective lines-of-sight to the central body (e.g. from sun sensors) is presented. Theoretical results are validated through numerical simulations. [View Full Paper]

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AAS 18-424

ORBIT DETERMINATION USING VINTI'S SOLUTION

Steven P. Wright[*] and William E. Wiesel[†]

Orbital altitudes congested with spacecraft and debris combined with recent collisions have all but negated the Big Sky Theory. As the sheer number of orbital objects to track grows unbounded so does interest in prediction methods that are rapid and minimally computational. Claimed as the "other solvable solution," the recently completed solution to orbital motion about the earth, based on Vinti's method and including the major effects of the equatorial bulge, opens up the prospect of much more accurate analytical models for space situational awareness. A preliminary examination of this solution is presented. A numerical state transition matrix is found using Lagrange partial derivatives to implement a nonlinear least squares fitting routine. Orbit fits using only the solvable solution for non-circular, non-equatorial trajectories less than 60 degrees inclination are on the order of a few hundred meters with projected, average error growth of less than a kilometer per day which is similar to the expected performance of the Air Force's method. Also, a classical perturbations approach to incorporate the dissipative effects of air drag using Hamiltonian action and angle formulation is developed. Predicted drag effects are 97.5% correct after one day and 87% correct after five days when compared to an integrated truth. Results are validated by performing a similar method on the two body problem. [View Full Paper]

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AAS 18-492

EXTENDED KALMAN FILTERING IN BURDET COORDINATES

David Ciliberto,[*] Puneet Singla[†] and Manoranjan Majji[‡]

Peculiarities associated with the linear error theory and the Kalman filter implementations associated with a class of nonlinear transformations of mechanical systems of interest in astrodynamics are discussed in the paper. Change of the independent variable using a nonlinear implicit equation transforms the measurement equations appropriately and provides additional conditions associated with the measurement times that are perfectly known. Since regularization process introduces redundant coordinates, linear error theory to explicitly account for the state constraints is developed. The paper then studies the tradeoffs obtained by the linear error propagation in the time updates and the nonlinearity incurred in the measurement update for problems in astrodynamics. [View Full Paper]

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SPACECRAFT GUIDANCE, NAVIGATION AND CONTROL

Session Chairs:

Monday Session 6: John Christian, Rensselaer Polytechnic Institute

Co-Chair: Roberto Furfaro, The University of Arizona

Tuesday Session 8: Diane Davis, a.i. solutions, Inc.

Co-Chair: Marcus Holzinger, University of Colorado Boulder

Wednesday Session 4: Roberto Furfaro, The University of Arizona

Co-Chair: Kyle DeMars, Missouri University of Science and Technology

The following papers were not available for publication:

AAS 18-287 Paper Withdrawn

AAS 18-335 Paper Withdrawn

AAS 18-348 Paper Withdrawn

AAS 18-463 Paper Withdrawn

AAS 18-483 Paper Withdrawn

AAS 18-201

TIME-OPTIMAL SPACECRAFT REORIENTATION WITH ATTITUDE CONSTRAINTS BASED ON A TWO-STAGE STRATEGY

Juntang Yang[*] and Enrico Stoll[†]

Time-optimal reorientation maneuver in the presence of complex attitude constraints is important for the spacecraft to quickly respond to missions. However, it is difficult to solve the problem even with direct methods, which results from the fact that a feasible initial guess for direct methods is usually not available. This paper proposes a new method to accelerate the computation based on a two-stage strategy. Firstly, a feasible solution is obtained using Bezier quaternion curves and inverse dynamics. Subsequently, the feasible solution obtained is used as an initial guess for the pseudospectral method. Compared with the pseudospectral method alone, the proposed two-stage approach can accelerate the computation to various extent. In some cases, the proposed method can be four times faster than the pseudospectral method alone. [View Full Paper]

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AAS 18-226

THE EVOLUTION OF DEEP SPACE NAVIGATION: 2006-2009*

Lincoln J. Wood†

The exploration of the planets of the solar system using robotic vehicles has been underway since the early 1960s. During this time the navigational capabilities employed have increased greatly in accuracy, as required by the scientific objectives of the missions and as enabled by improvements in technology. This paper is the fifth in a chronological sequence dealing with the evolution of deep space navigation. The time interval covered extends from 2006 to 2009. The paper focuses on the observational techniques that have been used to obtain navigational information, propellant-efficient means for modifying spacecraft trajectories, and the computational methods that have been employed, tracing their evolution through 14 planetary missions. [View Full Paper]

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AAS 18-227

LINEAR ANALYSIS AND CONTROL OF A TETHERED SYSTEM WITH TWO RIGID END BODIES

Nickolas J. Sabey[*] and Steven Tragesser[†]

A model is proposed for studying of the dynamics of a tethered satellite system with identical rigid end-masses, offset tether attachment points, and a massless tether. The equations of motion are developed and linearized for use within a linear control system. A Linear Quadratic Regulator (LQR) paired with a reduced order closed loop estimator is designed to control the attitude of each end mass individually using Reaction Wheel Assemblies (RWAs), assuming measured angular rates from gyroscopes on the end-masses and tether. Modal analysis shows the existence of a slow tether libration mode and two fast modes of end-mass oscillation. The oscillation is shown to be approximated by a rigid pendulum with an accelerating pivot point. Two control methodologies are investigated: one which aligns each end-mass with the nadir vector; and the other which aligns each end-mass with the tether. Results suggest that both modes of operation are controllable by a system architecture which employs LQR control and reduced-order closed loop estimation with a wide range of required control effort. [View Full Paper]

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AAS 18-229

CENTROIDING AND SIZING OPTIMIZATION OF ELLIPSOID IMAGE PROCESSING USING NONLINEAR-LEAST SQUARES

Stoian Borissov[*] and Daniele Mortari[†]

This paper covers the development and application of image processing algorithms used on images of celestial target bodies, specifically the Earth and Moon, when performing optical navigation (OpNav). These algorithms were originally developed by Texas A&M under contract with NASA Johnson Space Center as a backup navigation solution in the case of a loss of communications with ground stations on Earth. The algorithms work by first pre-processing the image ensuring that it can be processed. Then, an initial estimate of the apparent size and centroid of the observed body is produced. This initial estimate is then refined by using nonlinear least squares to fit a functional description to the limb of the observed body. The focus of this paper will be to provide the mathematical development of the nonlinear least squares and also demonstrate its implementation in the Orion OpNav system. Results of both real image and synthetic image processing will be presented and recommendations for further algorithm implementation will be presented.

[View Full Paper]

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AAS 18-230

THEORY OF CONNECTIONS APPLIED TO FIRST-ORDER SYSTEM OF ORDINARY DIFFERENTIAL EQUATIONS SUBJECT TO COMPONENT CONSTRAINTS

Daniele Mortari[*] and Roberto Furfaro[†]

Motivated by a class of first order differential equations generated by some optimal control problems this paper provides, using the methodology introduced by the Theory of Connections, least-squares solutions of first-order differential equations systems subject to linear constraints on the vector's components. This paper solves all different cases occurring in 2×2 linear time-varying systems with forcing term. Then, it shows how to solve a 4×4 system generated by a simple optimal control problem and how to solve a generic 3×3 time-varying differential equation system subject to relative and integral constraints on the vector components. [View Full Paper]

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AAS 18-253

ROBUST MYOPIC CONTROL FOR SYSTEMS WITH IMPERFECT OBSERVATIONS

Dantong Ge,[*] Melkior Ornik[†] and Ufuk Topcu[‡]

Control of systems operating in unexplored environments is challenging due to lack of complete model knowledge. Additionally, under measurement noises, data collected from onboard sensors are of limited accuracy. This paper considers imperfect state observations in developing a control strategy for systems moving in unknown environments. First, we include hard constraints in the problem for safety concerns. Given the observed states, the robust myopic control approach learns local dynamics, explores all possible trajectories within the observation error bound, and computes the optimal control action using robust optimization. Finally, we validate the method in an OSIRIS-REx-based asteroid landing scenario. [View Full Paper]

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AAS 18-258

A NEW APPROACH TO RELIABLE POWERED DESCENT GUIDANCE PROBLEM USING CONVEX OPTIMIZATION

K. Echigo[*] and T. Kubota[†]

Planetary landing missions have received a lot of attention all over the world. In order to increase the success rate of the mission, the spacecraft should land on the target body safely without receiving any command from the ground station. To achieve this goal, an onboard powered descent guidance algorithm is required. In this paper, a convex optimization based approach is proposed to solve the optimal-reliable powered descent guidance problem. The main contributions of this research are as follows. Firstly, this paper proposed the novel approach to the optimal-reliable powered descent guidance problem, which has non-convex and non-linear constraints. In addition, we show that this problem can be successfully converted into the Second Order Cone Programming (SOCP). SOCP is a subclass of convex optimization problem that can be solved in polynomial time. Secondly, the performance of the proposed method is then demonstrated by numerical simulations. Thruster magnitude for Reaction Control System (RCS) need to follow a bang-bang profile. In addition, the correctness of the overall transformation process should be ensured for the actual usage. This paper presents that this problem results in the optimal control solutions which satisfy these constraints. [View Full Paper]

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AAS 18-270

CLOSED LOOP GUIDANCE TRADE STUDY FOR SPACE LAUNCH SYSTEM BLOCK-1B VEHICLE

Naeem Ahmad,[*] Matt Hawkins,[†] Paul Von der Porten,[‡] Robin Pinson,[§] Greg Dukeman[**] and Thomas Fill[††]

The Space Launch System (SLS) Block-1B vehicle includes a low thrust-to-weight upper stage, which presents challenges to heritage ascent guidance algorithms. A trade study was conducted to evaluate two alternative guidance algorithms: 1) Powered Explicit Guidance (PEG), based on a modified implementation of PEG used on the Block-1 vehicle, and 2) Optimal Guidance (OPGUID), an algorithm developed for Marshall Space Flight Center (MSFC) and used on Constellation and other Guidance, Navigation, and Controls (GN&C) projects. The design criteria, approach, and results of the trade study are given, as well as other impacts and considerations for Block-1B type missions. [View Full Paper]

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AAS 18-273

LINEAR DIFFERENTIAL EQUATIONS SUBJECT TO RELATIVE, INTEGRAL, AND INFINITE CONSTRAINTS

Hunter Johnston[*] and Daniele Mortari[†]

This study extends prior work in the *Theory of Connections* (ToC) by detailing methods to incorporate relative, integral, and infinite constraints. In this, the method produces *analytical constrained expressions* that always satisfy the given constraints while remaining free in the function $g(x)$. For some cases, numerical tests were conducted where *least-squares solutions* are obtained for ordinary differential equations by using a two step process. First, the constrained expression is derived and the free function, $g(x)$, is then expanded as a linear combination of a set of basis functions (e.g., nonrational and rational orthogonal polynomials). In the second step, the unknown coefficients of this expansion are estimated by least-squares using collocation point discretization. The results obtained by the proposed method are then compared in terms of speed and accuracy with the solution provided by the Chebfun toolbox. In all numerical examples, the proposed methodproducesasolutionmoreaccurateandwithtwoordersofmagnitudefaster solution time compared to Chebfun.

[View Full Paper]

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AAS 18-285

THEORY OF THE F-RADIUS SPHERE MODEL

Daniele Mortari* **and Carl Leake†**

This paper continues the research initiated in Ref. [1] by proposing the f-radius sphere model for pin-hole calibrated cameras as a mathematical tool to remove radial distortion in CCD or CMOS camera receivers. Since the pin-hole model performs sphere-to-plane projection (gnomonic), it creates a radial distortion that increases with the dimension of the imager and/or when using a smaller focal length. The f-radius sphere model avoids this radial distortion by projecting the observed spherical 3-dimensional world onto a fictitious spherical imager. Thus, performing sphere-to-sphere projection, and no radial distortion is generated. The f-radius sphere models for continuous (infinitesimal pixel size) and discrete (pixels with finite dimensions) imagers are summarized. The main result of the f-radius sphere is: the geometric center of a pixel is not necessarily coincident with the "barycenter" of photon flux over the pixel. This model provides the correct location of a pixel's barycenter. The value of this correction for cameras with various fields-of-view (FOVs) is analyzed. The conclusion is that this correction is extremely small for existing imagers.

[View Full Paper]

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AAS 18-290

INTEGRATED GUIDANCE AND CONTROL FOR PINPOINT MARS LANDING USING REINFORCEMENT LEARNING

Brian Gaudet,[*] Richard Linares[†] and Roberto Furfaro[‡]

Future Mars missions will require advanced guidance, navigation, and control algorithms for the powered descent phase in order to target specific surface locations and achieve pinpoint accuracy (landing error ellipse < 5m radius). This requires both a navigation system capable of estimating the lander's state in real-time and a guidance and control system that can map the estimated lander state to body-frame actuator commands. In this paper we present a novel integrated guidance and control algorithm designed by applying the principles of reinforcement learning theory. The key innovation is the use of reinforcement learning to learn a policy mapping the lander's estimated state directly to actuator commands, with the policy resulting in accurate and fuel efficient trajectories. Specifically, we use proximal policy optimization, a policy gradient method, to learn the policy. demonstrating the guidance and control system's performance in a 6-DOF simulation environment, and demonstrate robustness to noise and system parameter uncertainty. [View Full Paper]

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AAS 18-291

ANALYSIS OF UNCERTAINTY PROPAGATION IN MARS ENTRY USING NON-INTRUSIVE POLYNOMIAL CHAOS

Xiuqiang Jiang[*] and Shuang Li[†]

Uncertainty quantification and propagation is a significant prerequisite and major technical challenge for the development of next generation Mars entry, descent, and landing technologies. Unfortunately, to date, few public reports have explored the uncertainty propagation in Mars atmospheric entry dynamics. In this study, the uncertainty propagation is investigated according to the initial state uncertainty at the entry interface, and the probabilistic quantification of entry trajectory is sought. The uncertainty propagation for Mars atmospheric entry is implemented under non-intrusive polynomial chaos framework.

[View Full Paper]

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AAS 18-297

FUEL-OPTIMAL CONTROL METHOD OF HOVERING FORMATION INITIALIZATION AND RECONFIGURATION

Yinrui Rao,[*] Huan Chen[†] and Chao Han[‡]

The teardrop hovering formation which can be formed by periodic pulse control has been concerned in recent years. In this study, a time-constrained fuel-optimal control problem of the hovering formation initialization and reconfiguration is exhaustively researched. Using the relative motion model based on relative orbit elements, a double impulse control equation based on relative Lambert's transfer is derived, which can be applied to solve the hovering formation control problem. In addition, combining the presented equation and the differential evolution algorithm, the time of the two maneuvers and the relative position of the second maneuver are optimized, and the fuel-optimal control strategies for the hovering formation initialization and reconfiguration are obtained. Several numerical simulations are conducted to demonstrate the proposed method's efficacy. [View Full Paper]

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AAS 18-300

AN ADAPTIVE NONSINGULAR TERMINAL SLIDING MODE TRACKING CONTROL USING NEURAL NETWORKS FOR SPACE MANIPULATORS ACTUATED BY CMGS

Xinhui Xia,[*] Yinghong Jia,[†] Shijie Xu[‡] and Xinlong Wang[§]

An adaptive non-singular terminal sliding mode (ANTSM) trajectory tracking control scheme based on neural networks is proposed for rigid space manipulators with control moment gyroscopes (CMGs) as reactionless actuators. A key feature of this scheme is that an adaptive neural network is used to learn the upper bound of the system lumped uncertainties with no prior knowledge. A non-singular terminal sliding surface is constructed to ensure that the tracking error converges to zero in finite time on the sliding surface. An adaptive law is also proposed for the control gain's adjustment. The closed-loop system is uniformly ultimately bounded proved by Lyapunov's method. Simulation results verify the effectiveness of the proposed controller and the robustness of the space manipulators.

[View Full Paper]

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AAS 18-308

CLOSED-FORM OPTIMAL IMPULSIVE CONTROL OF SPACECRAFT FORMATIONS USING REACHABLE SET THEORY

Michelle Chernick[*] and Simone D'Amico[†]

This paper addresses the spacecraft relative orbit reconfiguration problem of minimizing the delta-v cost of a set of impulsive control actions while achieving a desired state in fixed time. The problem is cast into relative orbit element space, which yields insight into the geometry of relative motion and allows for the straightforward inclusion of perturbations in linear time-variant form. Reachable set theory is used to translate the cost-minimization problem into a geometric path planning problem and to formulate a novel metric, the reachable delta-v minimum, for assessing the optimality of a proposed maneuver scheme. This metric in forms the derivation of closed-form globally energy-optimal maneuver schemes in eccentric and near-circular orbits. The proposed algorithms are tested and validated in high-fidelity simulations. For the first time in literature, general, closed-form, globally optimal maneuver schemes for relative orbit reconfiguration are derived in eccentric orbits. Furthermore, the newly proposed method based on reachable set theory can be applied to any linear time-variant dynamics system. [View Full Paper]

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AAS 18-353

ADVANCEMENTS OF THE RELATIVE POSITIONING IN SPACE WITHIN IRASSI MISSION CONCEPT

Mathias Philips-Blum, Thomas Pany, Harvey Gomez, Kathrin Frankl, Luisa Buinhas and Bernd Eissfeller*

The mission concept IRASSI is composed of five free-flying telescopes orbiting around the second Lagrange point, L2, of the Sun-Earth/Moon system. To achieve an unprecedented observation resolution, the baselines (i.e. physical separation) between each pair of telescopes must be known with an accuracy of 5 μm. To this end, a ranging system is employed to provide distance and angular measurements at micrometer-level and arcsec accuracy level between the ranging sensors located on top of each spacecraft. A crucial task in the IRASSI project is to develop a precise, real-time and robust relative positioning approach that determines the baselines between the telescope using the available measurements with the specified accuracy. In this work, a geometric snapshot method is presented that determines relative positions and attitude of each telescope using the measurements of only the current time instant. In a former work, the relative telescope positions are determined also by a snapshot method, but after transferring the measurements between the ranging sensors to the telescope reference points. Both methods are compared by means of a case study. Since such snapshot methods are very sensitive to outliers or missing measurements, filter-based approaches are an option to be studied in future to increase the robustness of the measurements. Since filter-based approaches normally include the acceleration forces due to gravity and solar radiation pressure in the process dynamics, also the modeling level of such forces within the process model will be analyzed. Thus, a suggestion is provided regarding when and to which extent the acceleration forces need to be taken into consideration in future. [View Full Paper]

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AAS 18-354

X-RAY PULSAR NAVIGATION OPTIMIZATION USING SPHERICAL PARTITIONS

Samuel McConnell,[*] Michael McCarthy, Ty Buchanan, Kevin Tang, Monte Wasson, Anthony Young, Stoian Borrisov[†] and Daniele Mortari[‡]

X-ray pulsars are stars which appear to periodically pulse due to the beams of energy which emanate from their magnetic poles as they rotate. This periodic pulsing proves useful and allows for X-ray pulsar based navigation (X-Nav) systems to be developed. However, the periodic nature of the signal makes it difficult to discern one pulse from the next when coming from the same pulsar. This introduces the problem of ambiguous measurements which leads to multiple possible solutions for position estimation algorithms which must be filtered in order to implement X-Nav. We investigate the use of a grid of spherical volumes to partition the mission space in order to reduce the computational load of resolving the ambiguity problem. Only spheres which may contain a potential position solution are analyzed further. The remaining spheres which have no chance of containing a potential solution can be ignored, thus reducing the computational complexity of the problem by prefiltering the potential locations in space where a valid position estimate may exist. We present a detailed implementation of this algorithm as well as preliminary simulation results which demonstrate the change in performance due to implementing this prefiltering.

[View Full Paper]

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AAS 18-358

PRESCRIBED PERFORMANCE CONTROL STRATEGIES FOR HALO ORBIT SPACECRAFT RENDEZVOUS

Dandan Zheng[*] Jianjun Luo,[†] Caisheng Wei[‡] and Renyong Zhang[§]

This paper studies finite-time libration point orbit autonomous rendezvous for spacecraft with external disturbances and velocity-free during the terminal phase. The proposed method is essentially a compound control method, which consists of a novel prescribed performance control (NPPC) and integral-chain differentiator observer (ICDO) methodology. The ICDO s used to estimate the unknown relative velocity information between two neighboring spacecraft, while theoretical analysis and rigorous proof show that the relative position and its rate can reach a small compacted region around zero within predefined time. Simulation results of a final closing rendezvous example are provided to demonstrate the effectiveness and robustness of the proposed composite ICDO-NPPC guidance approach. [View Full Paper]

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AAS 18-362

LEAST-SQUARES SOLUTION OF A CLASS OF OPTIMAL SPACE GUIDANCE PROBLEMS VIA THEORY OF CONNECTIONS

Roberto Furfaro[*] and Daniele Mortari[†]

In this paper, we apply a newly developed method to solve boundary value problems for differential equations to solve optimal space guidance problems in a fast and accurate fashion. The method relies on the least-squares solution of differential equations via orthogonal polynomial expansion and constrained expression as derived via Theory of Connection (ToC). The application of the optimal control theory to derive the first order necessary conditions for optimality, yields a Two-Point Boundary Value Problem (TPBVP) that must be solved to find state and costate. Combining orthogonal polynomial expansion and ToC, we solve the TPBVP for a class of optimal guidance problems including energy-optimal constrained landing on planetary bodies and fixed-time optimal intercept for a target-interceptor scenario. An analysis of the performance in terms of accuracy and computational time is provided to evaluate the performance of the proposed algorithm for realtime implementation. [View Full Paper]

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AAS 18-363

DEEP LEARNING FOR AUTONOMOUS LUNAR LANDING

Roberto Furfaro,[*] Ilaria Bloise,[†] Marcello Orlandelli,[‡] Pierluigi Di Lizia,[§] Francesco Topputo[**] and Richard Linares[††]

Over the past few years, encouraged by advancements in parallel computing technologies (e.g., Graphic Processing Units, GPUs), availability of massive labeled data as well as breakthrough in understanding of deep neural networks, there has been an explosion of machine learning algorithms that can accurately process images for classification and regression tasks. It is expected that deep learning methods will play a critical role in autonomous and intelligent space guidance problems. The goal of this paper is to design a set of deep neural networks, i.e. Convolutional Neural Networks (CNN) and Recurrent Neural Networks (RNN) which are able to predict the fuel-optimal control actions to perform autonomous Moon landing, using only raw images taken by on board optimal cameras. Such approach can be employed to directly select actions with-out the need of direct filters for state estimation. Indeed, the optimal guidance is determined processing the images only. For this purpose, Supervised Machine Learning algorithms are designed and tested. In this framework, deep networks are trained with many example inputs and their desired outputs (labels), given by a supervisor. During the training phase, the goal is to model the unknown functional relationship that links the given inputs with the given outputs. Inputs and labels come from a properly generated dataset. The images associated to each state are the inputs and the fuel-optimal control actions are the labels. Here we consider two possible scenarios, i.e. 1) a vertical 1-D Moon landing and 2) a planar 2-D Moon landing. For both cases, fuel-optimal trajectories are generated by soft-ware packages such as the General Pseudo-spectral Optimal Control Software (GPOPS) considering a set of initial conditions. With this dataset a training phase is performed. Subsequently, in order to improve the network accuracy a Dataset Aggregation (Dagger) approach is applied. Performances are verified on test optimal trajectories never seen by the networks. [View Full Paper]

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AAS 18-371

INFORMATION-THEORETIC SENSOR SCHEDULING UNDER COMMUNICATION CONSTRAINTS

Kirsten Tuggle* **and Maruthi Akella†**

The modern abundance of sensor systems with a large number of available sensor sources emphasizes the need for effective and practical sensor management. In designating management schemes, the overarching GN&C goal for the sensor system should be considered. The current work considers the problem of performing an LQG-type control task under limitations on the information or communications required. In general, this scheduling problem is both nonlinear and combinatorial, and therefore optimal solutions are computationally prohibitive for practical use. The current work exploits underlying mathematical properties concerning the evolution of information in the LQG problem to provide a well motivated relaxed solution that has real-time potential. [View Full Paper]

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AAS 18-379

HYPERBOLIC-TANGENT-BASED DOUBLE-SMOOTHING METHOD AND ITS APPLICATION IN OPTIMAL CONTROL

Ehsan Taheri[*] and John L. Junkins[†]

In a large number of dynamical systems and depending on the form of performance index, their Hamiltonian may turn out to be affine in control. Extremal control of such systems may switch between the bounds of the admissible set or take on values interior to its admissible set, i.e., singular arcs. On the other hand, the existence of singular arcs is not evident until certain existence and solvability conditions are satisfied and this logic complicates the detection and consequent inclusion of singular sub-arcs in the extremal trajectory. Moreover, the presence of abrupt changes in the control inputs jeopardizes the numerical solution of optimal control problems unless care is taken to isolate precise time transition points where sharp switches occur. This investigation illustrates a double-smoothing method capable for problem in which the extremal control has a composite structure. Application of the method is demonstrated by solving the maximum-altitude Goddard rocket problem with a known "bang-singular-bang" control structure. Additional physical insights on singular control are also offered by the use of associated singular surface and first principles.

[View Full Paper]

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AAS 18-412

IDENTIFICATION OF PARTIALLY RESOLVED OBJECTS IN SPACE IMAGERY WITH NEURAL NETWORKS

Christopher A. Ertl[*] and John A. Christian[†]

There are many scenarios where it may be useful to identify partially resolved space objects in an image and match it to a database of known objects. Through the use of machine learning the objects can be identified at various distances, relative attitudes, and phase angles. In this study, a fully-connected and a convolutional neural network are constructed and evaluated. Performance as a function of phase angle and distance are used to evaluate the capability of both neural networks. Multiple neural networks are then trained at overlapping regions of phase angles. [View Full Paper]

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AAS 18-414

MONTE CARLO METHODS AND SKEWED KALMAN FILTERS FOR STATE ESTIMATION

Louis Tonc, David Geller and Geordie Richards*

Under reasonable orbital conditions, the Extended Kalman Filter (EKF) and Unscented Kalman Filter (UKF) both diverge after several updates from optical measurements. We identify the source of divergence by studying a simplified model, and correct this problem by implementing a Monte Carlo based particle filter. However, the computational cost of the particle filter is high, and future work will implement a Skewed Unscented Kalman Filter as a substitute for the particle filter. We present evidence that this skewed unscented Kalman filter will avoid divergence at a reduced cost compared to the particle filter, and discuss Monte Carlo methods for validating this claim. [View Full Paper]

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AAS 18-419

THE CISLUNAR AUTONOMOUS POSITIONING SYSTEM, CAPS

Jeffrey S. Parker, Alec Forsman, Christopher Rabotin, Charles Cain, Bradley Cheetham and Jonathon Smith*

The Cislunar Autonomous Positioning System (CAPS) is a peer-to-peer, autonomous navigation solution that is self-sustaining, scalable, and evolvable. CAPS leverages substantial previous research and development of an algorithm known as LiAISON (Linked Autonomous Interplanetary Satellite Orbit Navigation). LiAISON is a well-developed technique that harnesses an asymmetric gravity field (as found in cislunar space) to derive absolute position and velocity information about two or more satellites using only inter-satellite range and range-rate tracking data. By using only inter-spacecraft measurements, CAPS is able to generate onboard navigation solutions that are independent of Earth-based tracking stations. This allows highly contested ground-contact time to be prioritized for spacecraft commanding and data return. Spacecraft participating in CAPS form a network in cislunar space and on the surface of the Moon that becomes increasingly effective at inertial navigation as more gravitational asymmetry is expressed in their combined geometry.

[View Full Paper]

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AAS 18-476

A SIX DEGREE-OF-FREEDOM SPACECRAFT DYNAMICS SIMULATOR FOR FORMATION CONTROL RESEARCH

Yashwanth Kumar Nakka,[*] Rebecca C. Foust,[†] Elena Sorina Lupu,[‡] David B. Elliott,[§] Irene S. Crowell,[**] Soon-Jo Chung[††] and Fred Y. Hadaegh[‡‡]

This paper presents a new six-degree-of-freedom robotic spacecraft simulator, the Multi-Spacecraft Testbed for Autonomy Research (M-STAR), for testing formation guidance, relative navigation, and control algorithms. The simulator dynamics are governed by five degrees of frictionless translational and rotational air-bearing motion and one degree of kinematic motion in the gravity direction with flight-like actuators, in a 1-g environment. M-STAR is designed to be modular and accommodates 3-DOF, 4-DOF, 5-DOF, and 6-DOF operation with minimal mechanical modifications. The simulator is modelled as a 3-D pendulum on a floating platform with sixteen thrusters and four reaction wheels as on-board actuators. Based on this plant model, a nonlinear hierarchical control law is proposed for position and attitude trajectory tracking. A weighted generalized pseudo-inverse strategy for control allocation to map control inputs to actuator inputs is discussed. The thruster actuation model for mapping smooth allocated input to non-smooth actuator input that achieves equivalent performance is derived. The control law, allocation scheme, and thruster model are tested on the simulator for real-time position tracking control using a Robot Operating System (ROS) based software framework. [View Full Paper]

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AAS 18-485

COMPUTATIONAL GUIDANCE FOR MARS ENTRY AND POWER DESCENT

Xiuqiang Jiang,[*] Shuang Li[†] and Roberto Furfaro[‡]

Traditional studies on Mars entry, descent, and landing usually take a divide-and-conquer approach where each phase is investigated separately. This paper proposed a new computational approach to generate optimal guidance for mid-lift high-mass Mars entry and powered descent. First, optimal Mars atmospheric entry and optimal powered descent problems are respectively modeled. Second, optimal handover problem is formulated to integrate the Mars entry and powered descent phases in a collaborative optimization manner. Third, optimal guidance for Mars entry and powered descent is produced through online solving energy-optimal entry, propellant-optimal powered descent, and optimal handover problems iteratively. Finally, numerical simulations verified the collaborative work of the proposed computational guidance framework, and the results demonstrated the significant benefit of the optimal integrated guidance. [View Full Paper]

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ASTERIOD AND NON-EARTH ORBITAL MISSIONS

Session Chairs:

Monday Session 7: Angela Bowes, NASA Langley Research Center

Co-Chair: Mar Vaquero, Jet Propulsion Laboratory

Wednesday Session 2: Simone Damico, Stanford University

Co-Chair: Mar Vaquero, Jet Propulsion Laboratory

The following paper was not available for publication:

AAS 18-280 Paper Withdrawn

AAS 18-217

COVERAGE ANALYSIS FOR POSITIONING IN THE ASTEROID MAIN BELT USING A SPACE NAVIGATION INFRASTRUCTURE

Luisa Buinhas,[*] Alena Probst[*] and Roger Förstner[*]

Asteroid mining has gained prominence in recent years due to the potential of asteroid bodies harbouring precious metals and resources. Mining activities come nonetheless with a set of logistical and operational challenges, such as the ability to position mining elements accurately and within an acceptable time frame. Earth-based navigation solutions suffer from systematic errors and time delays, and ground stations may become congested as increasingly more satellites are launched, making this approach unsustainable in the long term. Thus, novel navigation solutions have to be investigated. The paper provides a feasibility analysis for positioning in the Asteroid Main Belt by using triangulation from Lagrange points with the aim of supporting commercial asteroid mining activities. A framework is defined in which the space elements in charge of the execution and space logistics of asteroid mining are introduced. For supporting such complex mission operations and element coordination, a Space Communications and Navigation (SCaN) network is thereafter proposed. This underlying SCaN infrastructure should provide the NoMaD elements with accurate real-time position determination and allows for the mining constellation to communicate with the Earth and internally, among NoMaD members. The feasibility study is carried out to select the locations of the SCaN network which guarantee geometrical triangulation within a desirable accuracy for the highest percentage of time in the Main Asteroid Belt region, by considering three NoMaDs on different orbits. Results show that a combination of the Sun-Mars and Sun-Jupiter systems' libration points provides the best overall solution. Next, considerations regarding the system design are described. The paper concludes with a summary of the information presented, where relevant aspects for future analysis are identified. Note that this is an independent study and not related to, supported or sponsored by NASA's SCaN Program, although an overlap in terminology does exist.

[View Full Paper]

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AAS 18-221

LOW-ENERGY CAPTURE OF ASTEROIDS FOR THE LOGISTIC SUPPORT OF FUTURE MARS MISSIONS

Minghu Tan,[*] Colin McInnes[†] and Matteo Ceriotti[‡]

Low energy strategies for capturing asteroids and inserting them into orbits in the vicinity of the Sun-Mars L_1/L_2 libration points may be of significant benefit for future Mars missions. Such strategies could deliver resources to Lagrange point staging posts to support future crewed missions. Three asteroid capture strategies are investigated to achieve efficient delivery of asteroid resources. In the first strategy, the target asteroid is assumed to be deflected from its heliocentric orbit using some initial maneuver. Then, with a second maneuver, the candidate asteroid is inserted onto the stable manifold associated with the Sun-Mars L_1/L_2 periodic orbits. In principle it will then be asymptotically captured onto the final target periodic orbit without any propellant consumption. Therefore, the entire transfer trajectory for capturing the candidate asteroid can be designed by patching together the Sun-centered two-body problem and the stable manifold in the Sun-Mars circular restricted three-body problem. Moreover, a Mars flyby is also considered to capture asteroids onto the final periodic orbits around the Sun-Mars libration points. According to the periapsis distance threshold for aerobaking, two asteroid capture strategies using the Mars flyby are considered: a Mars flyby with aerobraking and without aerobraking to enhance the transfer trajectory from the candidate asteroid orbit to the stable manifolds associated with the Sun-Mars L_1/L_2 periodic orbits. Furthermore, all transfers are optimized with a global optimization method, using the total transfer cost as the objective function. Results show that the Mars flyby can enable some asteroids to be captured with a lower cost than the asteroid capture strategy without a Mars flyby in terms of energy requirements. [View Full Paper]

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AAS 18-225

SMALLSAT SWARM GRAVIMETRY: REVEALING THE INTERIOR STRUCTURE OF ASTEROIDS AND COMETS

William Ledbetter,[*] Rohan Sood[†] and James Keane[‡]

A growing database of interesting small bodies motivates research into rapid characterization methods for economic or scientific objectives. The computational tools developed in this work enable reconstruction of internal structure for irregularly shaped celestial bodies, thus aiding target selection and exploration. Simulations of on-orbit data are used to recover the density map of a multilayered polyhedron, and reconstruction accuracies are investigated across multiple scenarios. The presented results and analysis demonstrate successful density recovery of a fully heterogeneous, multilayered asteroid with on-orbit measurements. [View Full Paper]

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AAS 18-232

LINEARIZED RELATIVE ORBITAL MOTION DYNAMICS IN A ROTATING SECOND DEGREE AND ORDER GRAVITY FIELD

Ethan R. Burnett[*] and Eric A. Butcher[†]

A new linearized time-varying ODE model is introduced for spacecraft relative motion in a rotating second degree and order gravity field. The model is stand-alone and does not require integration of the chief orbit, but is restricted for use with near-circular chief orbits. Previous models have considered the effect of $C_{20} = -J_2$ alone, as well as additional zonal harmonics. However, the addition of C_{22} introduces additional time-varying dynamical effects due to the rotation of the primary body. Numerical simulations show that the newly obtained linearized model successfully captures these effects. [View Full Paper]

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AAS 18-238

A CONSISTENT SMALL BODY NAVIGATION FILTER USING FLASH-LIDAR DATA AND BEZIER TRIANGLES

Benjamin Bercovici[*] and Jay W. McMahon[†]

The knowledge of the orbited terrain is paramount to spacecraft safety and the fulfilment of mission objectives when performing proximity relative navigation. Customarily, the shape model of the targeted object is reconstructed on the ground after optical images captured by the spacecraft are downlinked. Unfortunately, this classical approach is not suitable for on-board implementation due to several constraints, such as high computing power requirements. Instead, we propose an algorithm relying on Flash-Lidar data to reconstruct the shape model of the orbited object, train an uncertainty model representative of shape reconstruction imprecision and sensor noise using a maximum-likelihood approach combined with a Particle-In-Swarm Optimizer, and perform model-based relative navigation by comparing range measurements from the on-board shape model to those provided by a Flash-Lidar sensor. Our algorithm yielded a satisfying estimate of the shape model of interest, along with a consistent measure of the range error that was derived by means of likelihood maximization over the measured range residuals. The reconstructed shape model of asteroid Itokawa and its associated uncertainty metric were provided to the model-based navigation Extended Kalman Filter. The filter returned an estimate of the spacecraft state that was consistent with the covariance envelopes, despite the defaults in the reconstructed shape. Future work focuses on making our approach robust to biases in the point cloud registration phase preceding navigation and adding the small body's attitude to the estimated state.

[View Full Paper]

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AAS 18-239

IMMERSION-AND INVARIANCE-BASED ADAPTIVE CONTROL OF ASTEROID-ORBITING AND - HOVERING SPACECRAFT

Keum W. Lee[*] and Sahjendra N. Singh[†]

The development of an immersion-and invariance-based adaptive state variable feedback control law for the closed orbit and hovering control of spacecraft in the vicinity of asteroids is the subject of this paper. The celestial body is assumed to be rotating with constant angular velocity about a fixed axis. Also, it is assumed that the mass and moments of inertia matrix of the asteroid, and the mass of the spacecraft are not known. The objective is to control the orbit of the spacecraft despite uncertainties in the system parameters. Based on the immersion and invariance theory, a noncertainty-equivalence adaptive control system is designed for steering the spacecraft along prescribe closed orbits or to fixed points for hovering control. The control system has a modular structure - consisting of an stabilizing control module and an parameter identifier. The control law is synthesized using filtered signals so as to circumvent the complexity of the immersion and immersion methodology. Unlike certainty-equivalence systems, the parameter estimates include judiciously selected nonlinear state-dependent algebraic functions and partial estimates derived from an integral update law. By the Lyapunov analysis, it is shown that the trajectory tracking error asymptotically converges to zero and all the signals in the closed-loop system are bounded. For illustration, numerical results are presented for control around Eros 433 and Ida asteroids. These results show that, despite uncertainties in the relative spacecraft dynamics, the adaptive law accomplishes closed orbit as well as hovering control. [View Full Paper]

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AAS 18-241

MISSION DESIGN FOR THE EXPLORATION OF ICE GIANTS, KUIPER BELT OBJECTS AND THEIR MOONS USING KILOPOWER ELECTRIC PROPULSION

Steven L. McCarty,[*] Steven R. Oleson,[†] Lee S. Mason[‡] and Marc A. Gibson[§]

The exploration of Ice Giants, Kuiper Belt Objects (KBOs) and their moons poses unique challenges from a mission design standpoint. NASA is currently developing a scalable 1-10 kW-electric space fission reactor, known as Kilopower, that may be useful in solving these challenges. The focus of this paper is to investigate the applicability of Kilopower Electric Propulsion to orbiting missions to Uranus, Neptune, and Pluto. This effort is broken into two parts for each destination. First, a broad search of interplanetary trajectories with multiple gravity assists is completed to identify a range of mission opportunities from 2025 to 2045. Second, preliminary analysis is completed to understand the accessibility of various destination orbits, including elliptical orbits around the primary body and circular orbits around the largest moons. Results suggest that orbital missions to Uranus and Neptune are feasible with reasonable time of flight on medium class launch vehicles. Further work is necessary to achieve similar success with Pluto missions, but preliminary results are promising. [View Full Paper]

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AAS 18-248

ANALYSIS OF THE 3GM GRAVITY EXPERIMENT OF ESA'S JUICE MISSION

Paolo Cappuccio,[*] Mauro Di Benedetto, Gael Cascioli and Luciano Iess

The ESA's JUICE mission will provide a thorough investigation of the Jupiter system and the Galilean moons through a suite of ten different scientific instruments. JUICE will perform flybys of Europa and Callisto, and will orbit around Ganymede in the last phase of the mission. The 3GM experiment will exploit accurate Doppler and range measurements to determine the moons' orbits and gravity fields (both static and tidal) and to infer their interior structure. This paper presents the attainable accuracies from the 3GM geodesy experiment under the current mission scenario. Our analysis includes the use of a high-accuracy accelerometer to remove the dynamical noise induced by propellant sloshing.

[View Full Paper]

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AAS 18-279

SEARCH FOR STABLE ORBITS AROUND 1999 KW4

Thais C. Oliveira[*] and Antonio F. B. A. Prado[†]

This paper is a study of the orbital motion of a space vehicle around the binary system 1999 KW4. The model used is the restricted full body problem, in which it is assumed that the mass of the spacecraft is negligible and that the binary system is composed of two-ellipsoid bodies. The equations of motion of the binary system are found using Lagrange's method. The solar radiation pressure perturbation is assumed to act on the spacecraft's dynamics along with the gravitational influence of the non-spherical asteroid bodies. The results are based on a grid search method to find stable orbits for a spacecraft to visit the 1999 KW4 system. Several types of families of orbits are found, such as orbits around one or both asteroid bodies. Trajectories ending in escapes from the double system or collisions with one of the asteroid bodies are also mapped because they need to be avoided. The eccentricity of the orbit of the binary system around the Sun is approximately 0.69, a large value, therefore the effect of the solar radiation pressure on the orbit of the spacecraft for short and long periods is investigated. [View Full Paper]

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AAS 18-283

APPLICATIONS OF THE DYNAMIC N-DIMENSIONAL K-VECTOR

Carl Leake,[*] Javier Roa[†] and Daniele Mortari[‡]

The n-dimensional *k*-vector (NDKV) is an appealing alternative to binary trees for resolving complex queries in large relational databases. The method has excelled in several applications involving static databases. The present paper extends the theory supporting the NDKV to handle dynamic databases, where the data is updated frequently. This includes deleting records, adding new entries, or editing existing elements. The merit of this new version of the NDKV, the dynamic *n*-dimensional *k*-vector (DNDKV), is that it is no longer necessary to recompute the *k*-vector tables (the main structure that indexes the data) every time a record changes. The algorithm updates the four constituents of the standard NDKV on the fly: the database, sorted database, index, and *k*-vector tables. As a result, the DNDKV becomes comparable in terms of capabilities and flexibility to state-of-the-art storage engines relying on structured query languages (SQL). The performance of the DNDKV is assessed by running typical read/write operations on a database that contains millions of pre-computed missions to celestial bodies. This database requires frequent updates whenever an orbit solution is refined or new bodies are discovered. The DNDKV is faster than rebuilding the *k*-vector tables completely, provided that the number of elements being added or removed is not excessively large. Direct runtime comparisons with MySQL suggest that the DNDKV is several times faster for reading but is slower for writing and updating the database. One limit of the technique is the elements being added must be within the range of the current *k*-vector tables. If this is not the case, the technique cannot be used and the *k*-vector tables must be rebuilt from scratch. [View Full Paper]

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AAS 18-295

SPACECRAFT SIX DEGREE OF FREEDOM OUTPUT FEEDBACK CONTROL BASED ON DUAL QUATERNION

Qingqing Dang,[*] Haichao Gui[†] and Shijie Xu[‡]

This paper investigates the observer-based output feedback control problem for the spacecraft in terms of dual quaternions. First, a coupled linear velocity and angular velocity observer, driven by the position and attitude (i.e., pose) measurements, is designed via the immersion and invariance (I&I) methodology. After dominating the cross terms in the pose dynamics induced by angular velocity by high-gain injection, the observer is shown to be exponentially convergent. An output-feedback pose tracking law is then derived by combining the proposed velocity observer and a full-state feedback proportional-derivative controller with proven separation principle. Finally, an asteroid hovering operation is simulated to demonstrate its effectiveness and application. [View Full Paper]

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AAS 18-299

HYBRID GRAVITY MODELS FOR KLEOPATRA, ITOKAWA, AND COMET 67P/C-G

Patrick T. Wittick[*] and Ryan P. Russell[†]

Future small body missions will benefit from improved gravity field and mass representations that benefit diverse disciplines like autonomous navigation, mission design, geophysical modeling, and guidance, navigation, and control (GNC). Here, a recently introduced hybrid gravity model is applied to several small bodies of interest with the intent of identifying efficient model constructions. The gravity model fits superposed point-mascon and spherical harmonic fields to a high-fidelity polyhedral model, resulting in reasonably fast and globally valid models. Many diverse models for each body are evaluated and optimized, minimizing runtime, field errors and memory footprints. Several Pareto-optimal models for each body are examined in detail and archived. Results indicate the performance of selected models exceeds that of polyhedral models of similar accuracies up to an order of magnitude in terms of execution time. Pareto-optimal hybrid models inherently provide memory-efficient discrete-element structures that can be fitted, in a similar way as conventional spherical harmonics fields, with in-situ spacecraft radiometric data. Estimated hybrid model mass distributions, such as those presented in this work, are likely to serve as good initial guesses for such fits, while they remain valid both internal and external to the circumscribing sphere. [View Full Paper]

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AAS 18-319

REAL TIME ADAPTIVE SHAPE RECONSTRUCTION FOR ASTEROID LANDING

Shankar Kulumani and Taeyoung Lee*

Knowledge of the shape of an asteroid is crucial for spacecraft operations. The standard method of determining the gravitational potential, through the use of a polyhedron potential model, is dependent on the shape model. Furthermore, accurate landing or low altitude operations requires accurate knowledge of the surface topology. The typical approach to shape determination requires an extensive "mapping" phase of the mission over which extensive measurements are collected and transmitted for Earth-based processing. Instead, we present an efficient method for estimating the shape of an asteroid in real time. Range measurements of the surface are used to incrementally correct an initial shape estimate according to Bayesian framework. Then, an optimal guidance scheme is proposed to control the vantage point of the range sensor to construct a more accurate model of the asteroid shape. This shape model is then used in a nonlinear controller to track a desired trajectory about the asteroid. This approach enables for an accurate shape determination around a potential landing site. We demonstrate this approach using several radar shape models of asteroids and provide a full dynamic simulation about asteroid 4769 Castalia.

[View Full Paper]

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AAS 18-320

PERTURBATION MAPS FOR A SPACECRAFT AROUND THE NEAR-EARTH ASTEROID (153591) 2001 SN_{263}

Diogo M. Sanchez[*] and Antonio F. B. A. Prado[†]

The Aster mission is the first Brazilian deep space mission. The target is the triple near-Earth Asteroid 2001 SN_{263}. In this work we use the method of the integral of the disturbing accelerations to generate perturbation maps of this system. These maps are used to find less disturbed regions in this asteroid system, and to provide the fuel consumption, in terms of delta-v, to keep a spacecraft as close as possible to a Keplerian orbit. The results of this work can be used for the planning of the Aster mission. [View Full Paper]

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AAS 18-375

SRP-BASED ORBIT CONTROL WITH APPLICATION TO SMALL BODY LANDING

Kenshiro Oguri[*] and Jay W. McMahon[†]

With appropriate control algorithms, solar radiation pressure (SRP) can be effectively utilized as a source of orbit control force around asteroids. In contrast to historical treatment of SRP as a disturbance at the weak gravity environment, the present paper finds active control of spacecraft attitude promising for orbit control. We develop an optimal control law for the SRP-based orbit control and demonstrates its effectiveness with numerical simulations on an asteroid landing scenario, which is inspired by a future small body exploration concept supported by NASA Innovative Advanced Concept (NIAC) program. The simulation results show the robustness of the control algorithms to possible disturbances, including the solar gravity, the irregular gravity field of the primary, and stochastic acceleration that can represent uncertainties in the dynamics modeling. [View Full Paper]

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AAS 18-402

DYNAMICS ANALYSIS OF HOPPING ROVERS ON IRREGULARLY-SHAPED SMALL BODIES

Xiangyu Li,[*] Amit K. Sanyal,[†] Rakesh R. Warier[‡] and Dong Qiao[§]

A hopping rover that is actuated by internal forces, is an ideal mobility approach for the exploration of small solar system bodies. The internal actuators are used to provide torques to rotate the hopper and the contact force on the surface will drive the hopper to hop from the asteroid. In this paper, the 3-D dynamics model of a hopping rover on an irregular-shaped small body is established based on a polyhedron model. The hopper is modeled as a cube with three reaction wheel actuators along three orthogonal body axes. The hopping dynamics model is developed in the asteroid-fixed frame. Initialization of a hop and determination of sliding behavior on the surface are analyzed. Then the orbital-attitude couple motion after hopping is calculated. Based on a model for the asteroid Bennu, the influence of surface coefficients, friction factors and other factors on hopping motions are discussed. Finally, the possibility of lift off from the surface of small bodies by hopping is studied. The simulations show that smaller surface stiffness coefficient will increase the hopping distance but the sliding will decrease it. Besides, the non-uniform gravity on the irregular-shaped small body will change the hopping direction. The 3-D dynamics model of a hopping rover can be applied to the preliminary analysis of the hopping motion in an irregular-shaped asteroid. Which provides a reference for future asteroid surface explorations.

[View Full Paper]

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AAS 18-416

PRELIMINARY INTERPLANETARY MISSION DESIGN AND NAVIGATION FOR THE DRAGONFLY NEW FRONTIERS MISSION CONCEPT

Christopher J. Scott,[*] Martin T. Ozimek,[*] Douglas S. Adams,[†] Ralph D. Lorenz,[‡] Shyam Bhaskaran,[§] Rodica Ionasescu,[**] Mark Jesick[**] and Frank E. Laipert[**]

Dragonfly is one of two mission concepts selected in December 2017 to advance into Phase A of NASA's New Frontiers competition. Dragonfly would address the Ocean Worlds mission theme by investigating Titan's habitability and prebiotic chemistry and searching for evidence of chemical biosignatures of past (or extant) life. A rotorcraft lander, Dragonfly would capitalize on Titan's dense atmosphere to enable mobility and sample materials from a variety of geologic settings. This paper describes Dragonfly's baseline mission design giving a complete picture of the inherent tradespace and outlines the design process from launch to atmospheric entry. [View Full Paper]

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AAS 18-448

AUTONOMOUS SWARMING FOR SIMULTANEOUS NAVIGATION AND ASTEROID CHARACTERIZATION

Nathan Stacey[*] and Simone D'Amico[†]

Completed asteroid missions have utilized a single spacecraft and depended extensively on ground-based systems for radiometric measurements, data analysis, and computation of estimation algorithms. In contrast, this paper describes an autonomous mission and estimation architecture to simultaneously navigate and estimate an asteroid's attitude, gravity field, and shape online. A swarm composed of a single main spacecraft and multiple nanosatellites in closed orbits about an asteroid take inter-satellite radiometric measurements while cooperatively tracking asteroid landmarks with optical sensors. This fully controllable swarm offers stereovision capabilities and a more geometrically diverse measurement set than a single, monolithic spacecraft. Measurements are also available for a longer period of time than autonomous asteroid characterization mission concepts in literature that use passive probes, which lack orbit control capabilities. All swarm measurements are combined in a novel unscented Kalman filter. The filter computation time is significantly reduced with no loss of accuracy by exploiting the matrix square root triangular structure and employing modified equinoctial elements for efficient numerical integration. High fidelity simulation is used to demonstrate the achievable navigation and asteroid characterization accuracy of the proposed mission and estimation concept. [View Full Paper]

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AAS 18-484

END OF THE ROAD: THE TESLA ROADSTER AS A KINETIC IMPACTOR FOR BINARY ASTEROID DEFLECTION

Thais C. Oliveira*

In this paper, the mechanics of deflecting binary asteroids is studied in the context of a particular case study. A similar version of the binary asteroid 65803 Didymos (1996 GT) is considered as the target of the AIDA mission. Our version of the Didymos orbit is modified such that our fictitious simulated version of Didymos collides with Earth. The optimized hypothetical maneuvers that are calculated and applied to the Tesla Roadster, launched by the Falcon Heavy launch vehicle, will cause the roadster to intercept our fictitious binary asteroid in a manner that prevents a collision with Earth. [View Full Paper]

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AAS 18-491

EUROPA LANDER TRAJECTORY DESIGN USING LISSAJOUS STAGING ORBITS

Ricardo L. Restrepo,[*] Ryan P. Russell[†] and Martin W. Lo[‡]

Lissajous orbits and approximation of their invariant manifolds are used to generate landing trajectories to the surface of Europa. Each lissajous is discretized into individual revolutions that each resemble a periodic orbit. The combined approximate unstable manifolds of the individual revolutions of a lissajous orbit generate more surface coverage than manifolds of simple libration point orbits such as halo or Lyapunov orbits. The stable manifolds propagated backwards in time from the individual lissajous revolutions provide direct connections to the last phase of a moon tour. The strategy developed produces ballistic landing trajectories with a wide surface coverage, and allows for the decoupling of the landing and moon tour phase by using the lissajous as an intermediate staging orbit. The multiple revolutions of the lissajous, multiple departure times along each revolution, and multiple quasi periodic options at each energy provide many degrees of freedom in the design process.

[View Full Paper]

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MISSION DESIGN FOR SPACECRAFT IN NEAR RECTILINEAR HALO ORBITS

Session Chairs:

Wednesday Session 7: Kathleen C. Howell, Purdue University

Co-Chair: Ryan Whitley, NASA, Diane Davis, a.i. solutions, Inc.

AAS 18-236

ANALYSIS OF NEAR RECTILINEAR HALO ORBIT INSERTION WITH A 40-KW SOLAR ELECTRIC PROPULSION SYSTEM

Steven L. McCarty,[*] Waldy K. Sjauw,[†] Laura M. Burke[†] and Melissa L. McGuire[‡]

This paper examines two low thrust insertion options for delivery of a 40-kW solar electric propulsion spacecraft to a Near Rectilinear Halo Orbit (NRHO). One option considered is a trans-lunar injection launch as a co-manifested payload on the Space Launch System. For this option, a reference trajectory is designed and a scan of launch dates is completed to understand the propellant mass sensitivity. A 15-day period cyclical variation in required propellant is observed that is attributed to solar gravity effects. A second option considered is to launch on a smaller commercial launch vehicle to a less energetic elliptical orbit and use SEP to spiral out to NRHO. For this option, analysis is completed to understand the trades between delivered mass to NRHO, total propellant required, time of flight, and solar array degradation. Results show that, while launching to lower altitudes can deliver greater payload mass to NRHO, significant solar array degradation can occur. In addition to a generic dataset that can be applied to any launch vehicle, spiral trajectory results are presented specific to launch on an Atlas V 551 and Falcon 9. [View Full Paper]

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AAS 18-289

DISPOSAL TRAJECTORIES FROM NEAR RECTILINEAR HALO ORBITS

Kenza K. Boudad,[*] Diane C. Davis[†] and Kathleen C. Howell[‡]

After completion of a resupply mission to NASA's proposed Lunar Orbital Platform – Gateway, safe disposal of the Logistics Module is required. One potential option is disposal to heliocentric space. This investigation includes an exploration of the trajectory escape dynamics from an Earth-Moon Near Rectilinear Halo Orbit (NRHO) and applies these insights to the design of a low-cost heliocentric Logistics Module disposal option. The effects of the solar gravitational perturbations are assessed in both the bicircular restricted 4-body problem and in an ephemeris force model. [View Full Paper]

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AAS 18-351

EXAMINING THE FEASIBILITY OF RELATIVE-ONLY NAVIGATION FOR CREWED MISSIONS TO NEAR RECTILINEAR HALO ORBITS

Michael J. Volle[*] and Diane C. Davis[†]

Recently, lunar Near Rectilinear Halo Orbits (NRHO) have been the focus of much study, and they have been selected as the target orbit for the Gateway mission, formerly the Deep Space Gateway. Also, the Deep Space Network (DSN) is increasingly congested and over-subscribed. In this work, the performance of relative-only navigation between a spacecraft in an NRHO and a relay in a Distant Retrograde Orbit is examined and compared to simulated DSN tracking using a Square Root Information Filter. Various tracking scenarios are examined using a closed-loop simulation where navigation errors inform maneuver planning and maneuver execution errors affect navigation performance. Results indicate that relative-only navigation can provide comparable levels of orbit determination error and orbit maintenance costs. [View Full Paper]

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AAS 18-388

STATIONKEEPING, ORBIT DETERMINATION, AND ATTITUDE CONTROL FOR SPACECRAFT IN NEAR RECTILINEAR HALO ORBITS

Clark P. Newman,[*] Diane C. Davis,[†] Ryan J. Whitley,[‡] Joseph R. Guinn[§] and Mark S. Ryne[**]

From a Near Rectilinear Halo Orbit (NRHO), NASA's Gateway at the Moon is planned to serve as a proving ground and a staging location for human missions beyond Earth. Stationkeeping, Orbit Determination (OD), and attitude control are examined for uncrewed and crewed Gateway configurations. Orbit maintenance costs are investigated using finite maneuvers, considering skipped maneuvers and perturbations. OD analysis assesses DSN tracking and identifies OD challenges associated with the NRHO and crewed operations. The Gateway attitude profile is simulated to determine an effective equilibrium attitude. Attitude control propellant use and sizing of the required passive attitude control system are assessed. [View Full Paper]

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AAS 18-406

EARTH-MOON NEAR RECTILINEAR HALO AND BUTTERFLY ORBITS FOR LUNAR SURFACE EXPLORATION

Ryan J. Whitley,[*] Diane C. Davis,[†] Laura M. Burke,[‡] Brian P. McCarthy,[§] Rolfe J. Power,[**] Melissa L. McGuire[††] and Kathleen C. Howell[‡‡]

NASA is planning the next phase of crewed spaceflight with a set of missions designed to establish a human-tended presence beyond low Earth orbit. The current investigation focuses on the staging post potential of cislunar infrastructure by seeking to maximize performance capabilities by optimizing transits in the lunar vicinity for both crewed and robotic spacecraft. In this paper, the current reference orbit for the cislunar architecture, known as a Near Rectilinear Halo Orbit (NRHO), is examined alongside the bifurcated L2 butterfly family for their use as a staging location to the lunar surface. [View Full Paper]

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AAS 18-421

ANALYSIS OF CISLUNAR TRANSFERS FROM A NEAR RECTILINEAR HALO ORBIT WITH HIGH POWER SOLAR ELECTRIC PROPULSION

Steven L. McCarty,[*] Laura M. Burke[†] and Melissa L. McGuire[‡]

This paper captures analysis completed in an effort to design efficient cislunar transfers of a massive spacecraft from an L2 Southern NRHO to a Distant Retrograde Orbit, L1 Northern NRHO, and Flat L2 Halo Orbit using low thrust Solar Electric Propulsion (SEP). For each transfer type, a reference transfer is designed for an assumed 39 t spacecraft with 26.6 kW SEP system. For each reference transfer, analysis is completed to understand the sensitivity of the transfer to changes in initial mass and SEP power and to identify the optimal number of thrusters to use for a given combination of mass and power. The outlined approach of characterizing a trajectory by the acceleration and required thrusting time is shown to be useful in understanding a wide range of mass and power combinations. In addition to showing the inverse relationship between spacecraft acceleration and propellant mass, the analysis shows that regions in the trade space exist where additional SEP power is not useful for reducing the required propellant. Further, regions are identified where operating more thrusters at a lower specific impulse requires less propellant than operating fewer at a higher specific impulse. [View Full Paper]

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INDEX

NUMERICAL INDEX*

VOLUME 167 I, II, III & IV

ADVANCES IN THE ASTRONAUTICAL SCIENCES, ASTRODYNAMICS 2018 (2019)

(AAS/AIAA Astrodynamics Specialist Conference, August 19–23, 2018, Snowbird, Utah, U.S.A.)

* Unless otherwise indicated all papers appear in Volume 167, *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 18-219 Wheel Cluster Formation for HEO Satellites — A Feasibility Study, Chia-Chun Chao (Part I)

AAS 18-220 The Effect of Differential Color Refraction on Short-Arc Estimation of the Area-to-Mass Ratio of Geostationary Objects Using Ground-Based Telescopes, Roman Geykhman and Kerri Cahoy (Part III)

AAS 18-221 Low-Energy Capture of Asteroids for the Logistic Support of Future Mars Missions, Minghu Tan, Colin McInnes and Matteo Ceriotti (Part IV)

AAS 18-222 Change of Inertia Tensor Due to a Severed Radial Boom for Spinning Spacecraft, Joseph E. Sedlak and Babak Vint (Part III)

AAS 18-223 Trajectory Optimization for Rendezvous with Bearing-Only Tracking, Xiaoyu Chu, Kyle T. Alfriend, Jingrui Zhang and Yao Zhang (Part I)

AAS 18-224 Fully-Coupled Spherical Modular Pendulum Model to Simulate Spacecraft Propellant Slosh, Paolo Cappuccio, Cody Allard and Hanspeter Schaub (Part I)

AAS 18-225 SmallSat Swarm Gravimetry: Revealing the Interior Structure of Asteroids and Comets, William Ledbetter, Rohan Sood and James Keane (Part IV)

AAS 18-226 The Evolution of Deep Space Navigation: 2006-2009, Lincoln J. Wood (Part IV)

AAS 18-227 Linear Analysis and Control of a Tethered System with Two Rigid End Bodies, Nickolas J. Sabey and Steven Tragesser (Part IV)

AAS 18-228 Methods for Passive Optical Detection and Relative Navigation for Rendezvous with a Non-Cooperative Object at Mars, Alan M. Didion, Austin K. Nicholas, Joseph E. Riedel, Robert J. Haw and Ryan C. Woolley (Part I)

AAS 18-229 Centroiding and Sizing Optimization of Ellipsoid Image Processing Using Nonlinear-Least Squares, Stoian Borissov and Daniele Mortari (Part IV)

AAS 18-230 Theory of Connections Applied to First-Order System of Ordinary Differential Equations Subject to Component Constraints, Daniele Mortari and Roberto Furfaro (Part IV)

AAS 18-231 Algorithms for Small Satellite Formation Initialization, Robert B. LaRue and Kirk W. Johnson (Part I)

AAS 18-232 Linearized Relative Orbital Motion Dynamics in a Rotating Second Degree and Order Gravity Field, Ethan R. Burnett and Eric A. Butcher (Part IV)

AAS 18-233 Comparison Between First and Second-Order Gauss's Variational Equations Under Impulsive Control, Gang Zhang and Daniele Mortari (Part I)

AAS 18-234 Not Assigned

AAS 18-235 Space Debris Field Removal Using Tether Momentum Exchange, Zachary D. Asher, Steven Tragesser, Christian Kneubel, Jennifer Hudson, Thomas H. Bradley and Ilya Kolmanovsky (Part III)

AAS 18-236 Analysis of Near Rectilinear Halo Orbit Insertion with a 40-kW Solar Electric Propulsion System, Steven L. McCarty, Waldy K. Sjauw, Laura M. Burke and Melissa L. McGuire (Part IV)

AAS 18-237 Not Assigned

AAS 18-238 A Consistent Small Body Navigation Filter Using Flash-Lidar Data and Bezier Triangles, Benjamin Bercovici and Jay W. McMahon (Part IV)

AAS 18-239 Immersion-and Invariance-Based Adaptive Control of Asteroid-Orbiting and -Hovering Spacecraft, Keum W. Lee and Sahjendra N. Singh (Part IV)

AAS 18-240 Not Assigned

AAS 18-241 Mission Design for the Exploration of Ice Giants, Kuiper Belt Objects and Their Moons Using Kilopower Electric Propulsion, Steven L. McCarty, Steven R. Oleson, Lee S. Mason and Marc A. Gibson (Part IV)

AAS 18-242 Not Assigned

AAS 18-243 Design of Interplanetary Trajectories with Multiple Synergetic Gravitational Assist Maneuvers Via Particle Swarm Optimization, Matthew J. Shaw and Robert G. Melton (Part II)

AAS 18-244 High Fidelity Collision Probabilities Estimated Using Brute Force Monte Carlo Simulations, Doyle T. Hall, Stephen J. Casali, Lauren C. Johnson, Brent B. Skrehart and Luis G. Baars (Part III)

AAS 18-245 Not Assigned

AAS 18-246 Enhanced Stationkeeping Maneuver Control Technique for Delta-V Cost Reduction in the Korea Pathfinder Lunar Orbiter, Diane C. Davis, Jae-ik Park, Sujin Choi, Ryan Whitley, John Carrico, Dong-Young Rew and Seok-Weon Choi (Part II)

AAS 18-247 Not Assigned

AAS 18-248 Analysis of the 3GM Gravity Experiment of ESA's JUICE Mission, Paolo Cappuccio, Mauro Di Benedetto, Gael Cascioli and Luciano Iess (Part IV)

AAS 18-249 SmallSat Navigation Via the Deep Space Network: Inner Solar System Missions, Jeffrey R. Stuart and Lincoln J. Wood (Part III)

AAS 18-250 MMS Extended Mission Design: Evaluation of a Lunar Gravity Assist Option, Trevor Williams, Dominic Godine, Eric Palmer, Ishaan Patel, Neil Ottenstein, Luke Winternitz and Steve Petrinec (Part II)

AAS 18-251 2018 Mars Insight Mission Design and Navigation Overview, Fernando Abilleira, Allen Halsell, Min-Kun Chung, Ken Fujii, Eric Gustafson, Yungsun Hahn, Julim Lee, Sarah Elizabeth McCandless, Neil Mottinger, Jill Seubert, Evgeniy Sklyanskiy and Mark Wallace (Part II)

AAS 18-252 Phobos Rotational Dynamics, James K. Miller and Gerald R. Hintz (Part I)

AAS 18-253 Robust Myopic Control for Systems with Imperfect Observations, Dantong Ge, Melkior Ornik and Ufuk Topcu (Part IV)

AAS 18-254 to -257 Not Assigned

AAS 18-258 A New Approach to Reliable Powered Descent Guidance Problem Using Convex Optimization, K. Echigo and T. Kubota (Part IV)

AAS 18-259 Evaluation of Optimal Control Techniques Used in Spacecraft Maneuver Planning, Christopher P. Lawler (Part II)

AAS 18-260 Low-Earth Orbit Determination Based on Atmospheric Drag Measurements, Rui Zhang, Fei Xu, Chao Han and Xiucong Sun (Part III)

AAS 18-261 Powered Aero-Gravity Assisted Maneuvers in Venus and Mars Changing the Bank Angle of the Spacecraft, Jhonathan O. Murcia P. and Antonio F. B. A. Prado (Part I)

AAS 18-262 Trajectory Analysis of a Spacecraft Making a Three-Dimensional Powered Swing-By Maneuver, A. F. S. Ferreira, R. V. Moraes, A. F. B. A. Prado and O. C. Winter (Part II)

AAS 18-263 Not Assigned

AAS 18-264 Exploration of Three-Dimensional Orbit Bifurcations in the CRTBP Using Cell Mapping, Dayung Koh, Rodney L. Anderson and Ivan Bermejo-Moreno (Part II)

AAS 18-265 to -266 Not Assigned

AAS 18-267 The Effect of Zonal Harmonics in the Circular Restricted Three Body Problem Near the Secondary Body, Luke Bury and Jay McMahon (Part I)

AAS 18-268 Q-Learning Algorithm for Path-Planning to Maneuver Through a Satellite Cluster, Xiaoyu Chu, Kyle T. Alfriend, Jingrui Zhang and Yao Zhang (Part III)

AAS 18-269 A Convex Optimization Approach to Mars Entry Trajectory Updating, Connor D. Noyes and Kenneth D. Mease (Part II)

AAS 18-270 Closed Loop Guidance Trade Study for Space Launch System Block-1B Vehicle, Naeem Ahmad, Matt Hawkins, Paul Von der Porten, Robin Pinson, Greg Dukeman and Thomas Fill (Part IV)

AAS 18-271 Arcus Mission Design: Stable Lunar-Resonant High Earth Orbit for X-Ray Astronomy, Laura Plice, Andres Dono Perez, Lisa Policastri, John Carrico and Mike Loucks (Part II)

AAS 18-272 Effect of Cross-Correlation of Orbital Error on Probability of Collision Determination, Stephen J. Casali, Doyle T. Hall, Daniel R. Snow, M. D. Hejduk, Lauren C. Johnson, Brent B. Skrehart and Luis G. Baars (Part III)

AAS 18-273 Linear Differential Equations Subject to Relative, Integral, and Infinite Constraints, Hunter Johnston and Daniele Mortari (Part IV)

AAS 18-274 IBEX Revisited: Operational Results for Long-Term Cislunar Orbit Propagation, John Carrico, Lisa Policastri and Stephen Lutz (Part I)

AAS 18-275 Not Available (Withdrawn)

AAS 18-276 Optimal Trajectories for a Dual-Spacecraft Outer Planet Mission, Hongwei Yang, Wei You, Shuang Li and Xiuqiang Jiang (Part II)

AAS 18-277 Mission Analysis for an ESA Contribution to the Mars Sample Return Campaign, Eric Joffre, Uwe Derz, Marie-Claire Perkinson, Jakob Huesing, Friederike Beyer and Jose-Manuel Sanchez Perez (Part II)

AAS 18-278 A Minimal Parameterization on Six D.O.F. Relative Orbital Motion Problem Using Dual Lie Algebra, Daniel Condurache (Part I)

AAS 18-279 Search for Stable Orbits Around 1999 KW4, Thais C. Oliveira and Antonio F. B. A. Prado (Part IV)

AAS 18-280 to -281 Not Available (Withdrawn)

AAS 18-282 The Theory of Connections Applied to Perturbed Lambert's Problem, Hunter Johnston and Daniele Mortari (Part II)

AAS 18-283 Applications of the Dynamic N-Dimensional K-Vector, Carl Leake, Javier Roa and Daniele Mortari (Part IV)

AAS 18-284 Not Available (Withdrawn)

AAS 18-285 Theory of the F-Radius Sphere Model, Daniele Mortari and Carl Leake (Part IV)

AAS 18-286 Not Assigned

AAS 18-287 Not Available (Withdrawn)

AAS 18-288 A Semi-Analytical Approach to Satellite Constellation Design for Regional Coverage, Hang Woon Lee, Koki Ho, Seiichi Shimizu and Shoji Yoshikawa (Part I)

AAS 18-289 Disposal Trajectories from Near Rectilinear Halo Orbits, Kenza K. Boudad, Diane C. Davis and Kathleen C. Howell (Part IV)

AAS 18-290 Integrated Guidance and Control for Pinpoint Mars Landing Using Reinforcement Learning, Brian Gaudet, Richard Linares and Roberto Furfaro (Part IV)

AAS 18-291 Analysis of Uncertainty Propagation in Mars Entry Using Non-Intrusive Polynomial Chaos, Xiuqiang Jiang and Shuang Li (Part IV)

AAS 18-292 Atmospheric Mass Density Calibration and its Application in LEO Object Orbit Prediction Using Angular Data from a Small-Telescope Array, Junyu Chen, Jizhang Sang, Zhenwei Li and Chengzhi Liu (Part III)

AAS 18-293 Trajectory Design for the Korea Pathfinder Lunar Orbiter (KPLO), Su-Jin Choi, Ryan Whitley, Gerald Condon, Mike Loucks, Jae-ik Park, Seok-Weon Choi and Se-Jin Kwon (Part II)

AAS 18-294 Not Available (Withdrawn)

AAS 18-295 Spacecraft Six Degree of Freedom Output Feedback Control Based on Dual Quaternion, Qingqing Dang, Haichao Gui and Shijie Xu (Part IV)

AAS 18-296 Statistical Approaches to Increase Efficiency of Large-Scale Monte-Carlo Simulations, David Shteinman, Thibaud Teil, Scott Dorrington, Huan Lin, Thomas Dixon, Hanspeter Schaub, John Carrico and Lisa Policastri (Part II)

AAS 18-297 Fuel-Optimal Control Method of Hovering Formation Initialization and Reconfiguration, Yinrui Rao, Huan Chen and Chao Han (Part IV)

AAS 18-298 Not Assigned

AAS 18-299 Hybrid Gravity Models for Kleopatra, Itokawa, and Comet 67P/C-G, Patrick T. Wittick and Ryan P. Russell (Part IV)

AAS 18-300 An Adaptive Nonsingular Terminal Sliding Mode Tracking Control Using Neural Networks for Space Manipulators Actuated by CMGs, Xinhui Xia, Yinghong Jia, Shijie Xu and Xinlong Wang (Part IV)

AAS 18-301 Orbit and Attitude Observability Using Accelerometer Measurements, David K. Geller and Rachit Bhatia (Part III)

AAS 18-302 Bilinearized Model-Based Discrete-Time Iterative Learning Control for Nonlinear Systems, Bing Song, Minh Q. Phan and Richard W. Longman (Part III)

AAS 18-303 Data-Driven Model-Free Iterative Learning Control Using Reinforcement Learning, Bing Song, Minh Q. Phan and Richard W. Longman (Part III)

AAS 18-304 Not Assigned

AAS 18-305 Development of Transient Basis Functions to Improve Basis Function Iterative Learning Control, Bowen Wang, Richard W. Longman and Minh Q. Phan (Part III)

AAS 18-306 to -307 Not Assigned

AAS 18-308 Closed-Form Optimal Impulsive Control of Spacecraft Formations Using Reachable Set Theory, Michelle Chernick and Simone D'Amico (Part IV)

AAS 18-309 Data-Driven Framework for Real-Time Thermospheric Density Estimation, Piyush M. Mehta and Richard Linares (Part I)

AAS 18-310 Two-Body Orbital Boundary Value Problems in Regularized Coordinates, Bharat Mahajan and Srinivas R. Vadali (Part II)

AAS 18-311 Not Assigned

AAS 18-312 State-Dependent Riccati Equation Control for Spacecraft Formation Flying in the Circular Restricted Three-Body Problem, Michael Tannous, Giovanni Franzini and Mario Innocenti (Part I)

AAS 18-313 On Novel Appointed-Time Inertia-Free Adaptive Attitude Control of Spacecraft, Caisheng Wei, Jianjun Luo and Kai Jin (Part III)

AAS 18-314 Trajectory Design for a Solar-Sail Mission to Asteroid 2016 HO_3 Jeannette Heiligers, Juan M. Fernandez, Olive R. Stohlman and W. Keats Wilkie (Part II)

AAS 18-315 The Extreme Behavior of the Simplest Form of Iterative Learning Control, Morgan T. Walker, Xiaoqiang Ji and Richard W. Longman (Part III)

AAS 18-316 Development and Laboratory Experimentation of a Magnetorquer Control System for CubeSat Using a Three-Axis Simulator, Guglielmo Cervettini, Hyeongjun Park, Dae Young Lee, Stefano Pastorelli and Marcello Romano (Part III)

AAS 18-317 to -318 Not Assigned

AAS 18-319 Real Time Adaptive Shape Reconstruction for Asteroid Landing, Shankar Kulumani and Taeyoung Lee (Part IV)

AAS 18-320 Perturbation Maps for a Spacecraft Around the Near-Earth Asteroid (153591) 2001 SN_{263}, Diogo M. Sanchez and Antonio F. B. A. Prado (Part IV)

AAS 18-321 Method of Characteristics Based Nonlinear Filter: Applications to Space Object Tracking, Nagavenkat Adurthi and Manoranjan Majji (Part I)

AAS 18-322 Spacecraft Rendezvous Guidance in Cluttered Environments Via Artificial Potential Functions and Reinforcement Learning, Brian Gaudet, Richard Linares and Roberto Furfaro (Part I)

AAS 18-323 Not Assigned

AAS 18-324 Concept of Operations for Earth-Moon Departures to Mars-Phobos Distant Retrograde Orbit Arrivals, Davide Conte and David B. Spencer (Part II)

AAS 18-325 Trajectory Design for LEO to Lunar Halo Orbits Using Manifold Theory and Fireworks Optimization, Davide Conte, Guanwei He, David B. Spencer and Robert G. Melton (Part II)

AAS 18-326 A Semi-Analytical Approach to Characterize the Relative Motion in the Vicinity of Phobos, Davide Conte and David B. Spencer (Part I)

AAS 18-327 Generalization Capability of Machine Learning Approach Among Different Satellites: Validated Using TLE Data, Hao Peng and Xiaoli Bai (Part III)

AAS 18-328 Obtain Confidence Interval for the Machine Learning Approach to Improve Orbit Prediction Accuracy, Hao Peng and Xiaoli Bai (Part III)

AAS 18-329 to -330 Not Assigned

AAS 18-331 A Hybrid Optimal Control Method for Time-Optimal Slewing Maneuvers of Flexible Spacecraft, Sandeep K. Singh, Ehsan Taheri and John L. Junkins (Part III)

AAS 18-332 Framework for Optimizing Many-Revolution Low-Thrust Transfers, Zubin P. Olikara (Part II)

AAS 18-333 Equilibria Associated with the Attitude Dynamics of a Rigid Body in Keplerian Motion, Roshan T. Eapen, Manoranjan Majji and Kyle T. Alfriend (Part III)

AAS 18-334 Good Performance Above a Feedback Control System Bandwidth Using a Partial Inverse Model Possibly Improved by ILC, Tianyi Zhang and Richard W. Longman (Part III)

AAS 18-335 Not Available (Withdrawn)

AAS 18-336 Streak Detection and Characterization in Ground-Based Optical Observations of Space Objects, N. Houtz and C. Frueh (Part III)

AAS 18-358 Prescribed Performance Control Strategies for Halo Orbit Spacecraft Rendezvous, Dandan Zheng Jianjun Luo, Caisheng Wei and Renyong Zhang (Part IV)

AAS 18-359 Optimal Motion Planning in Attitude Maneuver Using Non-Holonomic Turns for a Transformable Spacecraft, Kaoru Ohashi, Toshihiro Chujo and Junichiro Kawaguchi (Part III)

AAS 18-360 Not Assigned

AAS 18-361 Planar Orbit and Attitude Dynamics of an Earth-Orbiting Solar Sail Under J_2 and Atmospheric Drag Effects, Narcís Miguel and Camilla Colombo (Part I)

AAS 18-362 Least-Squares Solution of a Class of Optimal Space Guidance Problems Via Theory of Connections, Roberto Furfaro and Daniele Mortari (Part IV)

AAS 18-363 Deep Learning for Autonomous Lunar Landing, Roberto Furfaro, Ilaria Bloise, Marcello Orlandelli, Pierluigi Di Lizia, Francesco Topputo and Richard Linares (Part IV)

AAS 18-364 Low-Thrust Station-Keeping for an Elliptical Polar Lunar Orbit, Alexander J. Mazarr and David C. Folta (Part II)

AAS 18-365 Orbit Estimation Strategy for Low Earth Orbit and Geostationary Satellites, Abdulkadir Köker and Ozan Tekinalp (Part III)

AAS 18-366 Defining and Propagating Uncertainty on Regularized Manifolds, Lorraine M. Weis, Michael Mercurio, Christopher W. T. Roscoe, Matthew P. Wilkins and Paul W. Schumacher, Jr. (Part III)

AAS 18-367 Disturbance-Based High-Order Sliding Mode Observer-Based Control for Spacecraft High Accuracy Pointing, Divya Bhatia and Peter Hecker (Part III)

AAS 18-368 Not Assigned

AAS 18-369 Dynamics of Asymmetrical Motorized Momentum Exchange Tether by Kepler-Quaternion Method, YANG Yong, DU Qiuhua, LI Chao and QI Naiming (Part I)

AAS 18-370 An Ecliptic Perspective for Analytical Satellite Theories, Ioannis Gkolias, Martin Lara and Camilla Colombo

AAS 18-371 Information-Theoretic Sensor Scheduling Under Communication Constraints, Kirsten Tuggle and Maruthi Akella (Part IV)

AAS 18-372 Targeting Regions of Chaos in the GNSS Regime, Marielle M. Pellegrino and Daniel J. Scheeres (Part II)

AAS 18-373 Design of a Flexible, Scalable, and Extensible Cloud-Based Multi-Mission Flight Dynamics System, Rebecca Besser, Russell DeHart, Haisam Ido, Ryan Jim, Joseph Kaminsky, Craig Roberts, Jennifer Sager, Noah Williams, John Zarek, Eduardo Gurgel Do Amaral Valente and Dale Fink (Part I)

AAS 18-374 Navigation and Maneuver Requirements Determination for Elliptical Rendezvous Operation, Kai Jin, David Geller and Jianjun Luo (Part I)

AAS 18-375 SRP-Based Orbit Control with Application to Small Body Landing, Kenshiro Oguri and Jay W. McMahon (Part IV)

AAS 18-376 Disposal Design for Geosynchronous Satellites Revisited, Ioannis Gkolias and Camilla Colombo (Part II)

AAS 18-377 Physically-Constrained Inverse Optimal Control for Satellite Maneuver Detection, Richard Linares and Joseph B. Raquepas (Part III)

AAS 18-378 Not Assigned

AAS 18-420 Real-Time Angular Velocity Estimation of Non-Cooperative Space Objects Using Camera Measurements, Marcelino M. de Almeida, Renato Zanetti, Daniele Mortari and Maruthi Akella (Part I)

AAS 18-421 Analysis of Cislunar Transfers from a Near Rectilinear Halo Orbit with High Power Solar Electric Propulsion, Steven L. McCarty, Laura M. Burke and Melissa L. McGuire (Part IV)

AAS 18-422 Reorientation of Rigid Spacecraft Using Onboard Convex Optimization, Josep Virgili-Llop, Alanna Sharp and Marcello Romano (Part III)

AAS 18-423 Mars Ion and Sputtering Escape Network (MISEN) Mission Concept, Jeffrey S. Parker, Nathan Parrish, Rob Lillis, Shannon Curry, Dave Curtis, Janet Luhmann, Jordi Puig-Suari, Christopher Russell and David Brain (Part II)

AAS 18-424 Orbit Determination Using Vinti's Solution, Steven P. Wright and William E. Wiesel (Part III)

AAS 18-425 Sensor Tasking for Satellite Tracking Utilizing Observability Measures, Mitchel T. McDonald and Kamesh Subbarao (Part I)

AAS 18-426 Mean Values in Elliptic Motion: Averaging The Legendre Polynomials, Aaron J. Rosengren, Jeremy R. Correa and Daniel J. Scheeres (Part I)

AAS 18-427 Learning Capabilities of Neural Networks and Keplerian Dynamics, Damien Guého, Puneet Singla and Robert G. Melton (Part III)

AAS 18-428 Higher Order Polynomial Series Expansion for Uncertain Lambert Problem, Zach Hall and Puneet Singla (Part III)

AAS 18-429 Not Assigned

AAS 18-430 Analysis of a Threshold on Long-Term Orbital Collision Probability, Alan B. Jenkin, John P. McVey and Glenn E. Peterson (Part II)

AAS 18-431 Analytic Expressions for Derivatives from Series Solutions to the Three Body Problem, Nathan Strange (Part II)

AAS 18-432 to -433 Not Assigned

AAS 18-434 Orbital Maintenance for the Wide Field Infrared Survey Telescope: The Effects of Solar Radiation Pressure and Navigation Accuracies on Stationkeeping, Ariadna Farres, Cassandra Webster, Jennifer Donaldson and Dave Folta (Part II)

AAS 18-435 A High Order Filter for Estimation of Nonlinear Dynamic Systems, Taewook Lee, Puneet Singla and Manoranjan Majji (Part I)

AAS 18-436 Transfer from TLI to Lunar Polar Orbit Via Ballistic Lunar Capture, Anthony L. Genova and Brian Kaplinger (Part II)

AAS 18-437 Not Assigned

AAS 18-438 Uncertainty Quantification Using Non-Intrusive Generalized Polynomial Chaos Expansion for Orbital Debris Studies, Rajnish Bhusal and Kamesh Subbarao (Part II)

AAS 18-439 Assessing Measures to Reliably Predict Collisions in the Presence of Uncertainty, A. Burton, M. Zielinksi, C. Frueh, A. Mashiku and N. Memarsadeghi (Part III)

AAS 18-440 Multi-Target Tracking and Conjunction Assessment for Large Constellations, Nicholas Ravago and Brandon A. Jones (Part III)

AAS 18-441 A Light Curve Inversion Scheme for Artificial Objects, Siwei Fan and Carolin Frueh (Part III)

AAS 18-442 Robust Trajectory Optimization for Mars Atmospheric Entry Based on Uncertainty Propagation, Xiuqiang Jiang and Shuang Li (Part II)

AAS 18-443 Information Metrics for Observation-to-Track Association, Michael Mercurio, Eamonn J. Moyer, Matthew P. Wilkins, and Paul W. Schumacher Jr. (Part III)

AAS 18-444 Demonstration of a Propellantless Spacecraft Hopping Maneuver on a Planar Air Bearing Test Bed, Andrew R. Bradstreet, Josep Virgili-Llop and Marcello Romano (Part I)

AAS 18-445 Uncertainty Quantification for Mars Atmospheric Entry Using Modified Generalized Polynomial Chaos, Xiuqiang Jiang, Shuang Li and Roberto Furfaro (Part II)

AAS 18-446 Conjunction Analysis and Probability of Collision Using Relative Orbital Elements, Christopher T. Shelton and John L. Junkins (Part III)

AAS 18-447 RAAN-Agnostic 3-Burn Departure Methodology for Deep Space Missions from LEO Depots, Michel Loucks, Jonathan Goff, John Carrico and Brian Hardy (Part II)

AAS 18-448 Autonomous Swarming for Simultaneous Navigation and Asteroid Characterization, Nathan Stacey and Simone D'Amico (Part IV)

AAS 18-449 Covariance Matching Filter for IMU Error Estimation, Rahul Moghe, Renato Zanetti and Maruthi Akella (Part III)

AAS 18-450 Not Available (Withdrawn)

AAS 18-451 Multiple Hypothesis Tracking and Joint Probabilistic Data Association Filters for Multiple Space Object Tracking, Utkarsh R. Mishra, Nagavenkat Adurthi, Manoranjan Majji and Puneet Singla (Part III)

AAS 18-452 Not Available (Withdrawn)

AAS 18-453 LEO SSA at the SpOT Facility, Morgan Yost and Andrew Zizzi (Part III)

AAS 18-454 Not Available (Withdrawn)

AAS 18-455 Relative Equations of Motion Using a New Set of Orbital Elements, Pardhasai Chadalavada and Atri Dutta (Part I)

AAS 18-456 On the Solution to Every Lambert Problem, Ryan P. Russell (Part I)

AAS 18-457 Conceptual Design and Aerocapture Analysis for a Crew Transfer Vehicle for an Earth-Mars Cycler, Larissa Balestrero Machado, Markus Wilde, Brian D. Kaplinger and Robert W. Moses (Part II)

AAS 18-458 Not Assigned

AAS 18-459 Spacecraft Maneuver Detection Using Optimal Control Theory and Equations of Relative Motion, Atri Dutta and Joseph B. Raquepas (Part III)

AAS 18-460 Quasi-Hovering Formations in Elliptical Orbit, Huan Chen, Chao Han, Yinrui Rao and Jianfeng Yin (Part I)

AAS 18-461 Parallel Markov Chain Monte Carlo for Sensor Scheduling, Dilshad Raihan, Weston Faber, Suman Chakravorty and Islam Hussein (Part III)

AAS 18-462 Elliptical Orbit Proximity Operations Differential Games, Eric R. Prince, Joshuah A. Hess, Ryan W. Carr and Richard G. Cobb (Part II)

AAS 18-463 to -464 Not Available (Withdrawn)

AAS 18-465 Not Assigned

AAS 18-466 Not Available (Withdrawn)

AAS 18-467 A Piecewise-Constant Sundman Transformation for Spacecraft Trajectory Optimization, David Ottesen and Ryan P. Russell (Part II)

AAS 18-468 Angles-Only Navigation for Autonomous On-Orbit Space Situational Awareness Applications, Joshua Sullivan, T. Alan Lovell and Simone D'Amico (Part III)

AAS 18-469 Robust-Optimal Rule-Based Attitude Control of Spacecraft with a Partially-Filled Fuel Tank, Lilit Mazmanyan and Mohammad A. Ayoubi (Part III)

AAS 18-470 Not Assigned

AAS 18-471 An Optimization Formulation of Information Theoretic Sensor Tasking, Matthew J. Gualdoni and Kyle J. DeMars (Part III)

AAS 18-472 Precision Control of Microsatellite Swarms Using Plasmonic Force Propulsion, Pavel Galchenko and Henry Pernicka (Part I)

AAS 18-473 Not Assigned

AAS 18-474 First Order Approximation of the Effects of Solar Radiation Pressure on Relative Motion Using a Linearized Representation of Relative Orbital Elements, Hermann Kaptui Sipowa and Jay McMahon (Part I)

AAS 18-475 Not Available (Withdrawn)

AAS 18-476 A Six Degree-of-Freedom Spacecraft Dynamics Simulator for Formation Control Research, Yashwanth Kumar Nakka, Rebecca C. Foust, Elena Sorina Lupu, David B. Elliott, Irene S. Crowell, Soon-Jo Chung and Fred Y. Hadaegh (Part IV)

AAS 18-477 Laser Ranging to Unknown Objects for Initial Orbit Determination, A Feasibility Study, Mark L. Psiaki (Part III)

AAS 18-478 to -479 Not Available (Withdrawn)

AAS 18-480 Attitude Control of Spinning Solar Sails Based on Modal Analysis, Yuki Takao, Shota Kikuchi, Osamu Mori and Jun'ichiro Kawaguchi (Part III)

AAS 18-481 to -482 Not Assigned

AAS 18-483 Not Available (Withdrawn)

AAS 18-484 End of the Road: The Tesla Roadster as a Kinetic Impactor for Binary Asteroid Deflection, Thais C. Oliveira (Part IV)

AAS 18-485 Computational Guidance for Mars Entry and Power Descent, Xiuqiang Jiang, Shuang Li and Roberto Furfaro (Part IV)

AAS 18-486 Supersonic Retropropulsion on Robotic Mars Landers: Selected Design Trades, Aron A. Wolf, Connor Noyes, William Strauss, Joel Benito, Marcus Lobbia, John McCann, Barry Nakazono, Zachary R. Putnam, and Christopher G. Lorenz (Part I)

AAS 18-487 Morphing Hypersonic Waverider for Mars Entry, Jesse R. Maxwell (Part I)

AAS 18-488 Not Assigned

AAS 18-489 An Analytical 3D Shape-Based Algorithm Based on Orbits Interpolation for Multi-Revolutions Low-Thrust Trajectory Optimization with Eclipses and Perturbations, J. Prinetto and M. Lavagna (Part II)

AAS 18-490 Not Available

AAS 18-491 Europa Lander Trajectory Design Using Lissajous Staging Orbits, Ricardo L. Restrepo, Ryan P. Russell and Martin W. Lo (Part IV)

AAS 18-492 Extended Kalman Filtering in Burdet Coordinates, David Ciliberto, Puneet Singla and Manoranjan Majji (Part III)

AAS 18-493 to -500 Not Assigned

AUTHOR INDEX