ASTRODYNAMICS 2019

Front Cover Image:

STS092-368-003 (16 October 2000) — Tethered to Unity on the International Space Station (ISS), astronaut Michael López-Alegría prepares to snap a picture with a 35mm camera. A blanket of white clouds covers the part of Earth in the horizon scene beyond López-Alegría. This was the second of four STS-92 space walks for the crew and the first of two for López-Alegría. Credit: NASA photo.

ASTRODYNAMICS 2019

Volume 171

ADVANCES IN THE ASTRONAUTICAL SCIENCES

Edited by
Kenneth R. Horneman
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Brian W. Hansen
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Proceedings of the AAS/AIAA Astrodynamics Specialist Conference held August 11–15, 2019, Portland, Maine, U.S.A.

Published for the American Astronautical Society by
Univelt, Incorporated, P.O. Box 28130, San Diego, California 92198
Web Site: http://www.univelt.com

AAS Publications Office
P.O. Box 28130
San Diego, California 92198

Affiliated with the American Association for the Advancement of Science
Member of the International Astronautical Federation

First Printing 2020

Library of Congress Card No. 57-43769

ISSN 0065-3438

ISBN 978-0-87703-665-4 (Hard Cover Plus CD ROM)
ISBN 978-0-87703-666-1 (Digital Version)

Published for the American Astronautical Society
by Univelt, Incorporated, P.O. Box 28130, San Diego, California 92198
Web Site: http://www.univelt.com

Printed and Bound in the U.S.A.

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 2019, Volume 171, Advances in the Astronautical Sciences, consists of four parts totaling about 4,600 pages, plus a CD ROM/digital format version which also contains all the available papers. A chronological index by AAS paper number, 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 2019 appears as Volume 171, *Advances in the Astronautical Sciences*. This publication presents the complete proceedings of the AAS/AIAA Astrodynamics Specialist Conference 2019.

Astrodynamics 2018, Volume 167, Advances in the Astronautical Sciences, Eds. P. Singla et al., 3988p, four parts plus a CD ROM Supplement.

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 2019, Volume 168, *Advances in the Astronautical Sciences*, Eds. F. Topputo et al., 4388p., four parts, plus a CD ROM supplement.

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 2019 Astrodynamics Specialist Conference was held at the Westin in Portland, ME from August 11–15, 2019. 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. Registered attendance was 346 professionals (including 110 students and 11 retirees); attendees included engineers, scientists, and mathematicians representing government agencies, the military services, industry, and academia from the United States and abroad.

A total of 343 abstracts were submitted for the conference and finally, 277 technical papers were presented in 28 sessions on topics related to space-flight mechanics and astrodynamics. There were four special sessions:

- Artificial Intelligence in Astrodynamics I – Machine Learning
- Artificial Intelligence in Astrodynamics II – Reinforcement Learning
- GTOC - X (Global Trajectory Optimization Competition)
- NASA CARA CA Requirements Development Initiative

As the conference was held less than a month after the 50th anniversary of the Apollo XI moon landing, the guest speaker for the social off-site event was Michael López-Alegría, veteran of three space shuttle missions and one International Space Station mission. Also, special commemorative patches and stickers were designed and provided to all attendees.

Other special events for the conference included the Dirk Brouwer Award Plenary lecture by Dr. Martin Lo of the Mission Design & Navigation Section, Outer Planets Mission Analysis Group, Jet Propulsion Laboratory, California Institute of Technology, on the topic of *The Interplanetary Superhighway for the Development of the Earth's Neighborhood.* In addition to the plenary talk, the Breakwell Student Award was presented, and a special award was presented to Professor Kathleen Howell, Purdue University honoring her service as the editor-in-chief of the Journal of the Astronautical Sciences. Also recognized was one new AAS fellow: Professor Panagiotis Tsiotras, Professor and David and Andrew Lewis Chair, Guggenheim School of Aerospace Engineering, Associate Director, Institute for Robotics and Intelligent Machines, Georgia Institute of Technology.

The editors extend their gratitude to all the Session Chairs who ensured the smooth organization of all sessions: Ossama Abdelkhalik, Kyle T. Alfriend, Juan Arrieta, Natasha Bosanac, Angela Bowes, John Christian, Fabio Curti, Simone D'Amico, Diane Davis, Atri Dutta, Roberto Furfaro, Pradipto Ghosh, Brian Gunter, Yanping Guo, Matthew Hejduk, Siamak Hesar, Kenneth Horneman, Jennifer Hudson, Peter Lai, David Lujan, Alinda Mashiku, Craig McLaughlin, Anastassios Petropoulos, Anil Rao, Puneet Singla, Alex Sizemore, Rohan Sood, David B. Spencer, Jeffrey Stuart, Matthew Wilkins, and Roby Wilson.

Our gratitude also goes to Jim Way and the Web Administration Sub-committee for their support and assistance in the successful organization of this conference. We also extend our gratitude to the Westin staff, for their diligence and commitment to excellence both during the organization and execution of this event.

Dr. Islam I. Hussein **AAS Technical Chair**	**Dr. Christopher Scott** **AAS General Chair**
Dr. Kenneth R. Horneman **AIAA Technical Chair**	**Mr. Brian W. Hansen** **AIAA General Chair**

CONTENTS

Part III

Part IV

SPECIAL SESSION – NASA CARA CA REQUIREMENTS DEVELOPMENT INITIATIVE

EARTH ORBITAL AND PLANETARY MISSIONS

Session Chair:

Earth Orbital and Planetary Missions:
Kyle T. Alfriend, Texas A&M University

AAS 19-613

IMPULSIVE LEAST-SQUARES ORBIT MAINTENANCE USING GAUSS'S VARIATIONAL EQUATIONS

Gang Zhang* and Daniele Mortari†

Based on the Gauss's Variational Equations (GVEs), the least-squares approach is investigated in orbit transfer problems to estimate impulsive orbital-element corrections. Both single impulse and multiple impulses are considered using the 1st-order and 2nd-order integral-form of GVEs. For the single impulse, a nonlinear least-squares iteration method for the minimum error is provided to simultaneously solve impulse vector and impulse position. For the multiple impulses, a least-squares method for the minimum impulse cost is proposed to solve the three-impulse and two-impulse corrections for the in-plane and out-of-plane orbital elements, respectively. The impulse positions are analytically derived, and impulse vectors are obtained by the least-squares method. Numerical examples are provided to verify the proposed least-squares single-impulse and multiple-impulse methods.

[View Full File]

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AAS 19-649

OPTICAL METHODS FOR FINDING NEW NATURAL SATELLITES OF THE SOLAR SYSTEM'S OUTER PLANETS

Paul McKee,[*] William Parker[†] and John Christian[‡]

The distribution of orbits of the natural satellites (moons) around the outer planets offers important clues about the dynamical history of our Solar System. It is necessary, therefore, that we construct image acquisition strategies and data processing techniques that allow us to find new moons in a systematic way. Given the great distance between Earth and the outer planets, there are advantages to searching for moons --- especially very small moons --- with a spacecraft operating in the vicinity of the planet. In this paper we present an image processing technique based on the Radon Transform that can automatically find an unknown (new) moon in a sequence of images collected by an exploration spacecraft.

[View Full Paper]

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SOLAR RADIATION PRESSURE EFFECTS ON THE ORBITAL MOTION AT SEL2 FOR THE JAMES WEBB SPACE TELESCOPE

Ariadna Farres[*] and Jeremy Petersen[†]

Due to James Webb Space Telescope's large sunshield, which will always be facing the Sun to protect the observatory's instruments, Solar Radiation Pressure (SRP) has an important effect on its orbital motion around the Sun-Earth L2. Moreover, SRP is highly dependent on the observatory's attitude with respect to the Sun-observatory line. This paper explores the impact of SRP for different attitude profiles on the size of a reference orbit.

[View Full Paper]

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OPTIMAL DEORBIT FROM LOW EARTH ORBIT WITH ELECTRIC PROPULSION

Nathan L. Parrish,[*] Jeffrey S. Parker,[†] Cameron Meek[‡] and Aurelie Heritier[§]

As more and more spacecraft use the low Earth orbit (LEO) regime, it is critical that all players act responsibly and deorbit at end-of-life. Here, we analyze approaches to minimize the time to deorbit. Key parameters are identified and described, considering constraints on fuel budget and thrust limitations from eclipses. A simple and effective general strategy for deorbit is identified. The OneWeb internet constellation is used as an example for finding the optimal parameters. The objective of the deorbit strategy is to ensure safety for every vehicle in nearby orbits, while deorbiting quickly within propellant and operational constraints.

[View Full Paper]

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A SURVEY OF MISSION OPPORTUNITIES TO TRANS NEPTUNIAN OBJECTS, PART VI: A SEARCH FOR MULTI-TARGET MISSIONS

Daniel Johnson,[*] Zackery Crum,[*] Garrett Mitchell,[*] Samuel Walters,[*] Adam Dalton,[*] Brandon Davis,[*] Ben Dolmovich,[*] Meghan Green,[*] Amanda Williams,[*] Gerald Wise[*] and James Evans Lyne[†]

In the outermost reaches of the Solar System, beyond the orbit of Neptune, there lies a vast collection of unexplored bodies. This abundance of potential destinations (over 3000 as of 2019), affords the opportunity for missions with multiple targets. The present study describes the results of a search for such opportunities. The most favorable case found using a single probe is a Huya-Quaoar flyby mission, departing Earth in late 2027 with a departure C3 of 90.5 km2/s2. If launched two years earlier, a delta V Earth gravity assist could decrease the departure C3 to approximately 29 km2/s2. Both scenarios use Jupiter flybys to gain energy and lower propulsive requirements, and in both cases the periapse at Jupiter is greater than 16 Jovian radii, yielding an acceptably low radiation dose.

[View Full Paper]

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AAS 19-753

EXTENDED PHASE-SPACE REALIZATION FOR ATTITUDE DYNAMICS OF AN AXISYMMETRIC BODY IN ECCENTRIC ORBIT

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

This paper investigates the attitude dynamics of a rigid axisymmetric body in an eccentric orbit using a Hamiltonian formulation in the Serret-Andoyer variables. This is formulated using the extended phase-space, wherein the time-like variable arising from the eccentric nature of the orbit is treated as a coordinate. The gravity-gradient potential is modeled as a perturbation for averaging using a Lieseries method. Two formulations are developed to treat the case of a fast-rotating and slow-rotating body in an eccentric orbit, respectively. Analytical investigations lead to identifying resonant commensurabilities and relative equilibria in the slow-rotating rigid body problem.

[View Full Paper]

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DEEP SPACE ATOMIC CLOCK MISSION OVERVIEW

Todd A. Ely,[*] Jill Seubert,[†] John Prestage,[‡] Robert Tjoelker,[§] Eric Burt,[**] Angela Dorsey,[††] Daphna Enzer,[‡‡] Randy Herrera,[§§] Da Kuang,[***] David Murphy,[†††] David Robison,[‡‡‡] Gabrielle Seal,[§§§] Jeff Stuart[****] and Rabi Wang[††††]

The Deep Space Atomic Clock (DSAC), a NASA Technology Demonstration Mission (TDM), was launched on June 25, 2019 into low Earth orbit. The mission plan is to conduct a yearlong demonstration of a mercury ion ($^{199}Hg^{+}$) atomic clock to characterize its space-based performance, and to validate its utility for deep space navigation and radio science. This work will briefly review the DSAC technology and its benefits for deep space navigation and science then describe the DSAC mission's operational concepts, methods, and, finally, anticipated results.

[View Full Paper]

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OPTIMIZATION OF LOW THRUST TRANSFER ORBITS OF A SPACECRAFT CONSIDERING THE RADIATION HAZARD FROM THE VAN ALLEN BELTS

Rodrigo N. Schmitt,* Alexander Sukhanov,†
Antonio F. B. A. Prado‡ and Gerson Barbosa§

The goal of this work is to measure the amount of radiation a spacecraft receives once it leaves the sphere of influence of Earth in a Low Thrust Orbit (LTO). The spacecraft crosses the Van Allen belts many times during the transfer, in which particles such as protons and electrons can damage the onboard electronic equipment. Through mathematically modeling of the density of particles from the belt in space, it was possible to integrate it in time and compute the total dose of radiation absorbed by the spacecraft according to the chosen trajectory. Therefore, different trajectories were computed varying in eccentricity and type of propulsion system, which gave the following final parameters of interest: mission duration, fuel consumption, time in Van Allen belts and total fluence of radiation absorbed. Using an optimization algorithm, thousands of trajectories were tested and the best ones with respect to the final parameters were given as a table of results.

[View Full Paper]

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VEHICLE AND MISSION DESIGN OPTIONS FOR VERY LOW EARTH ORBIT CUBESATS

James W. Williams,* Michael I. Gray† and Zachary R. Putnam‡

Aerodynamics provide a small but significant effect on the dynamics of vehicles operating in low Earth orbit, especially CubeSats with limited control authority. Current analysis tools treat the translational and attitude dynamics of these vehicles in a decoupled sense. A coupling of these effects provides a more holistic view of the problem. In this work, various control system and physical properties of CubeSats are compared based on metrics of detumble time, total mission lifetime, and ram-pointing effectiveness. The control systems used are a magnetorquer with either a simplified Bcross detumble algorithm or a Quaternion Rate Feedback (QRF) pointing algorithm, or a set of reaction wheels using QRF. The physical properties examined are the total available control effort, the initial apoapsis of the orbit, the duty cycle of the control system, and the percent of eclipse in which control is active. Results indicate that a vehicle equipped with the Bcross algorithm will have limited pointing performance which limits the mission lifetime, while reaction wheels using QRF are capable of asymptotic stability around the ram direction, and magnetorquers using the same algorithm are able to provide nearly the same total mission duration, at a cost of worse pointing acquisition time.

[View Full Paper]

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STABLE LOW ALTITUDE LUNAR PERIODIC ORBITS USING THE GRAIL GRAVITY FIELD

Sean McArdle[*] and Ryan P. Russell[†]

Families of lunar periodic orbits are found in unaveraged dynamics using gravitational effects from Earth and a nonspherical lunar gravity field. This study revisits a periodic orbit search predating the GRAIL mission, now incorporating a higher fidelity gravity field with improvements to far side resolution. New differential correction equations are derived to account for generic plane crossings that can be useful for a variety of applications. These equations are used in conjunction with natural parameter continuation to drive periodic orbit family searches. The resulting repeat ground track solutions represent high fidelity lunar frozen orbits. The solver leverages parallelized high performance computing to account for the significant computational burden of the large spherical harmonics model. This study confirms the presence of stable periodic orbit families using the GRAIL derived gravity field. Stable orbits are found with perilune altitudes that start roughly 1000 km from the Moon's mean radius and are followed to impact trajectories. Stable, low eccentricity, periodic orbits that remain below 100 km altitude with inclinations near 85 deg are identified as ideal stationkeeping destinations for human spaceflight's return to the Moon.

[View Full Paper]

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GUIDANCE, NAVIGATION AND CONTROL

Session Chairs:

Guidance, Navigation and Control I: Anil Rao, University of Florida

Guidance, Navigation and Control II: Peter Lai, NASA Jet Propulsion Laboratory

GENERALIZED COMPOSITE NONCERTAINTY-EQUIVALENCE ADAPTIVE CONTROL OF ORBITING SPACECRAFT IN VICINITY OF ASTEROID

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

The paper presents composite noncertainty-equivalence adaptive control (NCEA) systems for the closed orbit and hovering control of spacecraft in the vicinity of a uniformly rotating asteroid. In this study, the mass and moment of inertia matrix of the asteroid, and the mass of the spacecraft are treated as unknown constant parameters. The objective is to control the orbit of the spacecraft despite uncertainties in gravitational force of asteroid. For the trajectory control of spacecraft, first a generalized composite noncertainty-equivalence adaptive (NCEA) control system - based on the immersion and invariance theory - is developed. This system consists of a control module for stabilization and an identifier for the estimation of parameters. The identifier includes a dynamic integral type parameter adaptation law, which is formed by combining the update laws of the NCEA system, gradient algorithm-based identification scheme, and the classical certainty-equivalence adaptive system. The classical component of the composite update law is used to cancel certain sign-indefinite function in the derivative of a Lyapunov function. The full estimate of each unknown parameter is the sum of an algebraic function and a signal generated by the composite integral type adaptation law. The gradient algorithm-based update rule is a function of estimation model error. Then by a proper choice of adaptation gains of the generalized control system, two additional composite control systems - (i) a NCEA system with gradient algorithm-based adaptation law, and (ii) a NCEA controller with classical update law – are derived. By the Lyapunov analysis, it is shown that in each composite closed-loop system, trajectory tracking error asymptotically converges to zero, and that the system trajectories converge to certain attractive manifold in the state space. The attractive manifold of the composite systems with gradient scheme is a subset of the attractive manifold of the NCEA system and also of the composite system with classical adaptation. Numerical results are presented which show that robust orbit control of spacecraft around 433 Eros and also hovering control in vicinity of Ida are accomplished despite parameter uncertainties and perturbing disturbance forces on the spacecraft.

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AAS 19-645

CHARACTERIZATION OF CANDIDATE VEHICLE STATES FOR XNAV SYSTEMS

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

This paper presents the framework for finding intersections of an infinite set of wavefronts from pulsars in 2D. The conditions for an intersection to exist are shown along with a numeric scheme for rapidly determining intersection feasibility. The numeric scheme reduces the dimensionality of the problem by one resulting in a much more computationally efficient solution. Using this algorithm the candidate intersections for 3, 4, or 5 pulsars is found for a phase tolerance between 10^{-3} and 10^{-5}. It was found that to minimize the number of candidate positions within a given domain it is more beneficial to increase the number of pulsars observed rather than decrease the measurement uncertainty. An additional solution is found analytically by solving the mixed-integer math problem. However, this solution does not incorporate any measurement error and there is no way to know how many function evaluations are required to find all solutions within a domain.

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SUN SEARCH DESIGN FOR THE PSYCHE SPACECRAFT

Daniel Cervantes,[*] Peter C Lai,[†] Alex Manka,[‡]
Aditi Ratnaparkhi[§] and Eric Turner[**]

Psyche is a scientific mission to explore the large asteroid (16) Psyche that orbits the Sun at ~3 AU. Managed by JPL, it is the first instance of Maxar's product line of geosynchronous communication satellites being repurposed for deep space. This paper presents the design of a unique sun sensor configuration for Safe Mode of the spacecraft. It enables quick, robust, and propellant-efficient safing while leveraging sensors, avionics, and algorithms that have extensive, flight-proven heritages.

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THE EVOLUTION OF DEEP SPACE NAVIGATION: 2009-2012*

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 sixth in a chronological sequence dealing with the evolution of deep space navigation. The time interval covered extends from 2009 to 2012. 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 11 planetary missions.

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MULTI-SENSOR MANAGEMENT UNDER INFORMATION CONSTRAINTS

Kirsten Tuggle[*] and Maruthi Akella[†]

Many emerging applications in astronautics such as space situational awareness are witnessing a significant increase in the need for operating autonomously and adaptively as well the configurability of rapid, real-time, plug-and-play sensing systems supporting these operations. Even though most applications also enjoy increased computational power, the underlying guidance, navigation, and control tasks can quickly overwhelm the ability to process them as the problem complexity increases over time and/or degrees of freedom. The current work offers an efficient algorithm for an information-penalized Linear Quadratic Gaussian (LQG) problem in the absence of process noise when selections must be made among multiple sensors at each time-step. This algorithm in particular selects among sensor sets over each time-step in a manner that efficiently approximates the effects of accepting or rejecting each measurement on the bases of both the underlying control problem and the specific amount of information entering the system. As a result, this work is suitable for a wide range of applications including those seeking to limit sensor use for communications as well as operational reasons.

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AAS 19-687

A FRAMEWORK FOR SCALING IN FILTERING AND LINEAR COVARIANCE ANALYSIS

Christopher D'Souza,[*] Renato Zanetti[†] and David Woffinden[‡]

Scaling is used extensively for numerical optimization and trajectory optimization. Its use in the estimation community is almost nonexistent. This paper creates the framework for practical scaling in space navigation, in general, and linear covariance analysis, in particular.

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FUEL-EFFICIENT POWERED DESCENT GUIDANCE ON PLANETARY BODIES VIA THEORY OF FUNCTIONAL CONNECTIONS 1: SOLUTION OF THE EQUATIONS OF MOTION

Enrico Schiassi,[*] Roberto Furfaro,[†] Hunter Johnston[‡] and Daniele Mortari[§]

We present a new approach to solving fuel-efficient powered descent guidance problems using the recently developed Theory of Functional Connections. The algorithm is designed to solve the non-linear Two-Point Boundary Value Problem arising from the application of the Pontryagin minimum principle via Chebyshev polynomials expansion of the boundary conditions-free and iterative least-squares method. The proposed algorithm follows under the category of indirect methods for optimal control problems, and it is demonstrated to be fast and accurate, thus potentially suitable for on-board implementation to generate optimal trajectories in real-time. The focus of this paper is on the solution of the equations of motion for the fuel-efficient powered descent guidance via Theory of Functional Connections. We have succeeded in getting solutions at machine error accuracy with just a few iterations, but still suboptimal as the transversality condition for the free-time problem is not yet met.

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PRELIMINARY SURFACE NAVIGATION ANALYSIS FOR THE DRAGONFLY MISSION

Ben Schilling,[*] Benjamin Villac[†] and Douglas Adams[‡]

On June 27, 2019, Dragonfly was selected to advance to Phase B as part of NASA's New Horizons 4 program. The mission will investigate Titan's habitability and prebiotic chemistry in situ. Leveraging the weak gravity and dense atmosphere of Titan, the proposed MMRTG-powered octocopter enables exploration of widespread locations, offering an immense impact on both the extent of the science campaign as well as a precedent for future surface exploration. This paper highlights preliminary surface navigation analysis conducted during the Phase A concept study, focusing on the day-in-the-life traverse flight navigation.

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AAS 19-726

CHANGO: A SOFTWARE TOOL FOR BOOST STAGE GUIDANCE OF THE SPACE LAUNCH SYSTEM EXPLORATION MISSION 1

Matt Hawkins,[*] Naeem Ahmad[†] and Paul Von der Porten[‡]

The Space Launch System (SLS) Exploration Mission 1 (EM-1) test flight will use open-loop guidance for Boost Stage (BS) flight. A table of attitude commands as a function of altitude, called the chi table, will be loaded onto the flight computers. The chi table will be generated using the measured winds on launch day by the Chi Angle Optimizer (CHANGO) software tool. Details of CHANGO's design are given, including a Three Degrees-of-Freedom (3-DOF) simulation and a numerical minimization routine. CHANGO's use in launch day operations is also described.

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AN ANALYSIS OF THE THEORY OF FUNCTIONAL CONNECTIONS SUBJECT TO INEQUALITY CONSTRAINTS

Hunter Johnston,[*] Carl Leake[†] and Daniele Mortari[‡]

The Theory of Functional Connections is a powerful mathematical framework deriving *constrained expressions*. These expressions allow to transform constrained optimization problems into unconstrained problems. Until now, the Theory of Functional Connections framework only included equality constraints, that is, constraints defined at specific values of the independent variables. This paper shows how to extend this theory to problems subject to inequality constraints for one-and two-dimensions. These kind of constraints appear in a large variety of areas including path planning and optimal control. In addition, this paper shows how to write constrained expressions for problems that have both equality and inequality constraints. In addition to the derivation of the constrained expression, a selected set of simple numerical examples are included.

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AN EXPLANATION AND IMPLEMENTATION OF MULTIVARIATE THEORY OF FUNCTIONAL CONNECTIONS VIA EXAMPLES

Carl Leake[*] and Daniele Mortari[†]

The Univariate Theory of Functional Connections (TFC) is a powerful mathematical framework that transforms constrained one-dimensional problems into unconstrained one-dimensional problems. This reduces the whole space of functions to just the space of functions satisfying the constraints. Univariate TFC has found multiple useful applications; the most notable is solving ordinary differential equations by least-squares. Recently, the theory has been extended to the n-dimensional case. The resultant Multivariate TFC extends the number of existing applications. One straightforward and important new application is in solving partial differential equations by least-squares. This paper explains Multivariate TFC in detail, and provides simple examples to clarify the theory as well as show how it can be implemented.

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LINEAR COVARIANCE ANALYSIS OF CLOSED-LOOP ATTITUDE DETERMINATION AND CONTROL SYSTEM OF SUB-ARCSEC POINTING THREE-AXES SPACECRAFT

Divya Bhatia*

Error analysis is indispensable, specifically for missions requiring stringent system performances. In this paper linear covariance techniques are employed for the error analysis of the closed-loop Attitude Determination and Control System (ADCS) of a three-axes spacecraft of a DLR future mission named 'InfraRed Astronomy Satellite Swarm Interferometer' with a sub-arcsec pointing requirement. Components of its closed-loop ADCS includes a Multiplicative Kalman Filter which fuses the measurements from a three-axes rate-integrating gyroscope and a star tracker; a sliding mode controller that provides robust control in the presence of external disturbances like the gravity-gradient torque, the solar radiation pressure torque and a random disturbance torque; and reaction wheels for the spacecraft actuation. Various sources of errors include the gyro errors and the misalignments, the control bias and the wheel misalignments, external disturbance torques, a suboptimal filter with model replacement and a sliding mode controller that utilizes a saturation function. A dimensionally large state vector of the true state vector and the navigation state vector is created owing to their coupled dynamics which results in a linear time-varying model of the entire closed-loop system. Associated closed loop covariance analysis equations are formulated to determine the variances of the true and the expected attitude estimation errors, variances of the true pointing errors of the closed-loop system and the variances of the required control effort. These results are verified by the nonlinear Monte Carlo simulations. The implementation substantiates the claim that the linear covariance analysis is a useful tool for fast analysis of a closed-loop ADCS.

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SUN-AVOIDANCE SLEW PLANNING ALGORITHM WITH POINTING AND ACTUATOR CONSTRAINTS

Mohammad Ayoubi* and Junette Hsin†

This paper presents a geometric approach for a sun (or any bright object) avoidance slew maneuver with pointing and actuator constraints. We assume that a gyrostat has a single light-sensitive payload with control-torque and reaction wheels' angular momentum constraints. Furthermore, we assume that the initial and final attitudes, instrument's line-of-sight (LOS) vector, and sun vector are known. Then we use Pontryagin's minimum principle (PMP) and derive the desired or target-frame quaternions, angular velocity and acceleration. In the end, a Monte Carlo simulation is performed to show the viability of the proposed algorithm with control-torque and angular momentum constraints.

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AAS 19-804

ANALYTICAL STATE TRANSITION MATRIX FOR DUAL-QUATERNIONS FOR SPACECRAFT POSE ESTIMATION

Andrew M. S. Goodyear,[*] Puneet Singla[†] and David B. Spencer[‡]

An analytical expression for a state transition matrix (STM) is preferable to numerical integration of the STM for real-time estimation of spacecraft pose. With a discrete STM for a dual quaternion state vector, the dual quaternion error covariance can be propagated analytically between two measurement time intervals. This work provides two analytic solutions for a dual quaternion STM, dual quaternion error STM, and discrete process noise covariance matrices. These state transition matrices are utilized to compute innovation terms in the update part of the EKF. Numerical simulations show that the STM agree with the numerically integrated dual quaternion kinematics, and the STM are also demonstrated to be viable for EKF development.

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ADAPTIVE AND DYNAMICALLY CONSTRAINED PROCESS NOISE ESTIMATION FOR ORBIT DETERMINATION

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

This paper introduces two new algorithms to accurately estimate Kalman filter process noise online for robust orbit determination in the presence of dynamics model uncertainties. Common orbit determination process noise techniques, such as state noise compensation and dynamic model compensation, require offline tuning and a priori knowledge of the dynamical environment. Alternatively, the process noise covariance may be estimated through adaptive filtering. However, current adaptive filtering techniques often use ad hoc methods to ensure the estimated process noise covariance is positive semi-definite, and cannot accurately extrapolate over measurement outages. Furthermore, adaptive filtering techniques do not constrain the discrete time process noise covariance according to the underlying continuous time dynamical model, and there has been limited work on adaptive filtering with colored process noise. To overcome these limitations, a novel approach is developed which optimally fuses state noise compensation and dynamic model compensation with covariance matching adaptive filtering. The adaptability of the proposed algorithms is a significant advantage over state noise compensation and dynamic model compensation. In contrast to existing adaptive filtering approaches, the new techniques are able to accurately extrapolate the discrete time process noise covariance over gaps in measurements. Additionally, the proposed algorithms are more accurate and robust than covariance matching, which is demonstrated through two case studies: an illustrative example and two spacecraft orbiting an asteroid.

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AAS 19-827

UNCERTAINTY ANALYSIS OF A GENERALIZED CONING ALGORITHM FOR INERTIAL NAVIGATION

James D. Brouk[*] and Kyle J. DeMars[†]

This paper investigates uncertainty propagation through a generalized coning algorithm used for inertial navigation systems. Coned measurements have often been considered uncertain variables as the statistics for raw measurements no longer apply to a coning algorithms result. Through the error analysis of a coning algorithm, two methods for mapping errors are introduced and an efficient and consistent propagation of state uncertainty is achieved, establishing that the errors in the algorithms need not be uncertain. Monte Carlo simulations reveal that the algorithms are shown to be consistent with typical methods of attitude dead-reckoning in simulations with and without coning motion.

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VARIATIONAL LAMBERT'S PROBLEM WITH UNCERTAIN DYNAMICS

Paolo Panicucci,[*†] Jay McMahon,[‡] Emmanuel Zenou[§] and Michel Delpech[**]

Lambert's problem is a widely-known problem in astrodynamics that addresses the need of finding a trajectory given two position vectors and the time of flight between them. It is widely used in mission design and in on-line guidance algorithm in order to predict the needed maneuvers or the spacecraft state on the computed trajectory. Previous work has investigated the influence of uncertainty in the positions vectors and linearization of the classical Lambert's problem for spacecraft autonomous applications. These approaches allow the uncertainty quantification, maneuver correction and orbit determination to be performed with respect to a nominal trajectory in a perfectly-known environment. Unfortunately, the increase number of missions to partially-known bodies of the Solar System, such as asteroids, comets and dwarf planets, requires to abandon the hypothesis of a deterministic dynamical environment as the forces acting on the spacecraft are accurately quantified only when the geophysical property of the body are known, thus when orbiting around it. This leads to the need of considering a stochastic dynamics to take into account uncertainties and errors introduced during mission design.

This paper presents the variational Lambert's problem with uncertain dynamics around a nominal trajectory and gather the formulas to characterize the probability density function and covariances of position, velocities and dynamical parameters. Then numerical simulations are presented by considering several dynamics effects, such as the spherical harmonics gravity, in order to validate the developed approach by comparison with Monte Carlo simulations. Results show good agreement between the two obtained solution. Finally, an operational simulation is presented to show an on-board autonomous application of the developed algorithm. In this scenario the spacecraft estimates on-board the new dynamics and corrects the guidance maneuvers by using the output of the variational Lambert's problem and the navigation data. The corrected trajectory shows a decrease of the error with respect to the nominal trajectory that implies the effectiveness of the applied corrections.

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AAS 19-881

ONBOARD OPTICAL NAVIGATION FOR ASTEROID EXPLORER BY ASTEROID SHAPE MODEL

Shuya Kashioka,* Genki Ohira,† Yuki Takao,‡ Takatoshi Iyota§ and Yuichi Tsuda**

We present an onboard navigation system for approaching and landing on an asteroid in deep space. The focus of this research is to apply the heuristic optical navigation method which is used in Hayabusa2 called GCP-NAV into an on-board processable algorithm. This technique is used to enable a spacecraft to touchdown correctly on a target point of a planetary surface during deep space mission operations. The focus of our approach is to estimate the position of the spacecraft using an asteroid shape model and imagery data obtained in real-time during spacecraft orbiting, descent, or landing. This novel approach will make possible to plan missions on asteroids farther than 3 AU. As a result, the estimation result that fits the error of up to 1 pixel on the image coordinates was obtained. Furthermore, the calculation time was decreased under 1/10 compared to calculation time on CPU.

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AAS 19-916

COLLISION AVOIDANCE AROUND SMALL BODIES USING LOW-THRUST GUIDANCE

Donald H. Kuettel III[*] and Jay W. McMahon[†]

A recent discovery from NASA's OSIRIS-REx mission confirmed that particles are being ejected from the surface of asteroid Bennu. While surprising and exciting, this discovery has many implications for small body missions around similar rubble-pile asteroids. One big question that needs to be answered is how to ensure that spacecraft in orbit around active rubble-pile asteroids do not collide with any of these ejected particles. Following previous work, this paper examines the capabilities of several continuous, finite-burn guidance algorithms in their abilities to avoid collisions with ejected particles under uncertainty. More specifically, this paper examines Lambert guidance and ZEM/ZEV guidance to quantify each algorithm's collision avoidance performance in the small body environment.

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CONTROL AND SIMULATION OF A DEPLOYABLE ENTRY VEHICLE WITH AERODYNAMIC CONTROL SURFACES

Benjamin W. L. Margolis,* Wendy A. Okolo,† Ben E. Nikaido,‡ Jeffrey D. Barton§ and Sarah N. D'Souza**

In this paper, we investigate the static stability of a deployable entry vehicle called the Lifting Nano-ADEPT and design a control system to follow bank angle, angle-of-attack, and sideslip guidance commands. The control design, based on linear quadratic regulator optimal techniques, utilizes aerodynamic control surfaces to track angle-of-attack, sideslip angle, and bank angle commands. We demonstrate, using a nonlinear simulation environment, that the controller is able to accurately track step commands that may come from a guidance algorithm.

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ADDRESSING VARYING LIGHTING CONDITIONS WITH APPLICATION TO TERRAIN RELATIVE NAVIGATION

Jonathan Manni,[*] Jay McMahon,[†] Nisar Ahmed[‡] and Courtney Mario[§]

Correlations between camera images and pre-defined templates collected for visual-inertial terrain relative navigation are largely dependent upon lighting conditions. The impact of varying lighting conditions on the performance of template correlations between rendered lunar reference maps and simulated spacecraft camera images with differing lighting conditions is assessed and an initial analysis into the impact of errors in spacecraft attitude estimates on correlations is presented. A method for analyzing the relationships between template correlations and lighting incidence angle and direction is introduced and initial findings are presented with application to terrain relative navigation on the Moon.

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RELATIVE MOTION, FORMATION FLYING, RENDEZVOUS AND PROXIMITY OPERATIONS

Session Chairs:

Relative Motion, Formation Flying, Rendezvous and Proximity Operations I:
Simone D'Amico, Stanford University
Alex Sizemore, NRC

Relative Motion, Formation Flying, Rendezvous and Proximity Operations II:
Jeffrey Stuart, Jet Propulsion Laboratory

DYNAMICAL ISSUES IN RENDEZVOUS OPERATIONS WITH THIRD BODY PERTURBATION

Giordana Bucchioni[*] and Mario Innocenti[†]

The paper presents the complete 6-DOF set of equations of relative motion that describes the dynamics and the kinematic of two spacecraft in non-inertial reference frames under the restricted three body problem hypotheses. The work was motivated by the increasing interest in missions that require the modelling of the third body perturbation to lead to an accurate synthesis if Guidance Navigation and Control systems, for this reason also the linearized models of the complete coupled translational-rotational dynamics are provided.

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HELIOSWARM: SPACE-BASED RELATIVE RANGING FOR A CUBESAT CLUSTER MISSION IN A 2:1 LUNAR RESONANT ORBIT

Lisa Policastri[*] and Jim Woodburn[†]

The *HelioSwarm* mission concept consists of a cluster design with 1 Hub and 8 Nodes co-orbiting the Earth in a 2:1 Lunar resonant orbit. A variety of navigation constraints, assumptions, and schedules were considered during design of the navigation strategy to minimize the need for ground-based tracking and communication. Each Node will only be capable of communicating with the Hub, with no direct connections to other nodes or the ground. The Hub will be tracked from the ground and perform two-way inter-satellite ranging with each Node. Simulated ground and space-based tracking measurements are used to determine the expected orbit accuracy.

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AAS 19-648

CONSTELLATION PLANNING METHODS FOR SEQUENTIAL SPACECRAFT RENDEZVOUS USING MULTI-AGENT SCHEDULING

Skylar A. Cox,[*] Nathan B. Stastny,[†] Greg Droge[‡] and David K. Geller[§]

This paper addresses the RPO constellation assignment problem by developing a responsive utility function for tasking a constellation of LEO satellites to several spacecraft servicing tasks. The paper develops the utility function that considers both value of servicing RSO spacecraft in conjunction with the associated ΔV cost. A highly-capable and operationally-relevant task allocation method, called the consensus-based bundle algorithm (CBBA), is leveraged for distributed processing and task allocation. This paper demonstrates that this methodology provides a robust technique for RPO constellation management.

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AAS 19-651

DESENSITIZED OPTIMAL ATTITUDE GUIDANCE FOR DIFFERENTIAL-DRAG RENDEZVOUS

Andrew Harris,* Ethan Burnett and Hanspeter Schaub†

Growing interest in fuel-constrained small satellites, large Low Earth Orbit (LEO) constellations, and robustness to thruster failure has motivated the use of drag forces for orbit control. This work presents a novel method of achieving differential-drag formation flight using only attitude control and spacecraft geometry while desensitizing the control to uncertainties in atmospheric properties. This work applies and extends the theory of desensitized optimal control to the attitude-driven differential drag problem and derives new strategies for coping with systems whose control sensitivities are dependent on uncertain parameters. These new attitude guidance strategies are compared versus traditional LQR-based strategies in nominal cases and under the presence of large deviations in atmospheric density.

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AAS 19-659

ANALYSIS OF A PARTICLE SWARM OPTIMIZER OF SPACE-BASED RECEIVERS FOR GEOLOCATION USING HETEROGENEOUS TDOA

David Lujan,[*] T. Alan Lovell[†] and Troy Henderson[‡]

Radio frequency localization is a passive method that can be used to geolocate a stationary radio transmitter. The use of two space-based receivers to accomplish the localization is investigated and optimized. For this method there are no common receiver locations among the collected measurements which defines the set of measurements to be heterogeneous. The purpose of this work is to optimize the receiver locations thereby optimizing their orbital geometry. A particle swarm optimizer is implemented to find the optima. Repeated simulations are performed to find a consistent set of solutions.

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AAS 19-662

CONSTRAINED ENERGY-OPTIMAL GUIDANCE IN RELATIVE MOTION VIA THEORY OF FUNCTIONAL CONNECTIONS AND RAPIDLY-EXPLORED RANDOM TREES

Kristofer Drozd,[*] Roberto Furfaro[†] and Daniele Mortari[‡]

In this paper, we present a new approach to solving constrained energy-optimal guidance problems for spacecraft relative motion. The proposed methodology is developed on two fundamental blocks, i.e. solution of boundary value problems via Theory of Functional Connections and generation of dynamically feasible optimal trajectory via Rapidly-explored Random Trees. The method enables fast generation of trajectories in relative motion that drive the chaser spacecraft and to the target in an energy-optimal fashion while satisfy state constraints arising from operational constraints.

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GEOMETRIC FORMATIONS USING RELATIVE ORBITAL ELEMENTS AND ARTIFICIAL POTENTIAL FUNCTIONS

Sylvain Renevey[*] and David A. Spencer[†]

In this paper, geometric relative orbit formations are established using a control algorithm based on relative orbital elements and artificial potential functions. Numerical simulations are presented to illustrate the effectiveness of the control algorithm. The first case study is that of a triangular lattice composed of ten spacecraft distributed onto two circular relative orbits. Then, the design and establishment of a thirty-seven spacecraft formation composed of two hexagonal lattices is presented. Finally, the algorithm is extended to a different set of relative orbital elements and is illustrated with the design of a helix trajectory for on-orbit inspection.

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AAS 19-685

DESENSITIZED OPTIMAL SPACECRAFT RENDEZVOUS CONTROL WITH POORLY KNOWN GRAVITATIONAL AND SOLAR RADIATION PRESSURE PERTURBATIONS

Ethan R. Burnett,* Andrew Harris† and Hanspeter Schaub‡

Robust rendezvous guidance is implemented in an environment with uncertain dominant gravitational harmonics C_{20} and C_{22} and poorly-known solar radiation pressure (SRP) effects. The rendezvous control design presumes the availability of a throttled low-thrust propulsion system, which can be achieved by pulsed plasma thrusters. The control minimizes an augmented cost function composed of the traditional Linear Quadratic Regulator (LQR) terms and terms that are quadratic in system sensitivity to multiple unknown dynamical parameters. Results show that there is much closer agreement between the linear designed trajectory and true controlled trajectory using the desensitized control strategy than there is for LQR.

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AAS 19-699

APPLIED REACHABILITY ANALYSIS OF SPACECRAFT RENDEZVOUS WITH A TUMBLING OBJECT

Costantinos Zagaris* **and Marcello Romano†**

Rendezvous and proximity operations are an essential part of space missions and are becoming more complex, requiring autonomy and the use of more sophisticated, computation-based, guidance and control techniques. Implementing such algorithms in an autonomous system raises important questions on maneuver feasibility. In this paper, backward reachability analysis is conducted in order to visualize a set of initial conditions from which a desired rendezvous maneuver is feasible within a given amount of time and control constraints. A roto-translational (6-Degrees-of-Freedom (6-DOF)) model of the spacecraft relative motion is derived. Due to the complexity of the 6-DOF relative dynamics, reachability computations are intractable with current tools. An analysis method is proposed, using minimum-time optimal control solutions, to visualize backward reachable sets of this complex dynamic system. The proposed method makes the reachability analysis tractable, and provides valuable insight into the feasibility of rendezvous maneuvers with a tumbling object.

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AAS 19-706

CONSTRAINED MOTION ANALYSIS AND NONLINEAR OPTIMAL TRACKING CONTROL OF TWO-CRAFT COULOMB FORMATION IN ELLIPTIC CHIEF ORBITS

M. Wasif Memon,* Morad Nazari,† Dongeun Seo‡ and Richard Prazenica‡

In this paper, the two-craft Coulomb formation in elliptic chief orbits is studied. A nonlinear optimal tracking feedback control is proposed to stabilize the dynamics of Coulomb formation and track a reference trajectory. Due to the effects of plasma shielding, a Debye length model is incorporated in the nonlinear dynamics as a linear function of altitude of the formation's center of mass. The control accelerations obtained using the nonlinear optimal tracking control are compared to the constraint accelerations obtained using the Udwadia-Kalaba (U-K) equations of constrained motion. Then, the components of constraint accelerations are analyzed to study the maximum contribution of the Coulomb effects in formation. The significance of using Coulomb effects in terms of fuel costs is highlighted by studying the integrated thruster control effort. Numerical simulations are provided for a) the highly eccentric Molniya and b) the near-circular near-GEO ERS-21 orbits.

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MORSE-LYAPUNOV-BASED DECENTRALIZED CONSENSUS CONTROL OF RIGID BODY SPACECRAFT IN ORBITAL RELATIVE MOTION

Eric A. Butcher* **and Mohammad Maadani†**

An algorithm is proposed for almost globally asymptotically stable consensus control of multi-agent rigid body spacecraft in orbital relative motion using Morse-Lyapunov analysis in the framework of SE(3). The control objective is to stabilize the relative pose configurations with velocity synchronization of the spacecraft which share their states according to a static communication topology in the presence of gravitational forces and torques. The feedback control design is conducted on the dynamic level where mass and inertia may be large and thus the strategy is applicable to quickly maneuvering and tumbling rigid spacecraft, and a potential-based collision avoidance scheme is also implemented.

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AAS 19-764

PRECISE RENDEZVOUS GUIDANCE IN CISLUNAR ORBIT VIA SURROGATE MODELLING

Satoshi Ueda[*]

This paper presents a precise rendezvous guidance technique for cislunar orbits via surrogate modelling. The guidance law must be tolerant of state variations due to navigation and control errors. Precise relative trajectory control is key to safety requirements such as collision avoidance during proximity operations. The conventional relative guidance law utilizing impulsive maneuvers such as the Clohessy-Wiltshire solution can control the position of a spacecraft at a specific time, whereas the spacecraft's velocity at the same time depends on estimated orbital states at the time of impulsive maneuver. Excessive guidance error in terms of velocity results in a wider dispersion of relative trajectories, possibly resulting in less safe trajectories and may lead to stricter accuracy requirements for navigation sensors and control devices, thereby making guidance accuracy a potential cost-driving factor. The proposed method aims to improve guidance velocity errors by controlling guidance parameters related to maneuver impulse timing and the time to target position. It uses surrogate modelling, which is utilized in the context of multidisciplinary system design optimization. A surrogate model is formulated to predict optimum guidance parameters according to position and velocity errors in the nominal rendezvous trajectory. This paper assesses rendezvous guidance in the Earth-Moon L2 near-rectilinear halo orbits as a practical scenario for Gateway-related missions. First, a relative guidance law suitable for cislunar environment is presented. Next, a surrogate model is generated by optimizing guidance parameters for distributed trajectories. Lastly, the proposed method is demonstrated through Monte Carlo simulations of a practical cislunar rendezvous.

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SECOND-ORDER SOLUTION FOR RELATIVE MOTION ON ECCENTRIC ORBITS IN CURVILINEAR COORDINATES

Matthew Willis,[*] Kyle T. Alfriend[†] and Simone D'Amico[‡]

A new, second-order solution in curvilinear coordinates is introduced for the relative motion of two spacecraft on eccentric orbits. The second-order equations for unperturbed orbits are derived in spherical coordinates with true anomaly as the independent variable, and solved by the method of successive approximations. A comparison of error trends against eccentricity and inter-spacecraft separation is presented between the new solution and prominent Cartesian, curvilinear, and orbital element based solutions from the literature. The second-order curvilinear solution offers a thousand-fold improvement in accuracy over the first-order curvilinear solution, and still greater improvement over first- and second-order rectilinear solutions when large along-track separations are present.

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ANALYTIC CENTER OF ILLUMINATION SOLUTIONS TO AID RELATIVE NAVIGATION WITH PARTIALLY RESOLVED IMAGERY

Kevin R. Kobylka,[*] Jacob H. Puritz[†] and John A. Christian[‡]

The distance between a pair of spacecraft executing a rendezvous changes by many orders of magnitude during their on-orbit encounter. If optical sensors are to be used for relative navigation in such a scenario, it is reasonable to assume that the observed spacecraft will transition from an unresolved object (at long range), to a partially resolved object (at intermediate range), to a fully resolved object (at close range). This work seeks to enhance techniques within the partially resolved regime by developing analytical solutions to relate the center of illumination to their geometric center for a number of common geometric primitives.

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AUTONOMOUS CHARACTERIZATION OF AN ASTEROID FROM A HOVERING TRAJECTORY

Shota Takahashi* and Daniel J. Scheeres†

Asteroid exploration missions must deal with large uncertainties in a target body's gravity and shape upon rendezvous. Parameters associated with the asteroid are typically estimated after arrival through costly ground-based observations. In this paper, we consider autonomous operation of a spacecraft as a solution to reduce the cost. We focus on the period between the interplanetary and close hovering phase. The spacecraft needs to localize itself, estimate the asteroid's model parameters, and travel closer to a target asteroid while properly controlling the trajectory. The goal of the paper is to investigate the information content of the onboard optical measurements and assess the feasibility of autonomous hovering. Covariance analysis is performed for two phases: distant self-localization phase and close mass estimation phase. It turns out the knowledge of SRP and ΔV is essential for precise navigation, which suggests the benefit of high-precision onboard accelerometers.

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AAS 19-913

MMS EXTENDED MISSION ECLIPSE MITIGATION AND SOLAR WIND TURBULENCE SCIENCE CAMPAIGN

Trevor Williams,[*] Eric Palmer,[†] Dominic Godine,[†] Jacob Hollister,[†] Neil Ottenstein[†] and Babak Vint[†]

Launch window design for the Magnetospheric Multiscale (MMS) mission ensured that no excessive eclipses would be encountered during the prime mission. However, it was not physically possible to find solutions that would satisfy the eclipse constraints indefinitely: most extended mission years would contain 1-3 eclipses long enough to potentially damage either the MMS spacecraft or its scientific instruments. It was found that raising apogee radius from 25 to 29.34 Earth radii moderated the peak eclipses significantly at relatively low fuel cost. These maneuvers were performed recently, and a science campaign to study turbulence in the solar wind piggy-backed onto it.

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AAS 19-920

SENSOR SELECTION STRATEGIES FOR SATELLITE SWARM COLLABORATIVE LOCALIZATION

William A. Bezouska[*†] and David A. Barnhart[‡]

A closely spaced group of collaborative satellites can fuse relative position and orientation measurements collected between individual team members to estimate the state of the entire swarm. Intelligently selecting only a subset of available measurements can reduce power and computation requirements while potentially avoiding poorly performing sensor configurations. This paper presents a greedy sensor selection strategy to reduce the number of measurements processed at each timestep. Performance of a Multiplicative Extended Kalman Filter using this reduced set is compared to randomly selecting the same number of sensors. We show through simulation on synthetic data as well as cooperative vision-based pose estimation using rendered images that this strategy can improve estimation performance.

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LAUNCH, TRANSPORT, AGGREGATION, AND ASSEMBLY OF AN IN-SPACE ASSEMBLED TELESCOPE

Bo J. Naasz*

This paper presents a preliminary concept of operations for launch, aggregation, and assembly of a large space telescope, based on work performed during the National Aeronautics and Space Administration (NASA) Science Mission Directorate (SMD) In-Space Assembled Telescope (iSAT) study. We also present observations on the assembly location trade, notional telescope cargo launch manifests, and results of a parametric launch and delivery cost study for several observatory sizes, and evaluating several options in the aggregation architecture trade space, including: 1) assembly at Earth-Moon L2 (EM-L2) or Sun-Earth L2 (SE-L2); 2) transfer orbit types (direct, lunar flyby, or manifold); 3) re-use of launch vehicle first stage; 4) use of a tug/tender or disposable cargo delivery vehicle. This parametric study allows us to make some observations about when, assuming there is no other customer, a re-usable space tug becomes cost effective as part of the ISAT architecture.

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DYNAMICAL SYSTEMS THEORY

Session Chairs:

Dynamical Systems Theory I: Natasha Bosanac, University of Colorado, Boulder

Dynamical Systems Theory II: Siamak Hesar, Blue Canyon Technologies

AAS 19-637

DESIGN AND CONTROL OF SPACECRAFT TRAJECTORIES IN THE FULL RESTRICTED THREE BODY PROBLEM

Isabelle Jean,* Arun K. Misra† and Alfred Ng‡

Asteroid missions are now an important component of space exploration and binary asteroids comprise approximately 16% the Near Earth Asteroids (NEA) population. This fact, combined with the planned mission to binary asteroid 65803 Didymos has generated a lot of interest in the study of spacecraft dynamics in the vicinity of binary asteroids. The combination of the effect of the irregular shape and the rotation of the primary bodies makes them not only non-linear, but also non-autonomous systems. The dynamics of a spacecraft in a binary environment with those characteristics is known as the Full Restricted Three Body Problem (FRTBP). This study develops a technique to design reference trajectories in the FRTBP using a fourth-order gravitational potential model of the two primary bodies. The rotation of the primary bodies, their elliptical mutual motion and the solar radiation pressure are also included in the model, which makes this study unique. It then compares the control effort required when these reference trajectories are used with that required when reference trajectories built with simpler models are used. The goal is to study how the choice of the model used to compute reference trajectories influences the control effort required to keep the spacecraft close to them.

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AAS 19-681

THE LONG-TERM FORECAST OF STATION VIEW PERIODS FOR ELLIPTICAL ORBITS*

Andrew J. Graven† and Martin W. Lo‡

In a previous paper, using ergodic theory, Lo[1] derived a simple definite integral that provided an estimate of the view periods of ground stations to satellites. This assumes the satellites are in circular orbits with non-repeating ground tracks under linear J_2 perturbations. The novel feature is that this is done without the propagation of the trajectory by employing ergodic theory. This accelerated the telecommunications mission design and analysis by several orders of magnitude and greatly simplified the process. In this paper, we extend the view period integral to elliptical orbits.

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AAS 19-696

HIGH-ENERGY LUNAR CAPTURE VIA LOW-THRUST DYNAMICAL STRUCTURES

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

Current and future spacecraft will leverage low-thrust propulsion to navigate from high-energy transfer trajectories to low-energy orbits near the Moon. Due to the long burn durations required for such energy changes, identifying suitable low-thrust arcs remains a design challenge. Periapse maps are employed to explore the dynamics of low-thrust, energy-optimal arcs in the lunar vicinity. Dynamical structures that separate transit and captured motion on these maps are identified and leveraged to construct preliminary low-thrust trajectory designs.

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AAS 19-717

OSIRIS-REX NAVIGATION SMALL FORCE MODELS

Jeroen L. Geeraert,[*] Jason M. Leonard,[*] Patrick W. Kenneally,[†] Peter G. Antreasian,[*] Michael C. Moreau[‡] and Dante S. Lauretta[§]

The Navigation Campaign of the NASA OSIRIS-REx mission consists of three phases: the Approach phase, Preliminary Survey phase, and the Orbital A phase. These phases spanned from August 2018 until February 28, 2019. The OSIRISREx spacecraft arrived at asteroid (101955) Bennu on December 3rd, 2018 thereby initiating the Preliminary Survey phase consisting of five 7-km altitude flybys of the asteroid. Orbit insertion followed on December 31st, 2018 commencing the Orbital A phase whereby the spacecraft's average frozen orbit radius was less than 2 km. In this paper the small forces are presented that govern the spacecraft dynamics near the asteroid for the Navigation Campaign. These small forces include: solar radiation pressure, spacecraft thermal re-radiation, the antenna and LIDAR radiation pressure, and trending from desaturation maneuvers (desats). Extensive work on modeling these forces has enabled the navigation performance to exceed expectations and has reduced the stochastic accelerations below 1 x 10^{-12} km/s^2 resulting in smaller trajectory predicted errors, essential for science planning of the mission.

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AAS 19-723

FREQUENCY STRUCTURE OF THE NRHO FAMILY IN THE EARTH-MOON SYSTEM

David Lujan*[*] and Daniel J. Scheeres[†]

A method for computing the frequencies and winding numbers of the center manifolds for Halo orbits is presented. This method defines a coordinate system in the center manifold to track a particle's position under the action of linear dynamics of the circular restricted three-body problem. The coordinate system is constructed using information about the left and right eigenvectors of the associated monodromy matrix of a Halo orbit. The frequencies and winding numbers presented here are for the Southern L2 Halo orbit family in the Earth-Moon system, however this method can be applied to periodic orbits in other three-body systems.

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AAS 19-724

TRANSFER TRAJECTORY OPTIONS FOR SERVICING SUN-EARTH-MOON LIBRATION POINT MISSIONS

David C. Folta[*] and Cassandra Webster[†]

Future missions to the Sun-Earth Libration L_1 and L_2 regions will require scheduled servicing to maintain hardware and replenish consumables. While there have been statements made by various NASA programs regarding servicing of vehicles at these locations or in Cis-lunar space, a practical transfer study has not been extensively investigated in an operational fashion to determine the impacts of navigation and maneuver errors. This investigation uses dynamical systems and operational models to design transfer trajectories between the Sun-Earth Libration region (QuasiHalo orbit) and the Earth-Moon vicinity (Distant Retrograde Orbit, QuasiHalo Orbit, Halo Orbit, and Near Rectilinear Halo Orbit). We address the total ΔV cost of transfers and operational considerations between each pair of locations using a Monte Carlo analysis.

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ACCESSING HIGHLY OUT-OF-ECLIPTIC SCIENCE ORBITS VIA LOW-ENERGY, LOW-THRUST TRANSPORT MECHANISMS

Jeffrey Stuart,[*] Rodney L. Anderson,[*] Christopher Sullivan[†] and Natasha Bosanac[†]

Several mission concepts entail the placement of a spacecraft into a high inclination orbit with respect to the ecliptic plane. Among these mission concepts are solar observatories targeting the polar regions of the Sun or spacecraft seeking an external vantage point on the zodiacal dust cloud of our solar system. In this investigation, techniques for low-thrust and low-energy trajectory design will be integrated into a cohesive framework to access these highly out-of-ecliptic science orbits. The focus of this investigation will be on spacecraft conforming to a SmallSat form-factor, enabling opportunistic science as secondary payloads or via smaller launch vehicles.

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SURVEY OF BALLISTIC LUNAR TRANSFERS TO NEAR RECTILINEAR HALO ORBIT

Nathan L. Parrish,[*] Ethan Kayser,[†] Shreya Udupa,[†] Jeffrey S. Parker,[‡] Bradley W. Cheetham[§] and Diane C. Davis[**]

This paper presents a survey of ballistic lunar transfer (BLT) trajectories from Earth launch to insertion into a near rectilinear halo orbit (NRHO). Results are described from a detailed set of related mission design studies: the evolution over time of families with and without an outbound lunar flyby; analysis of eclipses; analysis of the ΔV requirements of changing arrival time to rendezvous; and description of the trade space for time of flight vs deterministic ΔV. An ephemeris model is used throughout. These analyses are presented in order to inform future missions to NRHOs.

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AAS 19-744

ENABLING BROAD ENERGY RANGE COMPUTATIONS AT LIBRATION POINTS USING ISOLATING NEIGHBORHOODS[*]

Rodney L. Anderson,[†] Robert W. Easton[‡] and Martin W. Lo[†]

Isolating blocks have previously been used for computing complete sets of transit trajectories traveling through the L_1 and L_2 libration point gateways in the circular restricted three-body problem. They have also been used to compute close approximations to the hyperbolic invariant sets around the libration points and their associated invariant manifolds. Constructing typical isolating block boundaries can be challenging, and the energy range for which these isolating blocks may be computed is limited. The use of isolating neighborhoods is introduced here to provide a theoretically rigorous approach for these computations that eliminates the difficulties involved in constructing isolating block boundaries while expanding the applicable energy range.

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LINKING LOW- TO HIGH-ENERGY DYNAMICS OF INVARIANT MANIFOLD TUBES, TRANSIT ORBITS, AND SINGULAR COLLISION ORBITS

Kenta Oshima[*]

The first part of the present paper reveals interplays among invariant manifolds emanating from planar Lyapunov orbits around the three collinear Lagrange points L_1, L_2, and L_3 for high energies. Once the energetically forbidden region vanishes, the invariant manifolds together form closed separatrices bounding transit orbits in the phase space, deviating from the low-energy picture of invariant manifold tubes. Though the qualitatively different behavior of invariant manifolds emerges for high energies, associated transit orbits possess a common feature generalized from that of low-energy transit orbits. The second part extends our previous proposal of using singular collision orbits associated with the secondary to find trajectories reaching the vicinity of the secondary to low energies. Statistical analyses indicate that singular collision orbits are useful to find such transfer trajectories except for the very-low-energy regime. These results are numerically obtained in the Earth-Moon and Sun-Jupiter planar circular restricted three-body problems.

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AAS 19-785

ASTEROID DEFLECTION WITH ACTIVE BOULDER REMOVAL

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

A method of asteroid deflection is presented and examined. This method, dubbed mass driver deflection, uses small discrete launches of masses off an asteroid to prevent its collision with Earth. By using material from the asteroid itself, such as boulders or regolith deposits, mass driver deflection substantially reduces the required mass of the deflection system. The analysis in the paper seeks to optimize the deflection efforts, while minimizing unwanted effects on the deflected asteroid's state, both rotational and orbital. The results show that deflection is possible in time frames of several years in a variety of scenarios and that the deflection effects on the asteroid behavior do not pose a risk of disrupting the asteroid in a catastrophic way.

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AAS 19-798

STABILITY OF HIGHLY INCLINED ORBITS AROUND THE ASTEROID (153591) 2001 SN_{263}

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

In this work perturbation maps are used to measure the stability of highly inclined orbits around the triple asteroid 2001 SN_{263}, target of the Brazilian ASTER mission. The perturbation maps also provide the delta-v required to keep a spacecraft as close as possible to a reference orbit through orbital maneuvers. In our case the reference orbit is a Keplerian orbit. However, the reference orbit can be any, depending on the objectives of the mission. We compare the orbital stability of the spacecraft with three values area-to-mass ratio, to show the effect of the solar radiation pressure on the dynamical structure of the system. The results of this work can be used for the planning of the ASTER mission and for the planning of any space mission.

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AAS 19-808

DYNAMICAL STRUCTURES NEARBY NRHOS WITH APPLICATIONS IN CISLUNAR SPACE

Emily M. Zimovan-Spreen[*] and Kathleen C. Howell[†]

The development of a methodology to move through cislunar space along fundamental dynamical paths is relevant to NASA's cislunar transportation network goals. To enable an informed design approach for transfer trajectories departing from or arriving at a Near Rectilinear Halo Orbit (NRHO), higher-period orbits that bifurcate from the NRHO region of the halo orbit family are combined with other known structures, such as Lagrange point and resonant orbits, in the Earth-Moon neighborhood. As a consequence of this design strategy, novel impulsive transfer options between NRHOs and distant retrograde orbits that possess predictable geometries are constructed.

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AAS 19-814

TRANSFERS FROM GTO TO SUN-EARTH LIBRATION ORBITS

Juan A. Ojeda Romero* **and Kathleen C. Howell†**

Rideshares increase launch capabilities and decrease the cost for satellite manufacturers. However, the range of orbits available for secondary payloads is dependent on launch constraints for the primary. Additionally, communications constraints and limited propellant options must be incorporated in preliminary mission design for secondary payloads. Ridesharing opportunities are now available for orbit destinations beyond LEO. In this investigation, transfers from GTOs to Sun-Earth libration point orbits are generated using stable manifold transfers and Poincaré maps.

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AAS 19-821

KOOPMAN OPERATOR THEORY APPLIED TO THE MOTION OF SATELLITES

Richard Linares*

This paper investigates the application of Koopman Operator (KO) theory to Astrodynamics. The field of astrodynamics has a rich history in motivating the development of techniques in dynamical systems theory, going back to the revolutionary work of Poincaré. Recently, the KO has emerged as a promising alternative to the geometric prospective provided by Poincaré, where the KO formulates the analysis and dynamical systems in terms of observables. This paper investigates this observable based prospective for challenges in the field of astrodynamics. Additionally, new advancements in data-driven computational approaches have led to new ways of approximating the KO and this work investigates these computational tools for computing the eigenfunctions of the KO.

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AAS 19-825

OBSERVABILITY AND ESTIMABILITY ANALYSIS OF THE ORBIT PROBLEM

Alex M. Friedman* **and Carolin Frueh†**

With easier access to space, the challenge of tracking the resident space object (RSO) population becomes even more difficult. The connection of observability and the Kalman filter is explored for facing this RSO tracking challenge. Often, observability is computed without state and measurement uncertainties, but many stochastic observability methods have been developed. In addition, methods for evaluating estimation performance, called estimability, are useful to study alongside observability. A review of stochastic observability and estimability methods for the orbit problem is conducted. A consider filter approach utilizing specific observability and estimability methods is developed for improved RSO propagation and identification.

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CANONICAL TRANSFORMATIONS VIA A SPARSE APPROXIMATION-BASED COLLOCATION METHOD FOR DYNAMICAL SYSTEMS

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

Semi-analytical approaches to solve the Hamilton-Jacobi Partial Differential Equation that governs the transformation of coordinates to rectify the motion of a dynamical system are proposed in this paper. It is shown that recent advances in sparse approximation can be utilized to develop a collocation method to approximate the generating function for which closed-form solution to the HJ equation may not be obtained. By utilizing a family of trajectories in the domain of the relevant phase volume, the sparse approximation problem for the coefficients of the generating function is formulated and solved efficiently, for arbitrary choice of basis function sets.

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TRAJECTORY DESIGN AND OPTIMIZATION

Session Chairs:

Trajectory Design and Optimization I: Angela Bowes, NASA LaRC

Trajectory Design and Optimization II: Pradipto Ghosh, Analytical Graphics, Inc.

Trajectory Design and Optimization III: Yanping Guo, Johns Hopkins University Applied Physics Laboratory

Trajectory Design and Optimization IV: Jennifer Hudson, Western Michigan University

Trajectory Design and Optimization V: David B. Spencer, Pennsylvania State University

Trajectory Design and Optimization VI: Rohan Sood, University of Alabama

AAS 19-611

LOW THRUST VARIABLE SPECIFIC IMPULSE FUEL-OPTIMAL TRANSFERS BETWEEN PLANETARY PARKING ORBITS

Padmanabha Prasanna Simha[*] and R. V. Ramanan[†]

Optimizing low thrust transfers between Earth-Mars parking orbits is a challenging problem due to the large number of revolutions that the spacecraft has to perform during planetary escape and capture. A strategy has been arrived at to obtain near optimal solutions without multiple shooting or any approximations to handle the planet-centric revolutions. A power limited, variable specific impulse, constant efficiency thruster operating between minimum and maximum specific impulse bounds is considered. The optimal control law is obtained by the application of the Pontryagin's minimum principle and the Karush-Kuhn-Tucker conditions to enforce power and specific impulse constraints. The resulting two point boundary value problem has been solved using differential evolution, a search based global optimization technique without the need for homotopy. A three mode discontinuous control law is obtained which allows for coasting. This leads to fuel-optimal interplanetary transfers with thrusters having a much narrower range of operating specific impulses in comparison to results currently available in literature.

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REFINING LUCY MISSION DELTA-V DURING SPACECRAFT DESIGN USING TRAJECTORY OPTIMIZATION WITHIN HIGH-FIDELITY MONTE CARLO MANEUVER ANALYSIS

James V. McAdams,[*] Jeremy M. Knittel,[*] Kenneth E. Williams,[*] Jacob A. Englander,[†] Donald H. Ellison,[†] Dale R. Stanbridge,[*] Brian Sutter[‡] and Kevin Berry[†]

Recent advances linking medium-fidelity trajectory optimization and high-fidelity trajectory propagation/maneuver design software with Monte Carlo maneuver analysis and parallel processing enabled realistic statistical delta-V estimation well before launch. Completing this high-confidence, refined statistical maneuver analysis early enabled release of excess delta-V margin for increased dry mass margin for the Lucy Jupiter Trojan flyby mission. By 3.3 years before launch, 16 of 34 TCMs had 1000 re-optimized trajectory design samples, yielding tens of m/s lower 99%-probability delta-V versus targeting maneuvers to one optimal trajectory. One year later, 1000 re-optimized samples of all deterministic maneuvers and subsequent flybys further lowered estimated delta-V.

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AAS 19-618

END TO END OPTIMIZATION OF A MARS HYBRID TRANSPORTATION ARCHITECTURE

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

NASA's Mars Study Capability Team (MSCT) is developing a reusable Mars hybrid transportation architecture in which both chemical and solar electric propulsion systems are used in a single vehicle design to send crew and cargo to Mars. This paper presents a new integrated framework that combines Earth de-parture/arrival, heliocentric trajectory, Mars orbit reorientation, and vehicle sizing into a single environment and solves the entire mission from beginning to end in an effort to find a globally optimized solution for the hybrid architecture.

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AAS 19-633

OPTIMIZATION OF THE LUCY INTERPLANETARY TRAJECTORY VIA TWO-POINT DIRECT SHOOTING

Jacob A. Englander,[*] Donald H. Ellison,[†] Ken Williams,[‡] James McAdams,[§] Jeremy M. Knittel,[**] Brian Sutter,[††] Chelsea Welch,[‡‡] Dale Stanbridge[§§] and Kevin Berry[***]

Lucy is NASA's next Discovery-class mission and will explore the Trojan asteroids in the Sun-Jupiter L4 and L5 regions. This paper details the design of Lucy's interplanetary trajectory using a two-point direct shooting transcription, nonlinear programming, and monotonic basin hopping. These techniques are implemented in the Evolutionary Mission Trajectory Generator (EMTG), a trajectory optimization tool developed at NASA Goddard Space Flight Center. We present applications to the baseline trajectory design, Monte Carlo analysis, and operations.

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HIGH-FIDELITY MULTIPLE-FLYBY TRAJECTORY OPTIMIZATION USING MULTIPLE SHOOTING

Donald H. Ellison[*] and Jacob A. Englander[†]

Rendering a complex spacecraft trajectory in high fidelity can be an expensive endeavor, both computationally and from a human time/cost standpoint. However, in many cases, a low-fidelity trajectory that reasonably approximates a high-fidelity counterpart is much easier to obtain. Thus, it is important to have an efficient process for converting a trajectory from lower-fidelity model to high fidelity. We present a method for converting low-fidelity trajectories into high fidelity that relies on multiple shooting, nonlinear programming, and numerical integration. The procedure converts any zero-radius sphere-of-influence gravity-assist events to fully integrated flyby events. Several numerical examples are presented that showcase the flexibility of the high-fidelity rendering process across multiple mission types and flight regimes.

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THEORY OF FUNCTIONAL CONNECTIONS APPLIED TO NONLINEAR PROGRAMMING UNDER EQUALITY CONSTRAINTS

Daniele Mortari,[*] Tina Mai[†‡] and Yalchin Efendiev[§]

This paper introduces an efficient approach to solve quadratic programming problems subject to equality constraints via the Theory of Functional Connections. This is done without using the traditional Lagrange multipliers approach, and the solution is provided in closed-form. Two distinct constrained expressions (satisfying the equality constraints) are introduced. The unknown vector optimization variable is then the free vector g, introduced by the Theory of Functional Connections, to derive constrained expressions. The solution to the general nonlinear programming problem is obtained by the Newton's method in optimization, and each iteration involves the second-order Taylor approximation, starting from an initial vector $x^{(0)}$ which is a solution of the equality constraint. To solve the quadratic programming problems, we not only introduce the new approach but also provide a numerical accuracy and speed comparisons with respect to MATLAB's quadprog. To handle the nonlinear programming problem using the Theory of Functional Connections, a sketch of convergence analysis of the proposed approach is provided.

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AAS 19-686

CONSTRUCTING A SET OF MOTION PRIMITIVES IN THE CIRCULAR RESTRICTED THREE-BODY PROBLEM VIA CLUSTERING

Thomas R. Smith[*] and Natasha Bosanac[†]

To reduce the complexity of trajectory design in chaotic dynamical environments, data analysis techniques support the representation of a large and diverse solution space via a fundamental set of governing structures. Clustering is a data mining technique used to summarize a dataset by uncovering its underlying structures. In this paper, a variety of commonly used clustering algorithms are explored to construct a set of motion primitives that summarize a family of periodic orbits in the Circular Restricted Three-Body Problem (CR3BP). An overview of common clustering algorithms is provided and the motion primitive construction process for trajectories in a multi-body system is outlined. The impact of various clustering algorithms and feature vector definitions on the construction of motion primitives in the CR3BP is evaluated for the family of Distant Prograde Orbits (DPOs) in the Earth-Moon system.

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AAS 19-688

OPTIMAL LOW-THRUST GRAVITY PERTURBED ORBIT TRANSFERS WITH SHADOW CONSTRAINTS

Robyn Woollands*† and Ehsan Taheri‡

We present a new methodology to incorporate shadow- and time-triggered constraints within the indirect optimization methods to solve low-thrust fuel-optimal orbit transfer problems. Such constraints could represent, for instance, zero thrusting during an eclipse or a time interval during which the thruster has to be shut down during a mission science phase for data collection or communication purposes. Incorporation of the constraints is achieved in a straightforward manner through a hyperbolic tangent smoothing (HTS) method, which reduces the problem to a two-point boundary-value problem (TPBVP). A unique feature of the presented construct is that non-smooth components in the dynamics (e.g., engine throttle input and shadow- or time-triggered constraints) are all approximated by smooth representations. As a consequence of smoothing, the domain of convergence of the standard single-shooting methods used for solving the ensuing TPBVPs is drastically enlarged. The utility of the method is demonstrated through a fixed-time rendezvous-type maneuver from a geostationary transfer orbit to a geostationary equatorial orbit, where a high-fidelity spherical harmonic gravity model of the Earth is used. Moreover, the system dynamics are propagated with the Picard-Chebyshev numerical integrator and the TPBVP is solved using the method of particular solutions. The proposed construct affords several avenues for computational speedup that has appealing numerical features making them suitable for trajectory optimization using high-fidelity models.

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AAS 19-690

LAUNCH OPPORTUNITY ANALYSIS OF GEO TRANSFER WITH HIGH INCLINATION USING LUNAR GRAVITY ASSIST

Su-Jin Choi,[*] John Carrico,[†] Mike Loucks,[‡] Hoonhee Lee[§] and Se-Jin Kwon[**]

There is a possibility to launch a GEO mission at Naro space center even though Naro space center is located in mid-latitude in the northern hemisphere. When launched from Naro space center, the inclination after separation is 80°. Therefore, lunar gravity assist is required for a GEO transfer to avoid excessive plane change maneuvers. Two launch date intervals for a month and short/long coast options are considered. Three perigee maneuvers to raise GTO to lunar altitude and additional three perigee maneuvers after fly-by for GEO insertions are planned. Each option provides a launch opportunity of 6 days with less than 20° Earth inclination. BdotR, BdotT at fly-by and apogee altitude, orbital period after fly-by and total Delta-V are obtained in all options. Simulation results show that lower apogee altitude after fly-by is required to lower Delta-V. Two short coast options have the maximum and minimum Delta-V in all options. For one short option (Short-Date1), the required Delta-V is 1760 m/s with small Earth inclination. Therefore, this trajectory can be an alternative to overcome the need for a large plane change and the required Delta-V can be less than a general GEO transfer if the initial apogee altitude is higher than 65,000 km.

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THROUGH THE LOOKING GLASS: MISSION DESIGN USING INTERACTIVE AND IMMERSIVE VISUALIZATION ENVIRONMENTS[*]

Jeffrey Stuart,[†] Amos Byon,[‡] Alex Menzies,[†] Try Lam,[*] Brent Buffington,[*] and Sonia Hernandez[*]

Mission design and trajectory analysis is an intensive process requiring advanced computational resources, expert human intuition, and many successive human-in-the-loop iterations to converge on acceptable trajectory designs. One approach to alleviate this burden is through the judicious application of visually interactive environments that allow intuitive human assessment and real-time updates as options are explored. In this investigation we will specifically focus on the challenges presented in the early- to mid-development phases of a mission, where these phases are characterized by (sometimes rapid) shifts in mission objectives, spacecraft architecture, and concept of operations as trade spaces are explored.

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AAS 19-701

A TIME-DEPENDENT TSP FORMULATION FOR THE DESIGN OF AN ACTIVE DEBRIS REMOVAL MISSION USING SIMULATED ANNEALING

Lorenzo Federici,[*] Alessandro Zavoli[†] and Guido Colasurdo[‡]

This paper proposes a formulation of the Active Debris Removal (ADR) Mission Design problem as a modified Time-Dependent Traveling Salesman Problem (TDTSP). The TDTSP is a well-known combinatorial optimization problem, whose solution is the cheapest monocyclic tour connecting a number of non-stationary cities in a map. The problem is tackled with an optimization procedure based on Simulated Annealing, that efficiently exploits a natural encoding and a careful choice of mutation operators. The developed algorithm is used to simultaneously optimize the targets sequence and the rendezvous epochs of an impulsive ADR mission. Numerical results are presented for sets comprising up to 20 targets.

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AAS 19-705

LIBRATION ORBIT ECLIPSE AVOIDANCE MANEUVER STUDY FOR THE JAMES WEBB SPACE TELESCOPE MISSION

Wayne Yu* and Karen Richon†

Mission analysis of libration orbit trajectories at Sun-Earth/Moon L2 typically includes predictions of lunar and Earth eclipses during the mission life-time. The NASA James Webb Space Telescope (JWST) trajectory, by design, avoids these eclipses by pruning its launch window. In an off-nominal scenario where an eclipse is predicted, a maneuver strategy is needed. In this paper, trade studies are examined for JWST that characterize the burn magnitude, location, and epochs of multiple maneuver plans to avoid an eclipse. The results enable analysts to explore the space of feasible maneuver strategies during routine operations.

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COPERNICUS 5.0: LATEST ADVANCES IN JSC'S SPACECRAFT TRAJECTORY OPTIMIZATION AND DESIGN SYSTEM

Jacob Williams,[*] Anubhav H. Kamath,[†] Randy A. Eckman,[‡] Gerald L. Condon,[§] Ravishankar Mathur[**] and Diane C. Davis[††]

This paper describes the latest upgrades that have been made to JSC's Copernicus trajectory optimization program for the upcoming 5.0 release. Copernicus has undergone significant refactoring in recent years in order to make the tool more powerful, versatile, and user-friendly. The 5.0 release includes a new Python-based GUI and scripting interface, new 3D graphics upgrades, and a host of architectural modifications and new features. The implementation of the new architecture and its capabilities are discussed, including examples of how some of the new features can be used to solve different trajectory problems.

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RAPID EVALUATION OF LOW-THRUST TRANSFERS FROM ELLIPTICAL ORBITS TO GEOSTATIONARY ORBIT

Mason J. Kelchner[*] and Craig A. Kluever[†]

Low-thrust orbit transfers to geostationary-equatorial orbit (GEO) will likely use a combination of chemical- and electrical-propulsion stages to strike a balance between transit time, minimal power degradation, and delivered payload mass. Therefore, mission designers need a method for rapidly evaluating low-thrust transfers to GEO. Relying on full trajectory-optimization programs for preliminary studies is not a desirable option due the time associated with optimizing multiple trajectories. This paper develops an algorithm that rapidly determines the Δv for a low-thrust transfer from an arbitrary elliptical orbit to GEO. Transfer time to GEO is accurately computed by incorporating thrust interruption (due to Earth-shadow effects) and power degradation (due to passage through the Van Allen belts). The method relies on curve-fits of optimal transfers and simple polynomial expressions for the orbital-element histories. Hence, the technique is fast and does not require numerical integration of the powered equations of motion or a numerical search. We demonstrate our method by presenting several transfers to GEO and comparing the performance metrics with the associated optimal transfers.

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AAS 19-745

ENDGAME DESIGN FOR EUROPA LANDER: GANYMEDE TO EUROPA APPROACH*

Rodney L. Anderson,† Stefano Campagnola,† Dayung Koh,† Timothy P. McElrath† and Robyn M. Woollands†

The endgame scenario that was explored in this analysis consisted of the part of the trajectory starting at the last Ganymede flyby and ending at the final Europa approach. The basic design components included computing the phasing for the final Ganymede encounter, computing the required intermediate Europa flybys, determining the required maneuvers to transition between the intermediate resonances, and interfacing with a computed portal prior to the final approach. The JPL optimization software, COSMIC, was used in the ephemeris model to optimize solutions computed in the circular restricted three-body problem and compute bounds on the attainable set of solutions by sweeping various design parameters.

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SPACECRAFT MANEUVER STRATEGY OPTIMIZATION FOR DETECTION AVOIDANCE USING REACHABILITY SETS

Connor N. Clary,[*] Jason A. Reiter[†] and David B. Spencer[‡]

The Conjugate Unscented Transform allows for an easy calculation of reachability sets with a minimal number of full model propagations. The computation time savings that comes with this method encourages implementation of reachability sets in more complex problems. Spacecraft maneuver planning for detection avoidance is unique in that all objectives may not be met by moving some minimum distance from the nominal orbit. Combining ground-track manipulation and propellant-use in reachability-based multi-objective optimization gives planners a unique perspective when designing detection avoidance maneuvers. Taking into account multiple maneuvers provides an advantageous opportunity to optimize a complete maneuver strategy for detection avoidance.

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AAS 19-750

OPTIMIZATION IN SPACE-BASED PURSUIT-EVASION GAMES THROUGH COMPETITIVE COEVOLUTION

Jason A. Reiter* **and David B. Spencer†**

Optimization in space-based pursuit-evasion games is often computationally cost prohibitive given the size of the state and action spaces available to both players. Competitive coevolution can be used to augment the optimization process in a manner that results in dynamic search spaces. In competitive coevolution, the two players compete directly with each other and reciprocally drive one another to increasing levels of performance and complexity. This is accomplished by gradually increasing the size and complexity of the strategies available to both players. Using coevolution provides significant computational cost savings compared to traditional optimization methods while ensuring a globally optimal result.

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AAS 19-758

MISSION FEASIBILITY FROM TRAJECTORY OPTIMIZATION AND THE STATE OF SPACE SYSTEMS RESEARCH AT THE UNIVERSITY OF AUCKLAND

Darcey R. Graham,[*] Nicholas J. Rattenbury[*] and John E. Cater[†]

New Zealand has very recently become a space-faring nation, and so it is at an exciting time deciding where its interests lie. The current state of space systems research at the University of Auckland, where focus is on inexpensive small satellites, is presented with methods to assess the feasibility of future missions based on trajectory optimization. The low-thrust and low-Δv capabilities of both old and novel electric propulsion systems place significant limitations on future missions, so limiting Δv by minimizing fuel requirements will be the objective of trajectory optimization. Different methods of trajectory optimization are compared.

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A CONVEX OPTIMIZATION APPROACH FOR FINITE-THRUST TIME-CONSTRAINED COOPERATIVE RENDEZVOUS

Boris Benedikter,* Alessandro Zavoli† and Guido Colasurdo‡

This paper presents a convex approach to the optimization of a cooperative rendezvous, that is, the problem of two distant spacecraft that simultaneously operate to get closer. Convex programming guarantees convergence towards the optimal solution in a limited, short, time by using highly efficient numerical algorithms. A combination of lossless and successive convexification techniques is adopted to handle the nonconvexities of the original problem. Specifically, a convenient change of variables and a constraint relaxation are performed, while a successive linearization of the equations of motion is employed to handle the nonlinear dynamics. A filtering technique concerning the recursive update of the reference solution is proposed in order to enhance the algorithm robustness. Numerical results are presented and compared with those provided by an indirect method.
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AAS 19-767

MISSED THRUST ANALYSIS FOR A POTENTIAL MARS SAMPLE RETURN ORBITER

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

Studies for an international NASA-ESA Mars sample return consider a hybrid Earth return orbiter capable of performing chemical Mars orbit insertion and using elsewhere solar electric propulsion in order to achieve its mission. This work presents the approach used to analyze the impact of unplanned outages producing missed thrust in the outbound and inbound heliocentric transfers. Safe mode statistics from NASA missions and an iterative trajectory optimization process enable a probabilistic analysis using Monte Carlo simulation. Results of the analysis are fundamental to assess the adequacy of propellant and time margins used in trajectory design.

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DEPENDENT VARIABLE INTEGRATION FOR EVENT FINDING WITH VALIDATION IN ORBIT PROPAGATION

Anthony Iannuzzi*

Space mission planning is a task that may rely on orbital and system level events to trigger a desired response. These events are defined as zero-crossings of a mathematical function. As an alternative to iterative root-finders, Henon's Method is a non-iterative integration technique, capable of finding events in an autonomous system. A new category of event finders is introduced, called Integrate To Solve (ITS) methods. ITS methods include Henon's Method and two new methods: Single Robust Integration of System (SRIS), and Repeatedly Integrate Derivative of the Interpolator to Tolerance (RIDIT). SRIS and RIDIT build upon Henon's Method, making it applicable to non-autonomous systems. They predict the direction of ITS integration and implement bisection as a backup for robustness. A new technique is introduced that makes ITS methods derivative-free, extending applicability. Events describing when a ground station has access to a satellite and the max angular rate at which the station's antenna must move to track the satellite are used to evaluate the effectiveness of SRIS and RIDIT with and without the derivative. Because Henon's Method cannot be applied to these event functions, Brent's Method of root-finding is used as a standard of comparison. The improvements made by SRIS and RIDIT and the derivative-free option allows ITS methods to have the same broad applicability as other contemporary root-finders.

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AAS 19-770

ACCURATE LOW-THRUST ORBIT TRANSFER SOLUTIONS IN EQUINOCTIAL ELEMENTS USING AN ANALYTIC REPRESENTATION OF THE GEOPOTENTIAL[*]

Zachary J. Folcik[†] and Paul J. Cefola[‡]

Analytical gravity models are included in the equinoctial element formulation of the low-thrust optimal equations of motion and the adjoint equations for the Lagrange multipliers. Geopotential models of up to degree and order four are developed and tested in this paper; the capability to write analytic expressions for arbitrary degree and order geopotentials follows from the Maxima symbolic algebra approach employed. Previous work using tensors to transform accelerations from inertial coordinates to Euler-Hill coordinates is extended for a general geopotential. The correctness of the tensors is verified. Optimal low-thrust orbital transfer solutions under the influence of gravitational perturbations are described.

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This material is based upon work supported by the United States Air Force under Air Force Contract No. FA8702-15-D-0001. Any opinions, findings, conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the United States Air Force. (RAMS 1009855).

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AAS 19-774

SOLAR SAIL TRAJECTORIES AND ORBIT PHASING OF MODULAR SPACECRAFT FOR SEGMENTED TELESCOPE ASSEMBLY ABOUT SUN-EARTH L2

Gabriel J. Soto,[*] Erik Gustafson,[†] Dmitry Savransky,[‡]
Jacob Shapiro[*] and Dean Keithly[*]

In-space assembly of a segmented primary mirror is needed to produce a large primary mirror bigger than LUVOIR, about 30m in diameter. We propose a novel mission concept for a segmented space telescope where each identical mirror segment is placed on modular spacecraft. Individual modules are launched as payloads of opportunity that self-assemble about the Sun-Earth L2 point. They use a solar sail as a means of continuous thrust propulsion. After docking, the solar sails are steered to overlap and create a planar sun shield for the telescope. We provide the framework for minimizing the total mission assembly time.

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AAS 19-779

INTERPLANETARY LOW-THRUST DESIGN USING PROXIMAL POLICY OPTIMIZATION

Daniel Miller,[*] Jacob A. Englander[†] and Richard Linares[‡]

This paper aims to demonstrate a reinforcement learning technique for developing complex, decision-making policies capable of planning interplanetary transfers. Using Proximal Policy Optimization (PPO), a neural network agent is trained to produce a closed-loop controller capable of mass-optimal transfers between Earth and Mars. The agent is trained in an environment that utilizes a real ephemeris model of the Earth and Mars. Multiple scenarios are presented with both fixed and variable time steps. The results are compared against those generated by the Evolutionary Mission Trajectory Generator (EMTG) tool.

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HOMO- AND HETEROCLINIC CONNECTIONS IN THE SPATIAL SOLAR-SAIL EARTH-MOON THREE-BODY PROBLEM

Jeannette Heiligers*

This paper investigates homo- and heteroclinic connections between solar-sail periodic orbits in the Earth-Moon circular restricted three-body problem (CR3BP). While homo- and heteroclinic connections have been explored extensively in the classical Earth-Moon CR3BP, the inclusion of a solar-sail induced acceleration introduces a time-dependency into the dynamics. This time-dependency prevents the use of traditional tools that reduce the dimensionality of the problem in search for such connections (e.g., the Jacobi constant and spatial Poincaré sections). Previous work by the author has already demonstrated that homo- and heteroclinic connections can be found in the *planar* solar-sail Earth-Moon three-body problem for a perfectly reflecting solar sail by introducing: 1) a piece-wise constant sail attitude along the unstable and stable solar-sail assisted manifolds, 2) the concept of temporal Poincaré sections, and 3) a genetic algorithm approach. This paper extends the work to the *spatial* problem and will also, for the first time, explore the effect of non-specular reflectance properties of the solar sail on the connections. Both homo- and heteroclinic connections between planar Lyapunov orbits and between halo orbits are presented for different solar-sail models, with errors on the position and velocity at the connection of the unstable and stable manifolds of, on average, 1 km and 25 m/s for the planar case and 15 km and 56 m/s for the spatial case.

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AAS 19-789

PARKER SOLAR PROBE MISSION DESIGN

Yanping Guo*

A mission to the sun originally called Solar Probe was first considered in 1958 and stayed in concept and feasibility studies for five decades until 2007, when a new mission design was created that changed the original mission architecture. The re-designed mission was named Solar Probe Plus due to significant advantages in technical implementation and science return, and it was renamed Parker Solar Probe (PSP) in 2017. PSP was launched on August 12, 2018 as the first mission to touch the Sun. This paper presents an overview of the mission design changes over the mission development phase and the final PSP mission design, including the launch, launch targets, and full set of mission trajectories over the 24-day 2018 launch period. Core to the PSP mission design is a unique V^7GA mission trajectory that uses 7 Venus gravity-assists to spiral down to the Sun, as close as 9.86 solar radii from the Sun's center, and offers 24 solar encounters in 7 years of the mission by visiting the Sun 3 to 4 times per year.

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AAS 19-799

SURVEY OF LOW-THRUST, EARTH-MARS CYCLERS

Robert Potter,[*] James Longuski[†] and Sarag Saikia[‡]

Twenty-two, Earth-Mars cyclers are presented that produce a Pareto front from which mission designers can select. The number of cycler geometries investigated is based on three criteria: 1) a maximum number of four vehicles required to cover every crewed Earth-to-Mars and Mars-to-Earth transfer, 2) an average of less than 1 km/s of ΔV required per synodic period (2.1 years), and 3) a low-thrust propulsion system with a thrust-to-weight ratio of 0.1 N/Mg (mm/s^2). Twenty unique geometries and two hybrid geometries satisfy those constraints totaling 78 trajectories that were propagated using MALTO spanning 2018 to 2056. Out of the twenty-two cyclers, we have identified five that with the most desirable characteristics—Cycler 9, Cycler 10+12, Cycler 16, Cycler 4+5, and Cycler 2.

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LEVERAGING NASA'S LUNAR GATEWAY AND HUMAN LANDING SYSTEM FOR LOW-COST MARS ORBITAL MISSIONS

Robert Potter,* Sarag Saikia† and James Longuski‡

NASA is pushing to have a human presence in lunar orbit in the 2020s and a human landing on the Moon by 2024. This paper outlines three Mars orbital missions in 2035, 2039, and 2044 with excursions to Phobos and Deimos for minimal cost. The missions leverage the same systems used in NASA's proposed Lunar Gateway and Human Landing System. A stop-over and cycler architecture are compared in terms of cost (including hardware, launch, and operations) and logistics (launch manifest and supply aggregation locations). From 2025 to 2045, the stop-over and cycler architectures cost $46 and $39 billion respectively in 2019 constant purchasing power. The stop-over architecture is easier to initially implement but requires $5 billion per mission in propellant launches. The cycler architecture is more costly in the first half because a large Mars logistics node, an inbound cycler, and an outbound cycler must be built before the first mission, which may not be feasible, because it coincides with the first new Moon landings.

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AAS 19-806

L2 STATION KEEPING MANEUVER STRATEGY FOR THE JAMES WEBB SPACE TELESCOPE

Jeremy Petersen*

The station-keeping plan for the James Webb Space Telescope achieves zero velocity in the x-component at the fourth successive crossing of the XZ plane of the rotating libration point frame. A differential corrector is employed to determine the necessary delta-v. Maneuvering along the position component of the stable eigenvector of the monodromy matrix produces a minimum delta-v solution. The techniques developed to determine the minimum maneuver direction in a full ephemeris model, along with strategies to cope with the attitude constraints imposed by the sunshield that prevents the ability to maneuver along the stable eigenvector, are examined in this study.

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AAS 19-811

A UNIFIED FRAMEWORK FOR AEROCAPTURE SYSTEMS ANALYSIS

Athul Pradeepkumar Girija,[*] Sarag J. Saikia,[†] James M. Longuski[‡] and James A. Cutts[§]

A unified framework for aerocapture systems analysis studies is presented, taking into account the interconnected nature of interplanetary trajectory design and vehicle design. One of the limitations of previous aerocapture systems studies is their focus on a single interplanetary trajectory for detailed subsystem level analysis. The proposed framework and aerocapture feasibility charts enable a mission designer to perform rapid trajectory and vehicle design trade-offs, and is illustrated with its application to a Neptune mission. The approach can be applied to other atmosphere-bearing Solar System destinations. The framework can be implemented in an aerocapture software suite to enable rapid mission design studies.

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AEROCAPTURE PERFORMANCE ANALYSIS FOR A NEPTUNE MISSION USING A HERITAGE BLUNT-BODY AEROSHELL

Athul Pradeepkumar Girija,[*] Sarag J. Saikia,[†] James M. Longuski,[‡] Shyam Bhaskaran,[§] Matthew S. Smith[**] and James A. Cutts[††]

The large navigation and atmospheric uncertainties at Neptune have historically driven the need for a mid-lift-to-drag (L/D) vehicle with $(L/D)_{max}$ of 0.6–0.8. All planetary entry vehicles flown to date are low-L/D blunt-body aeroshells with L/D less than 0.4. The lack of a heritage mid-L/D aeroshell presents a long pole for Neptune aerocapture, as the development and testing of a new entry vehicle incurs significant cost, risk, and time. Techniques which may allow Neptune aerocapture to be performed using heritage low-L/D blunt-body aeroshells are investigated, and obviate the need for mid-L/D aeroshells. A navigation study is performed to quantify the delivery errors, and a new guidance algorithm with onboard density estimation is developed to accommodate atmospheric uncertainties. Monte Carlo simulation is used to analyze aerocapture performance of a vehicle with L/D = 0.4. One hundred percent of the cases captured successfully and show a 99.87% probability of achieving the desired science orbit with a total of 396 m/s propulsive ΔV budget, even with worst-case atmospheric uncertainties.

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AAS 19-816

MID-COURSE CORRECTION CONTINGENCY ANALYSIS FOR THE JAMES WEBB SPACE TELESCOPE

Taabish Rashied,[*] Benjamin Stringer,[*] Jeremy Petersen[†] and Karen Richon[‡]

This investigation details two analyses performed as part of an early orbit contingency operations study related to the James Webb Space Telescope's limited ability to maneuver in a sunward direction. First, contingency planning developed by the Flight Dynamics Team and shared with the Science and Operations Center to quickly assess the available timeline in the event of a delayed mid-course correction maneuver is presented. Second, the methods for recovering from a maneuver overburn using observatory geometry to exploit the solar radiation pressure perturbation contributions from the large sunshield as well as adjusting the maneuver campaign to recover the observatory are examined.

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AAS 19-824

REVISITING TRAJECTORY DESIGN WITH STK ASTROGATOR PART 1

**Cody Short,[*] Pradipto Ghosh[†]
and Austin Claybrook[‡]**

Despite more than six decades of ongoing presence in space, the process of spacecraft trajectory design remains challenging. As orbital regimes become more crowded and attainable from an expanding industry, new challenges arise. Research efforts to better understand previously unexploited strategies and drive innovation in the face of new constraints continue to increase. At the same time, all of these research and design efforts are restricted by the complication of a "lab" where designers cannot physically interact with their designs; they are confined to a virtual workbench. Indeed, it is not uncommon for trajectory designers to spend much of their time creating tools for that workspace. This situation is strange as most industries that involve design and analysis typically do not build their own tools. The Systems Tool Kit (STK) Astrogator module from Analytical Graphics, Inc. (AGI) is one such tool intended to improve the trajectory design and analysis process, both for the engineer and for the solution. Astrogator's evolving development is the subject of this paper.

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AAS 19-829

TRAJECTORY DESIGN FOR A SOLAR POLAR OBSERVING CONSTELLATION

Thomas R. Smith,[*] Natasha Bosanac,[†] Thomas E. Berger,[‡] Nicole Duncan[§] and Gordon Wu[**]

Space-based observatories are an invaluable resource for forecasting geomagnetic storms caused by solar activity. Currently, most space weather satellites obtain measurements of the Sun's magnetic field along the Sun-Earth line and in the ecliptic plane. To obtain complete and regular polar coverage of the Sun's magnetic field, the University of Colorado Boulder's Space Weather Technology, Research, and Education Center (SWx TREC) and Ball Aerospace are currently developing a mission concept labeled the Solar Polar Observing Constellation (SPOC). This concept comprises two spacecraft in low-eccentricity and high-inclination heliocentric orbits at less than 1 astronomical unit (AU) from the Sun. The focus of this paper is the design of a trajectory for the SPOC concept that satisfies a variety of hardware and mission constraints to improve solar magnetic field models and wind forecasts via polar viewpoints of the Sun.

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AAS 19-831

HELIOSWARM: SWARM MISSION DESIGN IN HIGH ALTITUDE ORBIT FOR HELIOPHYSICS

Laura Plice,[*] Andres Dono Perez[†] and Stephen West[‡]

Resolving the complex three-dimensional turbulent structures that characterize the solar wind requires contemporaneous spatially and temporally distributed measurements. HelioSwarm is a mission concept that will deploy multiple, co-orbiting satellites to use the solar wind as a natural laboratory for understanding the fundamental, universal process of plasma turbulence. The HelioSwarm transfer trajectory and science orbit use a lunar gravity assist to deliver the ESPA-class nodes attached to a large data transfer hub to a P/2 lunar resonant orbit. Once deployed in the science orbit, the free-flying, propulsive nodes use simple Cartesian relative motion patterns to establish baseline separations both along and across the solar wind flow direction.

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AAS 19-834

EXPLORATION OF THE IMAP SCIENCE ORBIT DESIGN SPACE TO BALANCE NOMINAL AND EXTENDED MISSION TRADES

Amanda Haapala[*] and Fazle Siddique[†]

The Interstellar Mapping and Acceleration Probe (IMAP) mission, planned for launch in 2024, will place a spacecraft in a Sun-Earth L_1 Lissajous orbit to study the boundary of the heliosphere that encapsulates and protects our solar system. The nominal mission is planned for two years, with an extended mission expected to continue the science and space weather objectives. While the design space is relatively small, the mission costs can vary significantly. Here, studies of the multidimensional trade space are presented that enable selection of the optimal science orbit that balances the needs of both the nominal and extended missions.

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NAVIGATING TO A KUIPER BELT OBJECT: MANEUVER PLANNING ON THE APPROACH TO ULTIMA THULE

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Nearly thirteen years and over 6.5 billion kilometers into its voyage out of the solar system, on January 1, 2019, the New Horizons spacecraft achieved the milestone of exploring the furthest, most primitive object ever observed up close. With a closest approach distance of just over 3500 km, New Horizons has yielded detailed, high resolution images of the Kuiper Belt Object Ultima Thule. This paper describes the experience of navigating to Ultima Thule over the final year prior to the closest approach. It discusses the optimal placement of maneuver opportunities, and shares the challenges of deciding which maneuvers to execute given the information available at the time.

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ROBUST TRAJECTORY OPTIMIZATION USING MINIMUM-UNCERTAINTY COST FUNCTIONS

Erica L. Jenson[*] and Daniel J. Scheeres[†]

In microgravity environments where maneuvers are propellant-inexpensive but uncertainties are high, a minimum-uncertainty trajectory optimization may be preferred over a minimum-propellant optimization. This paper presents a method to design open-loop, continuous thrust orbit transfers while minimizing final state error covariance. Both initial state uncertainty and control-linear noise are included. Linear covariance propagation is used to form a Bolza-type cost function, and locally-optimal trajectories are found with indirect single shooting. The method is applied to asteroid orbit transfers in the two body problem. Homotopy methods are used to investigate the solution space between minimum-energy and minimum-uncertainty solutions.

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AAS 19-847

MICRO-PULSED PLASMA THRUSTER MANEUVER CHARACTERIZATION

Andrew Wilchynski,[*] Nicholas Nuzzo[†] and Jennifer S. Hudson[‡]

The Optical Plasma Spectroscopy CubeSat (OPS-Cube) will consist of a 6U CubeSat equipped with a micro-pulsed plasma thruster and an optical emission spectrometer. The mission will demonstrate on-orbit electric propulsion thruster diagnostics via optical measurements of the thruster's plasma plume. The OPS-Cube mission offers a unique opportunity to characterize the micro-pulsed plasma thruster's capabilities for small satellite orbit maneuvers. This paper describes the orbit maneuver design for the OPS-Cube mission, including the effects of mission and system-level constraints on thruster operation and sensitivity to thrust vector misalignment.

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AAS 19-848

OPTIMAL SPACECRAFT DOCKING MANEUVER USING DIRECT AND INDIRECT COLLOCATION METHOD AND PARTICLE SWARM OPTIMIZATION

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

In this paper, an indirect method combined with a heuristic approach is investigated to solve an optimal spacecraft docking maneuver problem. The relative dynamic frames used are the fully nonlinear Clohessy-Wiltshire equations for relative translation dynamics and the Euler equations of rotation for rotation of the two spacecrafts. Both direct and indirect collocation methods are implemented and results from these two optimization methods are compared and discussed. Theoretically, the indirect method presents the difficulty that the problem size is large due to discretization of the costates in addition to requiring good enough initial guesses for the costates variables. This paper presents a new approach where a heuristic optimization (HO) algorithm is used beforehand to generate a sufficiently accurate initial guess for the costates variables used for the collocation method applied later on. The heuristic algorithm is able to perform a global search in the space of the unknown costates in order to efficiently initialize the collocation algorithm. In this work, the method will focus on a minimum time maneuver problem and a combined minimum time and minimum energy problem. Results show that the indirect collocation method with a good guess performs better than a purely direct approach. However, the direct method is useful to compare and gain insights for different kinds of problems as well as to give initial estimations of the total time and energy cost.

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LOW THRUST TRANSFERS BETWEEN HALO ORBITS IN THE EARTH-MOON SYSTEM

Mohammad S. Azhar[*] and Robert G. Melton[†]

This paper presents the use of particle swarm optimization (PSO) for optimizing the time and propellant consumed in low-thrust and finite-thrust transfers between halo orbits of various amplitudes in the Earth-Moon system, using the circular restricted 3-body problem dynamics. PSO is employed to find the optimum thrust pointing angles and the time of the transfer trajectory. The algorithm is able to determine optimum transfer trajectories between halo orbits around Earth-Moon L_1 and L_2 libration points for continuous low-thrust trajectories, as well as for finite-thrust trajectories with and without an assumed coasting arc.

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ANALYSIS OF A CONSTRAINED OPTIMAL MULTIPLE-PHASE LANDING TRAJECTORY FOR A SMALL ROBOTIC LUNAR LANDER

J.P. Carrico III,[*] Jae-ik Park,[†] Alisa Hawkins[‡] and Dong-Young Rew[§]

KARI is planning to launch a small robotic lunar lander using its own launch vehicle after the first Korean lunar orbiter, Korea Pathfinder Lunar Orbiter (KPLO). For the successful landing mission using comparatively small launch capability, minimization of the fuel necessary for landing is critical. We have performed preliminary design and analysis for the system configuration of a potential lunar lander, with a specific focus on understanding the necessary mass fractions, thrust level, and attitude during a powered descent. This paper details how the constrained optimal multiple-phase landing trajectory of a small robotic lunar lander was analyzed for the second phase of the Korean lunar exploration program.

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AAS 19-867

HELIOCENTRIC ESCAPE AND LUNAR IMPACT FROM NEAR RECTILINEAR HALO ORBITS

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

Spacecraft departing from the Gateway in a Near Rectilinear Halo Orbit (NRHO) experience gravitational forces from the Moon, the Earth, and the Sun, all of which can be simultaneously significant. These complex dynamics influence the eventual destinations of the departing spacecraft. The current investigation examines the flow of objects leaving NRHOs in the Bicircular Restricted Four-Body Problem, and results are applied to heliocentric escape and lunar impact trajectories in a higher-fidelity ephemeris model. Separation maneuver magnitude, direction, and location are correlated with successful departure to various destinations via maps and specific examples.

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AAS 19-878

SELECTING PLANNING HORIZON LENGTH FOR SEQUENTIAL LOW-THRUST ORBIT-RAISING OPTIMIZATION PROBLEM

Pardhasai Chadalavada* and Atri Dutta†

In this paper, we revisit the low-thrust multi-revolution orbit-raising problem formulated as a sequence of optimal control sub-problems, each of which computes the trajectory over a planning horizon. Each sub-problem solves an unconstrained optimization problem described in terms of dynamical coordinates, by minimizing a convex combination of three components reflecting the deviation of the maneuvering spacecraft from the geosynchronous equatorial orbit. This paper explores the impact of planning horizon time-length on the optimality gap of the computed solutions, by considering minimum-time solutions as the reference. Numerical results are presented by considering transfers starting from non-planar geosynchronous transfer orbits.

[View Full Paper]

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AAS 19-883

MISSED-THRUST ANALYSIS OF BEPICOLOMBO'S INTERPLANETARY TRANSFER TO MERCURY ORBIT

Pablo Muñoz*

After a successful launch on October 20th 2018, the BepiColombo mission will spend seven years in interplanetary cruise in order to reach Mercury orbit by means of nine planetary gravity assists (Earth, Venus and Mercury) and extensive usage of its solar-electric propulsion. In preparation for the autumn-2018 launch period, a missed-thrust analysis of BepiColombo's interplanetary transfer was carried out to evaluate the robustness of the reference trajectory against contingency thrust outages. This paper describes the assumptions, methodology, implementation choices and results of this analysis, as well as the derived conclusions, trajectory modifications and recommendations for flight operations.

[View Full Paper]

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AAS 19-893

RISK-AWARE TRAJECTORY DESIGN WITH IMPULSIVE MANEUVERS: CONVEX OPTIMIZATION APPROACH

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

Guaranteeing safety is a major concern in any space mission design. It is especially important for missions that need to operate in uncertain environment or that require spacecrafts make decisions autonomously. Although the current mission design typically takes heuristic safety margins for the design constraints, such approaches may not capture the actual realizations of the uncertainties. To address the issue, we propose a new approach termed risk-aware trajectory design that optimizes spacecraft trajectories under uncertainties by applying chance-constrained optimal control to astrodynamics. As a first part of our two-part series, this paper focuses on trajectory design with impulsive maneuvers. The developed algorithm optimizes trajectories via sequential convex optimization with probabilistic safety constraints. The theoretical development is numerically demonstrated with a science orbit transfer scenario around an asteroid inspired by the OSIRIS-REx mission.

[View Full Paper]

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OPTIMAL INSPECTION TRAJECTORIES WITH ENFORCEMENT OF CHIEF AND INSPECTOR-CENTERED DYNAMIC ZONE CONSTRAINTS

Mark R. Mercier*and Kirk W. Johnson†

The need for on-orbit optimal inspection missions has risen with the aging of important legacy space assets. It is of interest to complete inspection missions without interruption of mission operations which can be simulated via dynamic keep-in and keep-out zone constraints. In addition, inspection pointing requirements must be captured via a body-fixed, inspector-centered keep-in zone constraint. This study implements a technique capable of finding the optimal inspection trajectory in the presence of multiple dynamic zone constraints which are either chief or inspector-fixed. This technique is demonstrated in two examples with unique constraint zone scenarios.

[View Full Paper]

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AAS 19-904

FAST SOLUTION OF OPTIMAL CONTROL PROBLEMS WITH L1 COST

Simon Le Cleac'h[*] and Zachary Manchester[†]

We propose a fast algorithm for solving optimal control problems with L1 control cost. Convergence to the global optimum is guaranteed for systems with linear dynamics, and the algorithm can also be used to find local optima for nonlinear dynamical systems. Our approach relies on the alternating direction method of multipliers (ADMM) and uses a fast trajectory optimization solver based on iterative LQR. The low computational complexity coupled with the fast execution of this algorithm make it suitable for implementation in flight software.

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AAS 19-909

FLYBY IN THE SPATIAL THREE-BODY PROBLEM

Davide Menzio[*] and Camilla Colombo[†]

The spatial flyby map originates from the planar one to extend its applicability to the out-of-plane dynamics of the circular restricted three-body problem. A novel parametrisation enables to give new insights on the effect of the flyby on inclined orbits. The main contributions of this paper consists first of all in the development of the method itself, secondly, in the identification of two type of trajectories: prograde (type I) and retrograde (type II) flybys. Finally, the paper demonstrates that direct gravity assists (type I) are more efficient when compared to the retrograde ones. The new approach will enable a large-scale of applications in which inclined orbits are necessary for targeting non-coplanar objects but also to meet some specific mission requirements.

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RISK-AWARE TRAJECTORY DESIGN WITH CONTINUOUS THRUST: PRIMER VECTOR THEORY APPROACH

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

This two-part series shares the common objective: *design optimal spacecraft trajectories with guaranteed safety,* with different focuses in terms of the orbit control approaches. This paper presents a framework for solving risk-aware trajectory design problems with continuous thrust. In contrast to the impulsive maneuver case, convex optimization approaches are not suited for the continuous-thrust problems. Instead, this paper extends the primer vector theory to incorporate deterministic and stochastic state inequality constraints. The extended primer vector theory is combined with a direct/indirect hybrid numerical optimization framework to solve continuous-thrust trajectory design problems. Part of the theoretical result is demonstrated with numerical examples of many-revolution low-thrust trajectory design problems, showing the validity of the theoretical work.

[View Full Paper]

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AAS 19-915

REVISITING "HOW MANY IMPULSES?" QUESTION

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

Theodore Edelbaum asked a fundamental question in a 1967 paper: "How Many Impulses?" The question asks: For a general orbit transfer with some unknown number, N_{imp} of impulsive velocity changes: 1) how many impulses, 2) at what times, and 3) in what direction should these impulses be applied to minimize the total impulse, Δv? Impulsive solutions determine bounds on both minimum time and minimum fuel extremals and also provide reachability insights. We present a unified approach (through what we introduced *optimal switching surfaces*) that encompasses all extremal impulsive and low-thrust trajectories. It presents a systematic approach to answer Edelbaum's question and can be viewed as a unification in astrodynamics where the connection between impulsive and continuous-thrust trajectories.

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AAS 19-918

ENABLING SUSTAINABLE HUMAN EXPLORATION OF MARS VIA AN ORBITAL LOGISTICS NODE

Rachana Agrawal,[*] Robert Potter,[†] Sarag J. Saikia[‡] and James M. Longuski[§]

To enable sustainable human exploration of Mars, supply chains are crucial and must have nodes at critical locations such as the Earth's surface, Earth's orbit, cis-lunar space, Mars' orbit and the surface of Mars. In this paper, we define the functions of a Mars orbital logistics node; define its elements and configurations; and determine the implications of having such a node in Mars orbit. We describe one such logistics node in orbit around Mars, envisaged to with have aggregation, refueling, and refurbishing capabilities. To assess a node's efficacy, we present preliminary results from the assessment of impacts of arrival and departure interplanetary trajectories, and landing site on the selection of orbital logistics node orbit—one of the primary design drivers. A Low Mars Orbit is found to be most suitable node orbit in terms of overall ΔV requirement.

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CHEBYSHEV DYNAMICS APPROXIMATION METHOD

Tyler Doogan[*] and Manoranjan Majji[†]

A trajectory optimization approach that approximates the system dynamics, as opposed to transcribing the state trajectories is presented in the paper. Chebyshev polynomials are used to illustrate the methodology. The process of discretizing the system dynamics for dynamic optimization purposes is shown to be applicable to a wide variety of dynamic optimization problems. Approximating the system dynamics, along with the properties of the Chebyshev polynomials provides a unique pseudospectral method, with attractive properties. The advantages of using this method are demonstrated using benchmark problems, and its performance is compared to the well known pseudospectral methods.

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AAS 19-926

MANEUVER PLANNING FOR THE NISAR MISSION

F. Rogez,* S. Hatch† and A. Halsell‡

NISAR, a joint NASA-ISRO science mission will require maintaining an Earth-fixed ground track and altitude to accurately repeat every 12 days. We constructed a ballistic reference trajectory that meets the science requirements but excludes some forces. The latter are treated as perturbations to be either corrected or absorbed within the requirement tolerance. Perturbation prediction errors require frequent and rapid design activities, which drive us toward automation, robust implementation, and streamlined processes. Combining a simplified model of the effect of future maneuvers, with an accurate propagation of the current trajectory provides a robust control system with appropriate accuracy given the input uncertainty.

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UNCONSTRAINED SPACECRAFT TRAJECTORY OPTIMIZATION USING EMBEDDED BOUNDARY VALUE PROBLEMS

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

An optimization algorithm is described and demonstrated that leverages many solutions to embedded boundary value problems along a spacecraft trajectory discretized into many segments. For Keplerian dynamics, the boundary value problems are solved with an iteration-free, interpolated solution to Lambert's problem. The algorithm combines exact first-order gradients and the Broyden–Fletcher–Goldfarb–Shanno correction for the search direction, and implements a simple line search using the golden ratio method and quadratic interpolation. The formulation is purely unconstrained leading to fast runtimes and a simpler implementation than typical spacecraft trajectory optimization formulations that require constraints. The algorithm is useful as a flexible, preliminary direct method capable of minimizing the sum of delta-vs, the sum of the square of delta-vs, or a homotopy between the two. The algorithm incorporates different time-free transfers such as fixed-state to fixed-state or orbit to orbit, and approximates both high and low thrust. The optimization variables are primarily position enabling more intuitive, physical initial guess schemes. Unlike many trajectory optimization applications, this algorithm's computational runtime for two-body dynamics is dominated by large matrix manipulations after approximately 100 discretization nodes, not the computation of the dynamics nor gradients. This limitation, common to all direct methods, practically restricts the number of revolutions to approximately 50 or 100 in order to keep single-processor runtimes on the order of minutes or hours, respectively. On the other hand, this algorithm is highly efficient for transfers on the order of tens of revolutions. Several examples demonstrate the effect on performance of different initial guesses, optimizers, embedded boundary value problem solvers, cost minimizations, and node count. The optimal trajectories within these demonstrations use hundreds of segments, include up to 50 revolutions, and have single-processor runtimes on the order of seconds to minutes. The scope of this work is limited to two-body dynamics to emphasize the quickness of the algorithm and its utility to provide an initial guess for problems with two-body perturbations.

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AAS 19-932

DESIGN AND SYNTHESIS OF ENTRY, POWERED DESCENT AND LANDING MANEUVER TRAJECTORIES USING MOTION ENVELOPES

Melissa M. Onishi[*] and Dilmurat M. Azimov[†]

NASA's past Mars missions such as Mars Pathfinder, the Mars Exploration Rovers and the Mars Science Laboratory projects have led to the necessity of designing the next generation of landers, one of the goals of which is to achieve safe and precise landing. Previous studies focused on the formulation of manifolds of initial and final points for atmospheric entry, powered descend and landing. These manifolds can be generated by a construction of envelopes of the maneuver trajectories using a vast range of terminal conditions for the trajectory and lander's parameters. This paper proposes improvements to the current design of three primary phases throughout the entry, descent and landing maneuver. These phases are the exoatmospheric thrust phase, atmospheric transit phase and powered descent and landing phase. A two-dimensional trajectory analyses for each phase are presented for a wide range of constant specific impulse and thrust-to-weight ratio along with an illustrative example.

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ORBITAL DYNAMICS, PERTURBATIONS AND STABILITY

Session Chair:

Orbital Dynamics, Perturbations and Stability: Roby Wilson, Jet Propulsion Laboratory

AAS 19-601

LONG-TERM NUMERICAL PROPAGATION FOR EARTH ORBITING SATELLITES

David A. Vallado[*]

Numerical propagation techniques have been extensively studied and are routine for precise satellite operations. Most studies focus on time spans of a few days to several weeks, specific orbital classes, or interplanetary orbits. As long term numerical operations become more commonplace, it's useful to quantify accuracy performance for propagations of several months, to years. This paper performs long-term numerical propagation comparisons against reference orbits in a variety of orbital classes. Semianalytical techniques are also used in the comparisons including a general discussion of the initial osculating to mean element conversion. Finally, orbital size, shape, and orientation considerations are examined.

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AAS 19-624

COMPUTING KEPLER EQUATIONS FOR ANALYTIC ORBIT PROPAGATION

Gim J. Der*

This paper presents an innovative technique to compute 2-Body and perturbed Kepler equations accurately and robustly for analytic orbit propagation for all orbit regimes. The traditional Vinti algorithm that includes J_2, J_3 and most of J_4 is extended to include Sun and Moon perturbations for most of the deep space objects especially those in GEO. This efficient Vinti algorithm is applied to solve the computationally intensive correlation problem of catalog building between radar/optical detection data and cataloged objects. This algorithm can also predict state vector between 24-hour GPS locks (updates) for GPS equipped Cubesats, and consumes less than 3% of the energy of a GPS lock. This advantage is being flight tested in the GPSRM 1 Cubesats Proxima I & II.

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AAS 19-642

LONG-TERM SURVEY OF LAMR AND HAMR OBJECTS USING ANALYTIC TECHNIQUES

Smriti Nandan Paul,* Bryan D. Little† and Carolin Frueh‡

With the states of many objects unknown and an ever increasing space debris population, detection of new space objects, especially the ones like high area-to-mass ratio objects which are susceptible to large perturbations, is critical for monitoring of near-Earth space. As a proof of concept, this paper uses analytic techniques for the survey and follow-up of low area-to-mass ratio objects in the geosynchronous (GEO) region. The survey is based on the so-called 'k-surface' created using long-term propagation of hypothesis objects, which are loosely based on GEO catalog objects. The surface is able to detect a decent number of GEO catalog objects, which prompts a further investigation where survey is carried out for high area-to-mass ratio objects. The surface for high area-to-mass ratio objects is created using hypothesis objects based on heuristics. The initial states of these hypothesis objects are assumed to be uncertain because of measurement and modeling inadequacies. This paper uses analytic perturbation techniques to propagate uncertainties in initial Keplerian orbital parameters, area-to-mass ratio, and diffuse reflection coefficient. The uncertainty propagation is carried out in presence of Earth point gravity and its higher harmonics, solar and lunar gravity, and solar radiation pressure. Unscented transformation based sigma points is used for capturing the initial uncertainties.

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AAS 19-644

NAVIGATION MODELS FOR PSYCHE ELECTRIC PROPULSION UNCERTAINTY*

Nicholas Bradley,† John Steven Snyder,‡ Drew Ryan Jones,§ Denis Trofimov and Dayung Koh††**

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The Psyche mission is planned to be launched to the main belt asteroid (16) Psyche in August 2022, using four Hall Effect Thrusters as the sole method of deterministic thrusting. Hall Effect thrusters have never flown in deep-space, and their performance uncertainty must be accounted for to assess expected navigation accuracy for the mission. We first discuss existing data on which our models are based. Then, we present the evolution of the navigation uncertainty model for low-thrust, with stochastic and bias parameters. We explore trajectory uncertainty sensitivity to low-thrust uncertainty model parameters. Finally, current results of expected navigation performance are presented.

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ANALYTIC APPROXIMATIONS OF ORBIT GEOMETRY IN A ROTATING HIGHER ORDER GRAVITY FIELD

Ethan R. Burnett* and Hanspeter Schaub†

This paper introduces new analytic approximations of the orbital state for a subset of orbits in a rotating potential with gravitational harmonics $C_{20} = -J_2$ and C_{22}. An analytic expression for the orbit radius is first obtained, then used to obtain expressions for 3 other quantities, which may be combined with equations for the right ascension of the ascending node and inclination to fully characterize the orbital state. The approximations are fully developed for near-circular orbits with initial mean motion n0 around a body with rotation rate c. The approximations are shown to be valid for values of $\Gamma = c/n_0 > 1$, with accuracy decreasing as $\Gamma \rightarrow 1$, and singularities at $\Gamma = 1$. The methodology in this paper can be adapted to approximate eccentric orbits in more general asymmetric potentials, and the necessary modifications are discussed.

[View Full Paper]

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AAS 19-731

ANALYTIC APPROXIMATION FOR FIXED-ANGLE LOW-THRUST TRAJECTORIES VIA LINEAR PERTURBATION THEORY

Guanwei He[*] and Robert G. Melton[†]

This paper presents an analytic perturbation solution to the equations of a spacecraft moving in a single plane under constant, fixed-angle, low-level thrust, and influenced by an inverse-square gravitational field. The solution is derived by using linear perturbation theory, which treats the motion of spacecraft as a linear combination of Keplerian motion and perturbed motion caused by the low thrust. Comparisons with direct numerical integration show relatively low errors and advantages in calculating speed for the approximate solution.

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ORBIT PROPAGATION VIA THE THEORY OF FUNCTIONAL CONNECTIONS

Hunter Johnston[*] and Daniele Mortari[†]

This paper presents a new method to perform accurate perturbed orbit propagation based on the Theory of Functional Connections (TFC). This method uses the analytical solution for the unperturbed two-body problem as a baseline, and estimates the perturbing term to add to the baseline, capturing the perturbations modeled. The main characteristic of this approach is that the constraints of the IVP problem are analytically embedded into the solution model which transforms the orbit propagation problem into an unconstrained optimization problem. The proposed iterative method is validated by integrating an unperturbed two-body problem and using a poor initial orbit guess to study the accuracy and convergence behavior. The solution accuracy is quantified by determining the evolution of the orbital invariant parameters (orbit shape, energy, and angular momentum, and the final position after one orbit). An additional test is included where 10; 000 orbits are conducted subject to third-body affects from the moon. In this test, the method converges in 1 iteration for 99:99% of the orbit segments.

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AAS 19-780

QUASI-HELIOSYNCHRONOUS ORBITS

M. L. G. T. X. Costa,* R. Vilhena de Moraes,† A. F. B. A. Prado,‡ and J. P. S. Carvalho§

In order to solve correctly the task of searching for heliosynchronous orbits when the equations of motion become coupled due to the inclusion of sectoral terms in the disturbing potential, the concept of quasi-heliosynchronous orbits is introduced. Using the tools of nonlinear optimization, quasi-heliosynchronous orbits are found for artificial satellites around the following bodies: Moon, the Galilean satellites and Titan. Those orbits can be used in real applications in missions going to these important celestial bodies.

[View Full Paper]

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AAS 19-805

APPLICATION OF UDWADIA-KALABA FORMULATION TO THREE-BODY PROBLEM

Harshkumar Patel,* Troy A. Henderson† and Morad Nazari†

This paper introduces the Udwadia-Kalaba formulation of constrained dynamics as applied to the three-body problem (Sun-Earth-Spacecraft). A dynamic model of the restricted three-body system is presented to analyze the unconstrained motion of spacecraft at the Lagrange point L1. The results verify the instability of L1 due to perturbation from the solar radiation pressure (SRP). Then, the Udwadia-Kalaba formulation is applied to derive the equation of motion of spacecraft with additional constraints to the three-body systems. The results provide the thrust force required for the spacecraft to recover its position to the L1 to compensate for the perturbation of SRP. The Baumgarte's stabilization method is included to obtain results when the spacecraft is inserted into orbit with incorrect initial conditions (i.e. 10 *km* away from L1), as usually happens in practice.

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LUNISOLAR PERTURBATIONS OF HIGH-ECCENTRICITY ORBITS SUCH AS THE MAGNETOSPHERIC MULTISCALE MISSION

Trevor Williams,[*] Eric Palmer,[†] Jacob Hollister,[†] Dominic Godine,[†] Neil Ottenstein[†] and Rich Burns[‡]

For highly eccentric orbits such as that of the Magnetospheric Multiscale (MMS) mission, with apogee radius now 29.34 Earth radii, the third-body effects of Sun and Moon are the major perturbations. One key consequence is an oscillation in MMS perigee altitude, on an approximately 6 year cycle. This variation has already required perigee-raise maneuvers to avoid an untimely reentry. There is also a long-term evolution in the orientation of the MMS orbit, with period roughly twice as long. This effect may potentially be useful for MMS science studies, as it can bring the spacecraft into new regions of the magnetosphere.

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FLIGHT DYNAMICS, OPERATIONS AND ATMOSPHERIC GN&C

Session Chair:

Flight Dynamics, Operations and Atmospheric GN&C: Brian Gunter, Georgia Institute of Technology University

AAS 19-619

MID-LIFT-TO-DRAG RATIO RIGID VEHICLE 6-DOF EDL PERFORMANCE USING TUNABLE APOLLO POWERED GUIDANCE

Breanna Johnson,* Ping Lu† and Christopher Cerimele‡

The Mid-Lift-to-Drag ratio Rigid Vehicle (MRV) is a candidate in the NASA multi-center effort to determine the most cost effective vehicle to deliver a large-mass payload to the surface of Mars for a human mission. Products of this effort include six-degree-of-freedom (6DoF) entry-to-landing trajectory performance studies for each candidate vehicle. These high fidelity analyses help determine the best guidance and control (G&C) strategies for a feasible, robust trajectory. This paper presents an analysis of the MRV's G&C design by applying common entry and descent associated uncertainties using a Fully Numerical Predictor-corrector Entry Guidance (FNPEG) and tunable Apollo powered descent guidance.

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AAS 19-638

THE DEVELOPMENT OF AN OPEN-LOOP ANGULAR MOMENTUM UNLOAD METHODOLOGY FOR THE LUNAR RECONNAISSANCE ORBITER AND OF ALGORITHMS TO PREDICT SYSTEM PERFORMANCE

Russell DeHart*

The Lunar Reconnaissance Orbiter is a three-axis stabilized spacecraft launched in 2009. In August 2017, the intensity of one of the miniature inertial measurement unit lasers began to decline and in March 2018 the unit was powered off to reserve what functionality remained for critical activities. Starting in August 2018, the mission began executing open-loop 'one-shot' angular momentum unloads, in which operators briefly fire thrusters, waiting for attitude controller errors to settle between firings. This paper presents models predicting the performance of planned one-shot angular momentum unloads. Predicted angular momentum unload duration, fuel usage, and imparted delta-V are compared against operational data for unloads in 2018 and 2019.

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AAS 19-682

AEROBRAKING TRAJECTORY CONTROL USING ARTICULATED SOLAR PANELS

G. Falcone* and Z. R. Putnam†

In aerobraking, the orbital energy is reduced by the atmosphere of the planet instead of large propulsive maneuvers resulting in propellant mass savings, which in turn lower launch costs, make extra mass available for the payload, or extend mission lifetime by conserving propellant. However, aerobraking campaigns require 3-9 months to complete and are operationally intensive. Aerobraking has been performed seven times in history; in all of them, the solar panels were oriented perpendicular to the flow direction prior to each atmospheric pass and to the Sun after the pass. This study examines aerobraking in which the solar arrays are exploited to provide in-plane control to the spacecraft during the atmospheric pass. This concept has the advantage of being able to compensate for density variations during the atmospheric pass. This ability can be used to maintain the probe in a safe thermal environment while maximizing energy depletion per atmospheric pass. Over an aerobraking campaign, this will have the effect of not only minimizing the number of apoapsis propulsive maneuvers required to maintain a safe periapsis altitude, but also will reduce the time required to complete the aerobraking campaign. On the basis of an analytical solution obtained through Pontryagin's minimum principle, an online optimal control algorithm has been implemented, which is able to control the atmospheric pass by rotating the solar panels. The optimal controller has been built to assure that the solar panels never exceed the thermal constraints and to exploit real-time data to maximize the dissipated energy during an atmospheric pass. Performance analyses of the controller indicate that its use enables a decrease of over 70% to the aerobraking duration if the only heat rate is fixed and a decrease of over 50% if also the heat load is constrained. Moreover, results show that this strategy enables to set and achieve a defined final spacecraft state.

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AAS 19-725

IMPROVED ATMOSPHERIC ESTIMATION FOR AEROCAPTURE GUIDANCE

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Increased interest in Lunar or Mars-sample return missions encourages consideration of innovative orbital operations such as aerocapture, which generally provides significant mass-savings for orbital insertion at Earth or Mars. Drag modulation architectures offer a straightforward approach to orbital apoapsis targeting by enabling ballistic entry, among other benefits. A shortcoming of these architectures is the poor estimation of atmospheric density resulting in target apoapsis altitude errors. This research seeks to assess and improve upon current atmospheric density estimation techniques in order to support the flight viability of discrete event drag modulated aerocapture. Three different estimation techniques are assessed in terms of estimation error and apoapsis altitude error: a static density factor, a density array interpolator, and an ensemble correlation filter. The density interpolator achieves a 5% improvement in median apoapsis altitude over the density factor when entering at –5.9° and targeting a 2000*km* apoapsis altitude, while the ensemble correlation filter achieves a 7% improvement under identical simulation conditions. The ensemble correlation filter was found to improve with decreasing density search tolerance, achieving a 4:6% improvement in median apoapsis altitude for a tolerance of 1% over 5%. These improvements are dependent on entry and vehicle parameters and improve as the entry angle becomes more shallow or the target apoapsis is reduced. Errors in the density factor measurements are main contributors to the error in estimated versus true density profiles.

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AAS 19-747

THE FIRST COMMERCIAL LUNAR LANDER MISSION: BERESHEET

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On 22 February 2019, at 01:45 UTC SpaceIL's Beresheet spacecraft launched to the Moon atop a SpaceX Falcon 9 rocket from Florida. This was the first private mission to the Moon and was done by only the 4th country to attempt a soft Lunar landing. On 4 April 2019, Beresheet successfully entered Lunar Orbit, and attempted to land on the Moon on 11 April 2019. In this paper the authors describe the trajectory and maneuver strategy, the navigation plan, and the ground station and tracking network. The on-orbit results are also described and compared with the pre-launch estimate.

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RADIOMETRIC AUTONOMOUS NAVIGATION FUSED WITH OPTICAL FOR DEEP SPACE EXPLORATION[*]

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With the advent of the Deep Space Atomic Clock, operationally accurate and reliable one-way radiometric data sent from a radio beacon (i.e., a DSN antenna *or other spacecraft*) and collected using a spacecraft's radio receiver enables the development and use of autonomous radio navigation. This work examines the fusion of radiometric data with optical data (i.e. OpNav) to yield more robust and accurate trajectory solutions and the associated navigation algorithms that can be readily adopted for onboard, autonomous navigation. The methodology is characterized using a representative high-fidelity simulation of deep space cruise, approach, and delivery to Mars.

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AAS 19-856

ESTIMATION OF ENTRY VEHICLE PARAMETERS FROM TRAJECTORY DATA

Kevin Bonnet[*] and Robert D. Braun[†]

Trajectory data are used to estimate the shape of an entry vehicle. Vehicle ballistic coefficient, the lift-to-drag ratio and the instantaneous bank angle are estimated from the 3D equations of motion. Sets of possible vehicle shapes are then determined assuming Newtonian flow theory. Repeating this process over time can provide further detail on vehicle parameters and flight control strategies. The impact of errors in the atmosphere model on the estimates are assessed and a method is proposed to mitigate these errors. The estimate of ballistic coefficient is shown to be only as accurate as the knowledge of the atmospheric density; whereas estimates of lift-to-drag ratio and bank angle are shown to be independent of atmospheric density error. This analysis is applicable to derivation of vehicle knowledge from flight reconstruction and to the conceptual design of entry vehicles that meet a broad range of known mission constraints.

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AAS 19-928

AUTONOMOUS SATELLITE NAVIGATION USING INTERSATELLITE LASER COMMUNICATIONS

Pratik K. Davé* and Kerri Cahoy†

This work investigates the use of laser communication (lasercom) intersatellite links to obtain relative position measurements for autonomous navigation. Lasercom crosslinks have the potential to provide intersatellite range and bearing measurements in order to accurately navigate satellites in a wide set of orbit cases, including GNSS-denied, GNSS-limited, and deep-space environments. Numerical simulations are used to compare the lasercom crosslink approach with traditional positioning and navigation methods in example application cases in low Earth-orbit (LEO), geostationary Earth-orbit (GEO), highly elliptical orbit (HEO), and a Mars-orbiting constellation. The use of lasercom measurements in Earth-orbit results in errors on the order of 2 meters in LEO, 10 meters in GEO, and 50 meters in HEO, which is on-par with current GNSS-based navigation errors. A constellation of Mars-orbiters using the proposed navigation method results in 10-meter position errors, which is on-par with current DSN-based navigation errors, when DSN operations are available, and better than propagated state knowledge during DSN data gaps. Use of intersatellite lasercom systems for orbit determination also decreases dependence on ground-based tracking and navigation systems, enabling greater autonomy in space missions.

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AAS 19-933

ENTRY TRAJECTORY TRACKING USING EQUIVALENT ELEVATION STATE FEEDBACK*

Jason M. Tardy†

A new form of entry guidance is proposed which uses angular state feedback to track a reference trajectory via bank angle modulation. This state consists of an equivalent elevation angle, its derivative, and flight path angle. The mathematics of the state are developed with respect to time and specific energy, and the solution is shown to be unique. For proof-of-concept, a linear feedback law is used to simulate reference tracking by an HL-20 class vehicle. Results prove the feasibility of this approach and demonstrate implicit range tracking and robustness to dispersions.

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* Note: The opinions expressed in this paper are the author's and do not represent the views of Sierra Nevada Corporation.

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ORBIT DETERMINATION AND SPACE SURVEILLANCE TRACKING

Session Chairs:

Orbit Determination and Space Surveillance Tracking I:
Puneet Singla, The Pennsylvania State University
Orbit Determination and Space Surveillance Tracking II:
Craig McLaughlin, University of Kansas Aerospace Engineering
David Lujan, University of Colorado Boulder

AAS 19-625

COMPUTING MULTI-REV LAMBERT EQUATIONS FOR RADAR DATA PROCESSING

Gim J. Der*

This paper presents how to compute accurately and efficiently multi-rev 2-Body Lambert equations, pick the correct 2-Body multi-rev Lambert solution out of 2N+1 without guessing or searching, and then convert analytically to a perturbed Lambert solution via Vinti-targeting. By picking the correct 2-Body multi-rev Lambert solution and eliminating unnecessary minimum time calculations without loss of accuracy, the computational efficiency of the 2-Body multi-rev Lambert algorithm, perturbed initial orbit conversion and in turn catalog building are greatly improved. The rise of Cubesats presents new opportunities for inspection satellite missions using perturbed multi-rev Lambert solutions. This perturbed multi-rev Lambert algorithm has been tested and verified extensively using arbitrarily position vectors from the NASA2015 debris catalog and Astrodynamics Support Workstation (ASW) data.

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AAS 19-626

COMPUTING GAUSS-LAPLACE EQUATIONS FOR OPTICAL DATA PROCESSING

Gim J. Der*

This paper presents an analytic perturbed angles-only algorithm for rapid catalog building. The relationship between optical sensor angles data output and the positive real roots of the 2-Body Gauss-Laplace 8th degree polynomial equations is revisited, so as to provide a better method of picking the correct root, if there are multiple positive real roots. Once the correct root is chosen; a 2-Body initial orbit is found, which can be converted to a perturbed initial orbit via analytic Vinti targeting. The perturbed initial orbit is accurate enough to be used for uncorrelated target data correlation and delay differential correction processing until more correlated data becomes available. Numerical examples provided in this paper are computed from GEODSS, GPS, simulated and other real optical data.

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AAS 19-636

THE EFFECT OF SMALL FORCES ON JUNO ORBIT DETERMINATION DURING THE ORBIT PHASE*

Yu Takahashi,† Brian Rush‡ and Paul Stumpf§ **

The Juno spacecraft reached the Jovian system on 05 July 2016 UTC and has been orbiting around Jupiter since then. The primary force acting on the spacecraft is the gravity from Jupiter that allows it to orbit in a highly elliptical trajectory that makes one full orbit every 53 days. Other perturbation sources include the gravity from the Sun and Jovian satellites, the solar radiation pressure, the deterministic maneuvers that target the next perijove longitude, statistical maneuvers to trim the trajectory error, and the maneuvers associated with the precession turns. These precession turns are performed to maintain Juno's inertial orientation and also known as small forces. These small forces prove to be one of the key parameters to estimate for the Juno orbit determination team. It is the purpose of this paper to analyze the effect of this small force in terms of the performance between the predicted and reconstructed solution deliveries used for the maneuver design.

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CIS-LUNAR NAVIGATION ACCURACY USING OPTICAL OBSERVATIONS OF NATURAL AND ARTIFICIAL TARGETS[*]

Nicholas Bradley,[†] Zubin Olikara,[‡] Shyam Bhaskaran[§] and Brian Young[**]

On-board optical-based autonomous navigation (AutoNav) has the potential to significantly reduce reliance on ground-based assets, and can provide a robust back-up system for unexpected ground outages. We continue an investigation of AutoNav across the solar system by assessing optical-only navigation performance in cis-lunar space using simulated observations of the center of the Moon, lunar landmarks, artificial satellites, and asteroids. We show that AutoNav in cis-lunar space is feasible and effective, and that artificial satellites, the Moon center, and lunar landmarks are effective targets for navigation. Optical AutoNav is feasible within current technological capabilities.

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INDEPENDENT NAVIGATION TEAM ORBIT DETERMINATION ESTIMATION OF 2014 MU_{69} FOR NEW HORIZONS' KUIPER BELT OBJECT FLYBY

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This paper details the JPL Independent Navigation team's experience refining the ephemeris of (486958) 2014 MU69 through optical navigation and how imaging of the body from the spacecraft improved the ground-based orbit solution by reducing the *a priori* covariance ellipsoid. We discuss how the uncertainty in the target's orbital elements was improved and how this translated to changes in the B-plane solution. We give examples of solutions with and without the use of ground-based occultation data and show that this data proved a useful constraint on the time of flight to the body. Data weights, filter setup, and residuals are shown, with an emphasis on optical navigation and ephemeris estimation challenges for this flyby.

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NEW HORIZONS' NAVIGATION PERFORMANCE THROUGHOUT THE EXTENDED MISSION TO ULTIMA THULE

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The New Horizons' extended mission to 2014MU69 (nicknamed 'Ultima Thule') was akin to the early Apollo program where the project boldly leapt into the unknown relying on ingenuity to help solve unexpected, complex challenges along the way. Much like New Horizons' primary mission, it was once again a race against time, but now with only three and a half years to find a way to accurately determine the future position of a body that wasn't discovered until 2014. Success relied on new optical navigation methods to detect a dimly lit object against a dense background starfield as well as teaming up with scientists and astronomers to determine the most accurate ephemeris predictions possible for Ultima Thule. The Navigation Team also prepared for the potential challenge of encountering a binary system and needing to determine, without any *a priori* knowledge, each body's orbit about the other. This paper will focus on the key functions of the orbit determination process involving radio metric and optical measurements, the estimation of the Ultima Thule ephemeris, and the characterization of attitude control small forces acting on the spacecraft. A complete overview of the New Horizons extended mission is also presented in order to document the performance and results of the orbit determination and trajectory targeting maneuvers that enabled a successful flyby of Ultima Thule.

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APPLICATION OF DUAL NUMBER THEORY TO STATISTICAL ORBITAL DETERMINATION

Christopher B. Rabotin*

The problem of computing a matrix of partial derivatives with respect to a state to be estimated is shown to be solved using dual number theory. Specifically, hyper-dual spaces are used to compute the state transition matrix and the sensitivity matrix used in Kalman filtering. An implementation of this method has been demonstrated in a programming language called Rust. Benchmarks show similar computation time performance between the analytical method and the hyper-dual method for computing the state transition matrix.

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A STUDY ON EFFECTIVE INITIAL GUESS FINDING METHOD BASED ON BÉZIER CURVES: ORBIT DETERMINATION APPLICATIONS

Daegyun Choi,[*] Sungwook Yang,[*] Henzeh Leeghim[†] and Donghoon Kim[‡]

In celestial mechanics, proper orbits related to missions are obtained by solving two-point boundary value problems. Since a selection method of initial value affects the convergence of the solution, developing an effective method to find an initial guess is required. In this work, Bézier curves, which can describe complicated curves and surfaces, are utilized to find the initial guess. First, the given problems are transformed into Bézier curves forms, and Bézier curves' control points, which can handle the shape of curves, are selected by solving the system of nonlinear equations. Finally, the initial guess is obtained by substituting the calculated control points to Bézier curves. To validate the performance of the proposed method, numerical simulations are conducted with respect to three kinds of orbits, which are from circular to highly elliptical orbit (HEO). The proposed method is compared to the general shooting method. The comparison results show that the initial guess calculated by Bézier curves makes finding the solution more efficient in terms of computational time and iterations. Also, it shows that the proposed method finds the solution for the HEO while the general shooting method fails to find the solution.

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IMPLEMENTING AN IDAN SPEYER CAUCHY DRAG ESTIMATOR

Craig A. McLaughlin,[*] Micaela Crispin[†] and Frank J. Bonet[‡]

Recent work shows that drag related parameters can better be described by a Cauchy distribution than a Gaussian. For this reason, an Idan Speyer Cauchy drag estimator is nested within an extended Kalman filter orbit determination process. The estimator is tested along the CHAMP satellite orbit and the drag acceleration measurements are calculated using CHAMP accelerometer-derived densities. In addition, the distribution of the density residuals, defined as the difference between the accelerometer-derived density and the NRLMSISE-00 density, is examined to see if it better matches a Cauchy or Gaussian distribution.

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AN ESTIMATION-BASED DRAG COEFFICIENT MODEL FOR TRACKING VARIATIONS DUE TO ATTITUDE AND ORBITAL MOTION

Vishal Ray[*] and Daniel J. Scheeres[†]

In an earlier paper, we proposed dynamic drag coefficient models based on Fourier series expansions to capture variations in the drag coefficient. The body-fixed Fourier (BFF) model was developed to respond to changes in satellite orientation and the orbit-fixed Fourier (OFF) model to respond to periodic variations in ambient parameters. In this work, we combine the advantages of both of these approaches to capture the fully varying drag coefficient in the form of generic models called body-orbit double Fourier (BODF) and body-orbit summation (BOS) models. We analyze the performance of these models for various attitude profiles in an elliptical orbit such that the drag coefficient varies both due to attitude and ambient parameters. Additionally, biases in geomagnetic and solar activity are introduced in the filter density model to simulate density errors. We demonstrate improved performance of these models over the standard cannonball drag coefficient model used in literature through simulations and processing of real data. The proposed BODF model improves the prediction performance by almost 50 % over the standard model for real data.

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AAS 19-757

ROOT LOCUS METHOD OF DETERMINING SENSITIVITY OF POLYNOMIAL SYSTEMS TO ERROR IN ASTRODYNAMICS APPLICATIONS

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This paper presents an investigation into the behavior of solutions to polynomial systems under the effects of uncertainty using the root locus method. The method is first investigated on a set of two second order polynomials. The method is then extended to the geolocation of a radio frequency transmitter from space-based receivers. By plotting the root loci, a better understanding is ascertained of the effects of various aspects of this problem, including measurement error, receiver or observer location, and changes to design parameters.

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AAS 19-775

OPTIMAL QUADRATURE-BASED FILTERING IN REGULARIZED COORDINATES FOR ORBIT DETERMINATION

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

The development of quadrature-based filters for orbit determination and challenges associated with their implementations while using constrained regularized variables in astrodynamics are discussed. Since the regularization process introduces redundant coordinates, a quadrature based method to explicitly account for the state constraints is developed. In particular, a non-product quadrature method known as the Conjugate Unscented Transformation is used for filter development. Numerical experiments are conducted to validate the developed filter and results are compared with linear error theory based filter such as the constrained Kalman filter.

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AAS 19-781

ANALYSIS OF RELATIVE MERITS OF UNSCENTED AND EXTENDED KALMAN FILTERS IN ORBIT DETERMINATION

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The unscented and extended forms of the Kalman filter are compared in the context of orbit determination. Differences and similarities of the algorithms are identified with an emphasis on treatment of state-error uncertainty in the presence of uncertainty in the dynamics and measurement models. A hybrid filter which combines elements of both algorithms is proposed in search of an optimal combination of computational performance and accommodation of higher order effects during measurement processing. The filter variants are compared based on application to set of realistic orbit determination scenarios.

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AAS 19-788

LIGHT CURVE INVERSION OBSERVABILITY ANALYSIS

Alex M. Friedman,[*] Siwei Fan[*] and Carolin Frueh[†]

Resident space object (RSO) information beyond position and velocity is important for identification and accurate propagation. Measurements of most RSOs are non-resolved images, meaning details of object shape are not explicit in images. However, methods exist to recover shape information with light curve measurements from non-resolved images. The direct light curve inversion scheme consists of development of an Extended Gaussian Image followed by solving the Minkowski problem. Observability notions and methods are applied to the EGI generation process, and time between measurements is varied to study how measurements can be efficiently generated for use in the light curve inversion scheme.

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GAUSSIAN MIXTURE FILTER ANGLES-ONLY ORBIT DETERMINATION USING MODIFIED EQUINOCTIAL OSCULATING ELEMENTS

Mark L. Psiaki*

A Gaussian mixture orbit determination filter is developed using a state vector that consists of equinoctial-like osculating elements. This new filter seeks to reduce the number of Gaussian mixture elements that are needed in order to accurately model the Bayesian posterior distributions that apply to the angles-only orbit determination problem. The modified equinoctial elements replace the elements *h* and *k*, whose sum squared is bounded by 1. The two replacement elements are unbounded, and *h* and *k* can be determined from them. This modification allows the orbit determination filter to operate in an unbounded state space. The new state requires the development of a corresponding mixand covariance upper bound because such a bound is needed by the particular type of Gaussian mixture filter that is implemented. The upper bound is used in a mixture resampling algorithm in a way which ensures that extended Kalman filter calculations will be sufficiently accurate for each mixand's computations. The resulting filter is able to reduce the required number of mixands from 5000 to 500 for angles-only orbit determination of a geosynchronous spacecraft.

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ROBUST PARTICLE FILTER FOR SPACE OBJECTS TRACKING UNDER SEVERE UNCERTAINTY

Cristian Greco,[*] Lorenzo Gentile,[†] Massimiliano Vasile,[‡] Edmondo Minisci,[§] and Thomas Bartz-Beielstein[**]

This paper presents a robust particle filter approach able to handle a set-valued specification of the probability measures modelling the uncertainty structure of tracking problems. This method returns robust bounds on a quantity of interest compatibly with the infinite number of uncertain distributions specified. The importance particles are drawn and propagated only once, and the bound computation is realised by inexpensively tuning the importance weights. Furthermore, the uncertainty propagation is realised efficiently by employing an intrusive polynomial algebra technique. The developed method is finally applied to the computation of a debris-satellite collision probability in a scenario characterised by severe uncertainty.

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SENSOR CONFIGURATION TRADE STUDY FOR NAVIGATION IN NEAR RECTILINEAR HALO ORBITS

Sehyun Yun,[*] Kirsten Tuggle,[†] Renato Zanetti[‡] and Chris D'Souza[§]

Deep Space Gateway is a NASA program planned to support deep-space human exploration and prove new technologies needed to achieve it. One of the Gateway requirements is to operate in the absence of communications with the Deep Space Network (DSN) for a period of at least 3 weeks. In this paper three types of onboard sensors (a camera for optical navigation, a GPS receiver, and X-ray navigation), are considered to enhance its autonomy and reduce the reliance on DSN. A trade study is conducted to explore alternatives on how to achieve autonomy and how to reduce DSN dependency while satisfying navigation performance requirements. Using linear covariance analysis, the performance of a navigation system using DSN and/or the other sensors is shown.

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AAS 19-862

TRACK INITIATION FOR CUBESAT CLUSTER DEPLOYMENT TRACKING

John A. Gaebler* and Penina Axelrad†

A track initiation scheme is presented that efficiently generates initial conditions for new targets appearing in a surveillance region after a large-scale clustered deployment. Currently in can take weeks for all CubeSats to be appear in the space catalog after such a deployment. This work assumes initial conditions are unknown and must be estimated from uncorrelated tracks in the presence of clutter. Pairs of radar-derived position vectors defining an orbit within a constrained admissible region are used to identify candidate targets via Lambert's method. These targets are then processed with a Labeled Multi-Bernoulli filter. A simulation of the Planet Labs Flock 3 deployment is used to demonstrate the approach. Results indicate that the method is capable of finding all targets from the clustered deployment in the presence of false measurements in three days.

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AAS 19-872

CONSIDER FILTERING APPLIED TO MANEUVER DETECTION FOR RELATIVE ORBIT DETERMINATION

Peter C. Scarcella,[*] Kirk W. Johnson[†] and Joshuah A. Hess[‡]

Determining the orbit of a non-cooperative maneuvering spacecraft in real time must balance computational efficiency with accuracy of the estimation. The Variable State Dimension (VSD) approach has been widely studied and applied to this problem using a variety of estimation schemes. Instead of merely adding random process noise to the thrust covariance to help convergence, a Consider Kalman Filter is implemented to add the uncertainty in parameters related both to the quiescent system dynamics and to the maneuver dynamics to improve the fidelity of the solution. By adding the extra uncertainty from mildly observable parameters related to the maneuver, this approach provides a low-computational-cost improvement over the nominal VSD for orbit determination of a non-cooperative spacecraft. Simulations are conducted for a continuously thrusting spacecraft with no a priori knowledge of the maneuver duration. Results have shown improved orbit and thrust estimation when adding consider parameters to maneuver detection.

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AAS 19-875

MAXIMUM A POSTERIORI ESTIMATION OF HAMILTONIAN SYSTEMS WITH HIGH ORDER SERIES EXPANSIONS

Simone Servadio,[*] Renato Zanetti[†] and Roberto Armellin[‡]

This paper presents a new approach to Maximum A Posteriori (MAP) estimation. Representing probability density functions through Taylor series expansions and using Differential Algebra techniques, this work proposes to derive the MAP estimate directly from high order polynomials. The new method is applied to the nonlinear Orbit Determination problem.

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AAS 19-885

AUTOMATED NAVIGATION ANALYSIS FOR THE LUCY MISSION

Jeremy Knittel,* Dale Stanbridge† and Kenneth Williams‡

The Lucy interplanetary trajectory presents a computationally challenging numerical optimization problem. The number of small body encounters presents an onerous navigation analysis process. Automating the trajectory targeting, statistical delta-v estimation, tracking data simulation and orbit determination process has increased the overall robustness of the navigation plan. These new techniques will enable rapid trade studies to be performed comparing different navigation concepts of operations. This work will highlight the new tools written and put into practice for Lucy and the methodology of automating much of the navigation analysis.

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AAS 19-890

ORBIT DETERMINATION AND TESTS OF GENERAL RELATIVITY IN THE CRUISE PHASE OF BEPICOLOMBO

Luciano Iess,[*] Ivan di Stefano, Paolo Cappuccio and Gael Cascioli

During its 6-year long cruise phase to Mercury, the ESA spacecraft BepiColombo will probe the laws of gravity during superior solar conjunctions. The Solar Conjunction Experiment (SCE) goal is to constrain the value of the Parametrized Post Newtonian (PPN) parameter γ, which controls the space curvature produced by a massive body. Thanks to the state of the art microwave instrumentation of the Mercury Orbiter Radioscience Experiment (MORE), the SCE will be able to improve the previous limits on γ set by the Cassini spacecraft. Spacecraft tests of general relativity and alternative theories of gravity require excellent accuracies in range and range rate observables and an extremely stable platform. In the case of the MORE SCE non-gravitational accelerations induced by solar radiation pressure are, an important source of spacecraft buffeting. Those accelerations cannot be fully accounted for because of the random fluctuations of the solar irradiance, whose magnitude is 0.1-0.01% of the average value. In this work we first characterize the effect of this dynamical noise on the outcome of the experiment, then we discuss a mitigation strategy based upon stochastic dynamical models, and finally we estimate a realistic uncertainty in the determination of the PPN parameter γ.

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ASTEROID AND NON-EARTH ORBITING MISSIONS

Session Chairs:

Asteroid and Non-Earth Orbiting Missions I:
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Asteroid and Non-Earth Orbiting Missions II:
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Asteroid and Non-Earth Orbiting Missions III:
Siamak Hesar, Blue Canyon Technologies

AAS 19-623

INITIAL NEAR-EARTH OBJECT ACCESSIBILITY INSIGHTS FROM THE "NHATSchecker" UTILITY

Daniel R. Adamo*

The NHATSchecker utility is independently spawned from Near-Earth Object Human Space Flight Accessible Targets Study (NHATS, pronounced "gnats") software documentation as a means to assess that software baseline's output reproducibility and to study effects from contemplated capability changes. Evaluating accessibility for specific near-Earth object destinations as examples, NHATSchecker processing provides multiple insights relevant to NHATS users and software developers alike. Initial insights from these examples are documented herein.

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SPACECRAFT ASTEROID HOVERING USING UDWADIA-KALABA FORMULATION WITH TIME-VARYING COEFFICIENTS

Wesley Stackhouse,[*] Morad Nazari,[†] Troy Henderson[†] and Tansel Yucelen[‡]

The dynamics and control of a spacecraft hovering over an asteroid are studied using the Udwadia-Kalaba (UK) constrained motion analysis and linear quadratic regulator (LQR). The equations of the constraints for a spacecraft to hover over an asteroid are derived for two hover scenarios: asteroid body-fixed hovering and hovering over a desired trajectory above the asteroid. For body-fixed hovering, the accelerations required to satisfy and maintain those constraints in the presence of gravitational perturbations of the asteroid are obtained using the UK formulation and an optimal LQR controller. The results obtained by the two methods are compared in terms of the control signals and the integrated control effort for the same settling time envelope. The two methods are found to be equivalent in the maintenance of a body-fixed hover position. The second case of a hover trajectory is shown using the UK formulation only. The convenience of implementation of the UK technique is illustrated through both scenarios.

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AUTONOMOUS ARCHITECTURES FOR SMALL BODY EXPLORATION

Daniel J. Scheeres* **and Jay W. McMahon†**

Architectures for the autonomous exploration of a small body using a rendezvous spacecraft are studied. The approaches are inspired by the OSIRIS-REx mission, which will focus on placing the spacecraft into a stable orbit, and the Hayabusa2 mission, which will focus on controlling the spacecraft in a quasi-hovering state for an extended period of time. These different architectures will be analyzed in terms of necessary navigation measurements and model estimation requirements, robustness of operations, and other criterion. The goal is to identify the relative advantages of each approach and to formulate appropriate mission goals based on the architecture used.

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OSIRIS-REX NAVIGATION CAMPAIGN TRAJECTORY DESIGN AND MANEUVER PERFORMANCE

Daniel R. Wibben,* Andrew Levine,* Samantha Rieger,†
James V. McAdams,* Peter Antreasian,* Jason M. Leonard,*
Michael C. Moreau† and Dante S. Lauretta‡

The first six months of asteroid proximity operations for the OSIRIS-REx mission is known as the Navigation Campaign – a portion of the mission designed to optimize initial characterization of asteroid Bennu and its dynamical environment in support of initial orbit insertion and transition from star-based to landmark-based optical navigation. During this time, the spacecraft executed 16 maneuvers across a large range of ΔV magnitudes. This work discusses the spacecraft trajectory design of the Navigation Campaign, which enabled the collection of critical information that led to the achievement of these milestones, and a summary of the performance of executed maneuvers.

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AAS 19-677

OSIRIS-REX FROZEN ORBIT DESIGN AND FLIGHT EXPERIENCE

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The OSIRIS-REx mission successfully entered a closed orbit around target asteroid Bennu for the first time on December 31, 2018. Due to the extremely low gravity of the asteroid, a specific orbit design was necessary to balance the perturbations provided from solar radiation pressure in order to maintain spacecraft safety, meet mission requirements, and demonstrate orbit stability over a propagation period of several months. This paper describes the design for OSIRIS-REx's record-setting orbit and the as-flown performance of the spacecraft while it remained in orbit for two months without need for orbit maintenance.

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AAS 19-678

POSE AND SHAPE ESTIMATION OF A SMALL BODY VIA EXTENDED TARGET TRACKING

Enrico M. Zucchelli,* Brandon A. Jones† and Ryan P. Russell‡

This paper describes a method to estimate shape and pose of a small celestial body with lidar measurements, and using only an extended Kalman filter. The shape of the small body is represented with a Gaussian Process, which naturally provides a continuous representation of the distance of the surface from the origin of the body and corresponding uncertainty. The proposed method shows promising results, offering an RMSE of approximately 1% on the shape of 433 Eros with an initial prior for the shape of a sphere and 1-sigma uncertainties of 10 degrees, 10 degrees, and 17 degrees per hour, on the spin axis declination, ascension, and spin rate respectively. The method converges for even larger initial uncertainties, and is statistically verified with Monte Carlo simulations over a variation of several parameters.

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AAS 19-708

DYNAMICS OF A NON-RIGID ORBITAL SIPHON AT A NEAR-EARTH ASTEROID

Andrea Viale,[*] Colin McInnes[*] and Matteo Ceriotti[*]

The orbital siphon is a novel concept for propellantless payload transfer from the surface of a rotating body to orbit. In the context of asteroid mining, the orbital siphon represents an efficient solution to deliver mined material from the asteroid surface to an orbiting station for later processing or storage. The key idea is that the centrifugal-induced force exerted on a tether-connected chain of payload masses assembled from the surface of a rotating body can be large enough to pull the lower masses, to initialize an orbital siphon effect: new payloads are connected to the chain while upper payloads are removed. In this paper, the dynamics of an orbital siphon anchored to two irregularly shaped near-Earth asteroids is investigated, along with the particle dynamics of the material being transport. The siphon is modelled as a closed chain of tether-connected buckets, kept taut by two pulleys, one at the asteroid surface and one attached to an orbiting collecting spacecraft. Buckets are filled with asteroid material, to be delivered to the collecting spacecraft. It is shown that the irregularities of the gravitational field do not introduce instabilities to the orbital siphon system. Without any braking mechanism required, the radial velocity of the siphon does not diverge but reaches a constant value at a steady-state. Moreover, it is shown that the siphon effect is still generated when the anchor moves on the asteroid surface, allowing the mining location to be moved without interrupting the flow of material to the collecting spacecraft.

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SENSITIVITY OF TRAJECTORIES TO MASS PARAMETERS IN THE RESTRICTED FULL THREE BODY PROBLEM

Alex B. Davis* and Daniel J. Scheeres†

In support of future missions to binary asteroids, such as DART and HERA, we study the sensitivity of spacecraft in the restricted full three body problem (RF3BP) to the mass parameters and geometry of the target binary system. The RF3BP is a dynamical model in which a massless spacecraft or particle orbits two arbitrary asymmetric mass distributions, in this case asteroids. Because of their complex shapes, the gravitational effect of the asteroids on one another and the spacecraft are modelled using a Legendre polynomial expansion of their mass distribution, described by the inertia integrals of each body. To understand the sensitivity of spacecraft trajectories to the many unknowns in such a system we derive the state transition matrix (STM) for the asteroid and spacecraft states as well as a mass parameter sensitivity matrix (MPSM) which maps the sensitivity of the full system state to the mass parameters. In combination the STM and MPSM are used to map the uncertainty of the initial state of the system and the asteroid mass parameters into a full covariance of the system dynamics along an integrated trajectory. Applying this method, we evaluate the information content of a sample set of trajectories in the 65803 Didymos system, target of DART and HERA, as well as the 617 Patroclus system, a flyby target of LUCY.

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AAS 19-714

OSIRIS-REX ORBIT DETERMINATION PERFORMANCE DURING THE NAVIGATION CAMPAIGN

Jason M. Leonard,[*] Jeroen L. Geeraert,[†] Brian R. Page,[†] Andrew S. French,[†] Peter G. Antreasian,[‡] Coralie D. Adam,[§] Daniel R. Wibben,[**] Michael C. Moreau[††] and Dante S. Lauretta[‡‡]

The OSIRIS-REx mission Navigation Campaign consists of three sub-phases: Approach, Preliminary Survey, and Orbital A. Approach was designed for initial characterization of Bennu while matching Bennu's heliocentric velocity. Preliminary Survey provided the first spacecraft-based estimate of Bennu's mass. This phase consisted of five target flybys with a close approach distance of about 7 km. Orbital A was a two-month phase devoted to the Navigation Team learning the close proximity operations dynamics and environment around Bennu and transitioning from center-finding optical navigation to landmark feature-based navigation. This paper provides a detailed summary of the orbit determination performance throughout the Navigation Campaign.

[View Full Paper]

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AAS 19-738

MULTI-ARC FILTERING DURING THE NAVIGATION CAMPAIGN OF THE OSIRIS-REX MISSION

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Daniel J. Scheeres[†] and Dante S. Lauretta[§]

The Navigation Campaign of the OSIRIS-REx mission consisted of three phases: Approach, Preliminary Survey and Orbital A. These phases were designed to optimize the initial characterization of Bennu's mass, shape and spin state to support a safe orbit insertion and a quick transition to landmark-based optical navigation tracking. The standard orbit determination filtering techniques used to navigate the spacecraft were unable to fit data from these three phases simultaneously due to numerical issues associated with the nonlinear dynamics and the long arc length. Consequently, a multi-arc filtering algorithm was implemented in order to combine the information from each of these arcs. Multi-arc solutions for Bennu's spin state and gravity field are presented here.

[View Full Paper]

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AAS 19-756

EARTH-MOON HALO ORBIT –GATEWAY OR TOLLBOOTH?

**David W. Dunham,[*] Kjell Stakkestad,[†] James V. McAdams,[‡]
Anthony Genova[§] and Jerry Horsewood[**]**

This paper describes some of the history that has resulted in NASA's plans for a Lunar Gateway (or just Gateway), and how building it to become a Deep Space Transport (DST) could result in savings over the current plan. The paper also describes how a DST can reach a variety of interesting destinations from an Earth-Moon halo orbit. Robert Farquhar promoted a lunar halo orbit station in 1971 and 2004. His ideas were expanded upon by others to create what is now known as the Lunar Gateway. But a "Moon-direct" approach is more efficient if the goal is only exploration of the lunar surface. For human missions to Mars and near-Earth objects, a lunar halo orbit is a good high-energy perch for a reusable Deep Space Transport (DST) between missions. The Gateway might be changed to a DST; building only one maneuverable habitat instead of two provides large savings. A technique that we call Phasing Orbit Rendezvous (PhOR) is proposed for exploration by the DST, to transfer astronauts and supplies to it just before its departure from Earth to an interplanetary destination. PhOR might also be used for astronaut repair of space observatories that normally operate in the Sun-Earth L2 region.

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AAS 19-761

FAST ESTIMATION METHOD FOR TRAJECTORIES TO NEAR-EARTH ASTEROIDS

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The paper presents a new approximate method for the estimation of minimum ΔV and propellant consumption for electric propulsion missions to Near-Earth asteroids. The method is purely algebraic and therefore very fast, as integration of the equations of motion is not required. It is based on the decomposition of the propulsive effort into basic burns; each burn has a specific purpose (i.e., change of perihelion or aphelion distance). The effects and the cost of the basic burn arcs are evaluated for almost-circular orbits with small inclination changes. An approximate suboptimal control law, which was initially developed for continuous thrust maneuvers, is employed. In general, results show a very good accuracy, with errors below 10-15% of the propellant consumption. Larger errors occur for specific combinations of the orbital parameters, when the plane change maneuver does not follow the expected scenario. Suggestions for improvements of the estimation method are highlighted, as the analysis of the results gives insight about the characteristics of missions to different NEAs.

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DESIGN AND RECONSTRUCTION OF THE HAYABUSA2 PRECISION LANDING ON RYUGU

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The Hayabusa2 spacecraft successfully landed on the asteroid Ryugu on February 22nd, 2019. Because of the abundance of boulders, the touchdown operation required high accuracy for spacecraft safety. This research, therefore, investigates a precision landing sequence using retroreflective marker tracking. The trajectory for the touchdown operation is computed based on a high-fidelity gravity model to minimize the landing error. This paper provides trajectory reconstruction results based on actual flight data. Consequently, it is demonstrated that a landing accuracy of 3 m can be achieved, resulting in the successful touchdown.

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AAS 19-819

NASA GODDARD INDEPENDENT NAVIGATION RESULTS FOR OSIRIS-REX INITIAL ENCOUNTER AT BENNU

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Throughout the OSIRIS–REx initial encounter with asteroid Bennu, a variety of optical navigation and orbit determination processes were used in support of spacecraft operations. The OSIRIS–REx Flight Dynamics Team consists of engineers from KinetX Aerospace, NASA Goddard Space Flight Center (GSFC), and the Aerospace Corporation working as an integrated team. While KinetX is responsible for a majority of the official navigation deliveries for operations, NASA personnel perform independent assessments of navigation performance with Goddard heritage tools, while also providing surge or backup support for operations. This paper describes the Goddard independent navigation effort and highlights results from the Approach, Preliminary Survey, and Orbital A mission phases.

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AAS 19-871

OPTICAL NAVIGATION FOR NEW HORIZONS' FLYBY OF KUIPER BELT OBJECT (486958) 2014 MU_{69}

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Catherine B. Olkin[†] and S. Alan Stern[†]

Due to relatively large a priori spacecraft to target uncertainties, optical navigation has played an integral role in the orbit determination and navigation of NASAs New Horizons spacecraft to its most recent target, Kuiper Belt Object (486958) 2014 MU_{69}. Key functions of the New Horizons optical navigation process include observation planning, attitude determination, planetary modeling, star and target centroiding, and other astrometric reduction techniques. These key functions as well as the approach and trajectory reconstruction optical navigation results and lessons from New Horizons flyby of 2014 MU_{69} are explored.

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AAS 19-876

EXPERIMENTAL FIELD TESTING AND CONFIRMATION OF PARTICLE SWARM OPTIMIZATION FOR AUTONOMOUS EXTRATERRESTRIAL SURFACE SEARCH AND EXPLORATION

Gregory D. Hatfield,[*] Alexander E. Cook[†] and May-Win Thein[‡]

Recent public policy shift and the national push toward "boots on the ground" missions to the Moon and other extraterrestrial surfaces will require extensive onsite habitats and facilities. Diverse resource requirements for any extraterrestrial habitation and the prohibitive cost and complexity of resource transportation away from Earth necessitate the gathering of resources from the inhabited surface. It is natural that preemptive prospection of various resources will be necessary for any habitation mission or extended exploration. Such prospecting missions would allow for immediate harvesting upon arrival and reduced payload requirements as a result. Previous work at the University of New Hampshire examined an autonomous methodology for the generic search mission on extraterrestrial surfaces via Particle Swarm Optimization (PSO). In this paper, the authors propose to apply the developed techniques to a fleet of ground-based robots as a proof of concept to demonstrate the efficacy of PSO as a search (i.e., prospecting) method for a prescribed area. (For testing practicality and without loss of generality, the robots are tasked to located peak terrain altitudes.) Numerical simulations and field test results using various benchmark topological functions and Lunar/Martian surface data sets show that PSO is consistently able to correctly determine the optimal (i.e., highest altitude) locations within the defined search space.

[View Full Paper]

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AAS 19-886

NAVIGATION PREPARATIONS FOR A POSSIBLE BINARY SYSTEM DURING THE NEW HORIZONS EXTENDED MISSION

Joel T. Fischetti, John Y. Pelgrift, Erik J. Lessac-Chenen, Jeremy A. Bauman, Derek S. Nelson, Fred J. Pelletier, Dale R. Stanbridge, Michael J. Salinas, Peter J. Wolff, and Bobby G. Williams[*]

Mark E. Holdridge and Harold A. Weaver[†]

John R. Spencer, Simon B. Porter, Marc W. Buie, Catherine B. Olkin, and S. Alan Stern[‡]

The New Horizons spacecraft recently completed the most distant close flyby in spaceflight history, at 43.3 AU from the sun, during its encounter with (486958) 2014 MU69, a Kuiper Belt Object (KBO). The image resolution necessary to determine whether MU69 was a single body or binary system was not attainable until days before encounter. This presented a challenge for navigation, as the mission needed to be prepared for the possible discovery and subsequent orbit determination of a binary system up until encounter. This paper presents the algorithm development, simulations, and results of operational readiness tests in preparation for a binary system.

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AAS 19-887

SPACECRAFT TRAJECTORY TRACKING AND PARAMETER ESTIMATION AROUND A SPLITTING CONTACT BINARY ASTEROID

Tiago M. Silva,[*] Jean-Baptiste Bouvier,[†] Kathleen Xu,[‡] Masatoshi Hirabayashi[§] and Koki Ho[**]

Increasing interest in asteroid mining and in-situ resource utilization will lead to an increase in asteroid surface operations. The geophysical properties of asteroids are often unknown, many of which play a significant role in gravitational forces. Surface operations such as mining may significantly alter the asteroid's structure or, in the case of contact binary asteroids, cause the asteroid to split depending on the rotational condition. The coupled problem of estimating unknown parameters of a splitting contact-binary system and controlling a spacecraft's trajectory in the system's vicinity is investigated. An indirect adaptive control scheme is utilized to simultaneously meet both objectives. The results are compared with the traditional 2-body controller and the improvement enabled by the proposed scheme is demonstrated.

[View Full Paper]

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HIGH PERFORMANCE COMPUTING, LARGE SPACE STRUCTURES AND TETHERS

Session Chair:

High Performance Computing, Large Space Structures and Tethers:
Fabio Curti, School of Aerospace Engineering,
Sapienza University of Rome, Italy

AAS 19-639

A UNIFIED FRAMEWORK FOR STATE-SPACE BASED RECOVERY OF MASS, STIFFNESS AND DAMPING MATRICES

Minh Q. Phan,[*] Dong-Huei Tseng[†] and Richard W. Longman[‡]

This paper provides a unified framework to recover a structure mass, stiffness, and damping matrices from its identified state-space model. In previous formulations, position, velocity, or acceleration measurements are treated as three separate cases where position measurement is mathematically the simplest yet the least practical, and acceleration measurement is the most practical yet mathematically the most complicated. In this paper, we derive relationships to transform a model with any type of measurement to another with any other type of measurement thus allowing techniques developed for one type of measurement to be translated to another type of measurement, thus offering a unified framework for all three types of measurements.

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VALIDATION OF SIMULATION OF SPACE NET DEPLOYMENT PHASE WITH PARABOLIC FLIGHT EXPERIMENT DATA

Rachael Gold* **and Eleonora M. Botta†**

A proposed solution to capture large debris is tether nets. This paper validates a simulator for the deployment of a net in space, implemented with the multibody dynamics simulation tool Vortex Dynamics. The dynamics of the simulated net, modeled with a lumped parameter approach, is compared to data taken during a parabolic flight experiment. Results show good agreement between the trajectory of the net in the experiment and in the simulation, when residual gravitational and Coriolis acceleration are accounted for. These results imply that the simulator can be confidently used to study the deployment dynamics of nets in space.

[View Full Paper]

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AAS 19-793

ROBUST OPTIMAL FUZZY SUN-POINT CONTROL OF A LARGE SOLAR POWER SATELLITE SUBJECT TO ACTUATORS AMPLITUDE AND RATE CONSTRAINTS

Chokri Sendi,[*] Antonio Won[†] and Luke McCue[‡]

This paper focus on the control design for attitude stability of a large solar power spacecraft made of a rigid platform, transmitting antenna and a rotating reflector. The solar sail experiences external disturbances due to the solar pressure, gravity-gradient moment, atmospheric drag, magnetic torques, and model uncertainties. Therefore, one of the main features of the designed fuzzy controller is to be made robust to withstand uncertainties, disturbances and to guarantee the Sun-pointing accuracy of the spacecraft. It should be noted that the designed controller stabilizes the attitude despite the fact that the spacecraft dynamic is subject to actuators amplitude and rate saturation. The proposed fuzzy controller is based on the Takagi-Sugeno (T-S) fuzzy model. The problem is formulated as a set of linear matrix inequalities and utilizes the parallel distributed compensator to obtain the feedback gains. Numerical simulations are provided to measure the performance of the proposed controller.

[View Full Paper]

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NLPAROPT: A PARALLEL NONLINEAR PROGRAMMING SOLVER - APPLICATIONS TO ASTRODYNAMICS RELATED OPTIMIZATION

Ryne Beeson,[*] Patrick Haddox,[†] Samah Karim,[‡] Bindu Jagannatha,[§] Devin Bunce,[**] Kyle Cochran,[††] Edgar Solomonik[‡‡] and Alexander Ghosh[§§]

In this paper, we present ongoing research and development on a new parallel nonlinear programming solver, NLPAROPT, that is being developed by CU Aerospace with collaboration from the University of Illinois at Urbana-Champaign. The solution of a nonlinear program is at the heart of many optimal control software packages; the result of a control transcription of the optimal control problem, using both direct or indirect approaches. Hence nonlinear programming solvers play a pivotal role in astrodynamics applications. Currently, all available (commercial or open source) nonlinear programming solvers are inherently serial, with trivial parallelism or parallelism that has not necessary been designed holistically. With this paper, we present the overall architecture of NLPAROPT, discuss how structure from the dynamic optimization problem can be exploited and how users can best setup their problems from a robustness and numerical efficiency standpoint, and conclude with current results on spacecraft trajectory and control related optimization problems.

[View Full Paper]

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DESIGN OF A DISTRIBUTED MODULAR ATTITUDE CONTROLLER FOR SPACECRAFT COMPOSED OF RECONFIGURABLE JOINED ENTITIES WITH COMPLIANT COUPLING

Deepti M. Kannapan*

We present a procedure for designing a simple distributed attitude control system for a reconfigurable spacecraft composed of joined entities, which are relatively rigid compared to the compliant interfaces between them. This problem is challenging due to flexible modes of the spacecraft, caused by the compliant interfaces, and inertial properties that take an ensemble of values as the spacecraft reconfigures.

We frame the problem as: pre-selecting control parameters and mechanical properties of the interfaces to ensure stability and performance for an ensemble of required configurations of the spacecraft, by identifying and designing for a bounding "worst-case" configuration from the ensemble.

[View Full Paper]

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AAS 19-874

CLOUD COMPUTING METHODS FOR NEAR RECTILINEAR HALO ORBIT TRAJECTORY DESIGN

Sean M. Phillips[*] and Diane C. Davis[†]

Complicated mission design problems require innovative computational solutions. As spacecraft depart from a proposed Gateway in a Near Rectilinear Halo Orbit (NRHO), recontact analysis is required to avoid risk of collision and ensure safe operations. Escape dynamics from NRHOs are governed by multiple gravitational bodies, yielding a trajectory design space that is exhaustively large. This paper summarizes the recontact analysis for departure from the NRHO and describes how the Deep Space Trajectory Explorer (DSTE) trajectory design software incorporates high performance cloud computing to compute and visualize the orbit design space.

[View Full Paper]

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SPECIAL SESSION – GTOC-X (GLOBAL TRAJECTORY OPTIMIZATION COMPETITION)

Session Chair:

Special Session: GTOC - X (Global Trajectory Optimization Competition):

Anastassios Petropoulos, NASA / Caltech JPL

GTOC X: SETTLERS OF THE GALAXY PROBLEM DESCRIPTION AND SUMMARY OF THE RESULTS*

Anastassios E. Petropoulos,† Eric D. Gustafson,‡ Gregory J. Whiffen§ and Brian D. Anderson**

The Global Trajectory Optimization Competition was inaugurated in 2005 by Dario Izzo of the Advanced Concepts Team, European Space Agency, as a means of fostering innovation in trajectory design and cross-fertilization with other fields. GTOC2 through GTOC9 were organized by the winning teams of the preceding GTOC editions. Keeping this tradition, the Outer Planet Mission Analysis Group and Mission Design and Navigation Section of the Jet Propulsion Laboratory organized the tenth edition of the competition, GTOC X. The futuristic problem posed may loosely be described as a "Settlers of the Galaxy" challenge, wherein trajectories must be designed for humanity to settle throughout the galaxy. After the release of the precise problem statement, the 73 registered teams had four weeks to work on the problem. Solutions were submitted to the competition website for automated verification and scoring on a leaderboard. A total of 42 teams returned solutions. In this paper we describe the GTOC X problem, and give an overview of the solutions and their verification and ranking. Six teams presented their work at a special GTOC X session of this Conference, including the winning team led jointly by the National University of Defense Technology and the Xi'an Satellite Control Center, both of China.

[View Full Paper]

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AAS 19-894

GTOC X: SOLUTION APPROACH OF TEAM SAPIENZA-POLITO

**Alessandro Zavoli,[*] Lorenzo Federici,[†] Boris Benedikter,[‡]
Lorenzo Casalino[§] and Guido Colasurdo[**]**

This paper summarizes the solution approach and the numerical methods developed by the joint team Sapienza University of Rome and Politecnico di Torino (Team Sapienza-PoliTo) in the context of the 10th Global Trajectory Optimization Competition. The proposed method is based on a preliminary partition of the galaxy into several small zones of interest, where partial settlement trees are developed, in order to match a (theoretical) optimal star distribution. A multi-settler stochastic Beam Best-First Search, that exploits a guided multi-star multi-vessel transition logic, is proposed for solving a coverage problem, where the number of stars to capture and their distribution within a zone is assigned. The star-to-star transfers were then optimized through an indirect procedure. A number of refinements, involving *settle time re-optimization, explosion*, and *pruning*, were also investigated. The submitted 1013-star solution, as well as an enhanced 1200-point rework, are presented.

[View Full Paper]

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AAS 19-896

GTOCX: METHODS AND RESULTS FROM THE HIT BACC TEAM

Qi Ouyang, Yong Liu,* Pengfei Cao, Zichen Fan, Yabo Hu, Cunyan Xia, and Gang Zhang†

This paper presents the methods proposed by the joint team of Harbin Institute of Technology and Beijing Aerospace Control Center in the 10th Global Trajectory Optimization Competition (GTOCX). The task is divided into five problems, including the multiple-impulse Lambert rendezvous problem of non-Kepler orbit, the multi-target flyby problem, the settlement scheme of mother ships and fast ships, the settlement scheme of the settler ship, and the optimization for propulsive velocity. The corresponding solving algorithms are provided. The best score of our team is 1167.42.

[View Full Paper]

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AAS 19-897

GTOC-X: OUR PLAN TO SETTLE THE GALAXY (ESA-ACT)

Dario Izzo,[*] Marcus Märtens,[†] Ekin Öztürk,[‡] Mate Kisantal,[§] Konstantinos Konstantinidis,[**] Luís F. Simões,[††] Chit Hong Yam[‡‡] and Javier Hernando-Ayuso[§§]

The 10th edition of the Global Trajectory Optimization Competition (GTOC-X) invited participants all over the world to compete against each other to design efficient missions with the goal to settle our galaxy. Leveraging concepts of interstellar space travel like generational ships, the participants were tasked to develop settlement plans as each newly settled star system could spawn new settlement ships. This work presents the solution strategies developed by the ESA-ACT during the month long competition. In particular, we unfold the mathematical structure of the objective function that demanded a uniform spread throughout the galaxy and discuss its implications. We describe a tree search that is able to grow settlement trees concurrently over time starting from multiple initial points. Furthermore, we deploy several techniques to rearrange already established settlement trees in order to reduce the overall propulsive velocity change required.

[View Full Paper]

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AAS 19-898

GTOCX: RESULTS AND METHODS OF TEAM 38 – TSINGHUA & XINGYI

Zhibo E,[*] Di Wu,[†] Shiyu Chen,[‡] Haiyang Li[§] and Yu Song[**]

This paper summarizes our computing methods and results of solving GTOCX problem. The GTOCX problem is referred to settlement of one hundred thousand suitable galaxy star systems during 90 million years. Solving such a large-scale problem requires tremendous amount of calculation. To overcome this difficulty, our team proposed a series of optimization strategies based on genetic algorithms. First, we design a partitioning strategy to generate the initial set of settlement stars, which are settled by fast ships and mother ships. Then, a multiple phase optimization strategy based on genetic algorithm is proposed to generate substantial settlement stars. After that, in order to decrease the fuel consumption, a local optimization method is applied to exchange different transfers. Finally, fuel consumption of all the transfers are optimized by NPSOL and PSO. The final score of our team's results is 2070.53.

[View Full Paper]

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AAS 19-899

GTOCX: RESULTS AND METHODS OF NATIONAL UNIVERSITY OF DEFENSE TECHNOLOGY AND XI'AN SATELLITE CONTROL CENTER

Ya-Zhong Luo,[1*] Hong-Xin Shen,[1†] An-Yi Huang,[‡] Tian-Jiao Zhang,[§] Yue-He Zhu,[**] Zhao Li,[§] Peng Shu,[**] Zhen-Jiang Sun,[**] Jian-Hui Li,[§] Zhen-Yu Li,[††] Jian-Jun Shi,[††] Bing Yan,[††] Xiang-Nan Du[††] and Zhen Yang[‡‡]

This paper describes the methods used and the results obtained by team NUDT&XSCC (a collaboration team between National University of Defense Technology and Xi'an Satellite Control Center) for the 10th edition of the Global Trajectory Optimization Competition. The resulting trajectory won the 1st place in the competition, achieving a final mission value of J = 3101.15. The methods used by our team are described. These methods mainly include star-targeting technique, allowing one to flyby 2 to 3 stars using a single impulse or two impulses; targets layout optimization technique, enabling one to select the targets to get optimal spatial distribution based on the insights into the ideal configuration; ant colony optimization, permitting one to construct feasible settlement trees for the selected optimal targets.

[View Full Paper]

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AAS 19-902

SETTLER OF THE GALAXY: THE CSU SOLUTION TO GTOCX

Chen Zhang,[*] Chi-hang Yang,[†] Hao Zhang,[‡] Ren-yong Zhang,[§] Hao Peng[**] and Yang Gao[††]

This work describes the CSU's solution to the GTOC-X. It is first noted that dynamics has several integrals and stars/spacecrafts move on invariant planes. Then galactic Lambert's problem is formulated to compute the transfers between two arbitrary stars. An algorithm is presented to fast evaluate the reachability from a star to its neighborhood, via dynamics dimension reduction, line transfer approximation, shooting with analytic derivatives, etc. The settlement tree is constructed by a two-step approach. The first step is to obtain a good initial layout of the settled stars by randomizing flight times. The second step aims to improve the score by locally changing the tree structure. Several strategies are developed, which are replacing nodes, regrowing branches and optimizing time of flight, respectively. The CSU team got the 6th place and the final score is 1111.01 points with about 1200 stars.
[View Full Paper]

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AAS 19-900

GTOC X: QUESTION AND ANSWER FORUM*

Anastassios E. Petropoulos†

In this presentation slot, a question-and-answer forum was held to conclude the Special Session on the Tenth Global Trajectory Optimization Competition. The Global Trajectory Optimization Competition was inaugurated in 2005 by Dario Izzo of the Advanced Concepts Team, European Space Agency, as a means of fostering innovation in trajectory design and cross-fertilization with other fields. GTOC2 through GTOC9 were organized by the winning teams of the preceding GTOC editions. Keeping this tradition, the Outer Planet Mission Analysis Group and Mission Design and Navigation Section of the Jet Propulsion Laboratory organized the tenth edition of the competition, GTOC X. The futuristic problem posed may loosely be described as a "Settlers of the Galaxy" challenge, wherein trajectories must be designed for humanity to settle throughout the galaxy. After the release of the precise problem statement, the 73 registered teams had four weeks to work on the problem. Solutions were submitted to the competition website for automated verification and scoring on a leaderboard. A total of 42 teams returned solutions. The Special Session was devoted to seven papers, one describing the competition and overall results, and six from the top ranked teams. The papers are included in the conference proceedings. The winning team, led jointly by the National University of Defense Technology and the Xi'an Satellite Control Center, both of China, is tentatively planning to host the next GTOC in early 2021, with the workshop at the ISSFD in April 2021 in China.

Only an abstract was available for this presentation.

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GTOC X: TROPHY PRESENTATION*

Anastassios E. Petropoulos†

In this presentation slot, the GTOC floating trophy, as well as the GTOC X award plaque, were presented to Zichen Fan who accepted them on behalf of the winning team, led jointly by the National University of Defense Technology and the Xi'an Satellite Control Center, both of China. The Global Trajectory Optimization Competition was inaugurated in 2005 by Dario Izzo of the Advanced Concepts Team, European Space Agency, as a means of fostering innovation in trajectory design and cross-fertilization with other fields. GTOC2 through GTOC9 were organized by the winning teams of the preceding GTOC editions. Keeping this tradition, the Outer Planet Mission Analysis Group and Mission Design and Navigation Section of the Jet Propulsion Laboratory organized the tenth edition of the competition, GTOC X. The futuristic problem posed may loosely be described as a "Settlers of the Galaxy" challenge, wherein trajectories must be designed for humanity to settle throughout the galaxy. After the release of the precise problem statement, the 73 registered teams had four weeks to work on the problem. Solutions were submitted to the competition website for automated verification and scoring on a leaderboard. A total of 42 teams returned solutions. The Special Session was devoted to seven papers, one describing the competition and overall results, and six from the top ranked teams. The papers are included in the conference proceedings. The winning NUDT-XSCC team is tentatively planning to host the next GTOC in early 2021, with the workshop at the ISSFD in April 2021 in China.

Only an abstract was available for this presentation.

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SPECIAL SESSION –
NASA CARA CA REQUIREMENTS DEVELOPMENT INITIATIVE

Session Chairs:

Special Session: NASA CARA CA Requirements Development Initiative:
Alinda Mashiku, NASA GSFC
Matthew Hejduk, Astrorum Consulting LLC

AAS 19-612

ASSESSING GEO AND LEO REPEATING CONJUNCTIONS USING HIGH FIDELITY BRUTE FORCE MONTE CARLO SIMULATIONS

Luis Baars,[*] Doyle Hall[†] and Steve Casali[‡]

Probability of collision (P_c) estimates for Earth-orbiting satellites typically assume a temporally-isolated conjunction event. However, under certain conditions two objects may experience multiple high-risk close approach events over the course of hours or days. In these repeating conjunction cases, the P_c accumulates as each successive encounter occurs. The NASA Conjunction Assessment Risk Analysis team has updated its "brute force Monte Carlo" (BFMC) software to estimate such accumulating P_c values for repeating conjunctions. This study describes the updated BFMC algorithm and discusses the implications for conjunction risk assessment.

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AAS 19-631

DETERMINING APPROPRIATE RISK REMEDIATION THRESHOLDS FROM EMPIRICAL CONJUNCTION DATA USING SURVIVAL PROBABILITY METHODS

Doyle T. Hall[*]

Satellites sometimes maneuver before conjunctions to remediate the risk of an on-orbit collision. Many missions use probability of collision (P_c) thresholds to decide when such maneuvers should be performed. These thresholds tend to be conservative because of policies that require satellites survive their lifetimes without collision with high confidence (e.g., 99.9%). This study presents a semi-empirical method to estimate remediation P_c thresholds that satisfy such lifetime risk requirements. The formulation combines survival probability analysis with empirical conjunction histories to estimate remediation thresholds as a function of satellite size, remaining on-orbit duration, lifetime collision probability limit, collision consequence, and other parameters.

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AAS 19-632

IMPLEMENTATION RECOMMENDATIONS AND USAGE BOUNDARIES FOR THE TWO-DIMENSIONAL PROBABILITY OF COLLISION CALCULATION

Doyle T. Hall[*]

The two-dimensional (2D) probability of collision (P_c) estimation method relies on several assumptions that must be satisfied for accurate results. Monte Carlo analysis of ~44,000 conjunctions indicates that 2D-P_c provides accurate estimates for most typical conjunctions, but occasionally underestimates P_c significantly, indicating an assumption violation. A test to detect large-amplitude underestimation inaccuracies can be based on how much "offset-from-TCA" 2D-P_c values vary during a well-defined time interval bracketing closest approach. The test successfully detects all large-amplitude 2D-P_c underestimations found to date, but with a high false-alarm rate. The analysis also provides implementation recommendations and usage boundaries for the 2D-P_c method. [View Full Paper]

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SATELLITE CONJUNCTION "PROBABILITY," "POSSIBILITY," AND "PLAUSIBILITY": A CATEGORIZATION OF COMPETING CONJUNCTION ASSESSMENT RISK ANALYSIS PARADIGMS

Matthew D. Hejduk[*] and Dan E. Snow[†]

A number of different conjunction assessment (CA) risk analysis methods and metrics have been proposed in the critical literature, and they vary widely in purport and form. However, they tend to be proposed individually and episodically, so that it is difficult for a CA practitioner to take stock of the possibilities, understand their fundamental differences, and make informed choices for their particular CA risk assessment enterprise. The present study seeks to collect the major proposals for risk assessment methods and parameters and organize them categorically, under the proposed divisions of "probability," "plausibility," and "possibility," as well as formulate what appears for each to be its fundamental question and, where applicable, null hypothesis. This activity can, through a bottom-up approach, provide some of the building blocks for an overarching CA philosophy, as well as establish concepts and terminology potentially useful to the broader discussion of these topics.

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AAS 19-668

NASA CONJUNCTION ASSESSMENT RISK ANALYSIS UPDATED REQUIREMENTS ARCHITECTURE

Lauri K. Newman,* Alinda K. Mashiku,† Matthew D. Hejduk,‡
Megan R. Johnson§ and Joseph D. Rosa**

The NASA Conjunction Assessment Risk Analysis (CARA) program has been performing routine on-orbit satellite conjunction risk analysis for unmanned NASA spacecraft since 2005, and has developed a robust operations procedure and set of recommended best practices for operational conjunction assessment. However, a number of recent developments in Space Situational Awareness and commercial space operations conduct, such as the imminent deployment of much more sensitive space sensing systems and the launching of much larger satellite constellations, have begun to challenge these standard collision risk parameters and calculations. In response CARA has pursued a multi-year evaluation initiative to re-examine risk assessment algorithms and techniques, to develop needed improvements, and to assemble analysis-based operational requirements. This paper gives an overview of the principal parts of the Conjunction Assessment (CA) risk analysis process used at CARA, outlines the technical challenges that each part presents, surveys the possible solutions, and then indicates which particular solution is being recommended for NASA.

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AAS 19-669

AN OPERATIONAL ALGORITHM FOR EVALUATING SATELLITE COLLISION CONSEQUENCE

Travis F. Lechtenberg*

Risk is properly considered as the combination of likelihood and consequence; but conjunction assessment has usually limited itself to the consideration of only collision likelihood. When considered from an orbital regime protection perspective, the focus shifts to the question of the amount of debris that a collision might produce (the "consequence"). The present paper presents an operational algorithm for determining the expected amount of debris production should a conjunction result in a collision, and an assessment of the algorithm's fidelity against a database of characterized objects.

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AAS 19-671

MULTIVARIATE NORMALITY OF CARTESIAN-FRAMED COVARIANCES: EVALUATION AND OPERATIONAL SIGNIFICANCE

Travis F. Lechtenberg[*]

Collision avoidance relies on representative Cartesian uncertainty volumes in order to calculate probabilities of collision. Among the potential shortcomings of a covariance matrix representation of state errors, the most worrisome is the coordinate mismatch between the Cartesian framework in which these matrices are distributed and the curvilinear path that satellite orbits actually follow. The present study compares curvilinear-based and Cartesian covariance representations for ~50,000 conjunctions to determine the frequency in which significant deviations from Gaussianity are observed, then compares the 2-D Pc result from the Cartesian covariance to a Monte Carlo Pc conducted in element space to assess operational significance.

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AAS 19-702

RECOMMENDED METHODS FOR SETTING MISSION CONJUNCTION ANALYSIS HARD BODY RADII

Alinda K. Mashiku[*] and Matthew D. Hejduk[†]

For real-time conjunction analysis (CA) operations, computation of the Probability of Collision (Pc) typically depends on the state vector, its covariance, and the combined hard body radius (HBR) of both the primary and secondary space objects. However, most algorithmic approaches that compute the Pc use generic conservatively valued HBRs that may tend to go beyond the physical limitations of both spacecraft, enough to drastically change the results of a conjunction assessment mitigation decision. On the other hand, if the attitude of the spacecraft is known and available, then a refined HBR can be obtained that could result in an improved and accurate numerically-computed Pc value. The goal of this analysis is to demonstrate the various number of different HBR calculation techniques and the resulting calculated Pc values obtained, based on spacecraft orientations in the encounter or conjunction plane at the time of closest approach (TCA). Since in most conjunctions the secondary object tends to be a space debris object and thus orders of magnitude smaller than the primary, the greatest operational benefit is wrought by developing a better size estimate and representation for the primary object. We present an analysis that includes the attitude information of the primary object in the HBR calculation and evaluating the resulting Pc values for conjunction analysis and risk assessment decision-making.

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SPECIAL SESSION – ARTIFICIAL INTELLIGENCE IN ASTRODYNAMICS I: MACHINE LEARNING

Session Chairs:

Special Session: Artificial Intelligence in Astrodynamics I - Machine Learning:

Simone D'Amico, Stanford University
Islam Hussein, Applied Defense Solutions

CALIBRATION OF ATMOSPHERIC DENSITY MODEL BASED ON GAUSSIAN PROCESS

Tianyu Gao,[*] Hao Peng[†] and Xiaoli Bai[‡]

Neutral mass density is presently the predominant uncertain term among all the factors affecting the atmospheric drag – the dominant perturbation force for space objects at low altitude. The current best density estimation performance is often achieved by empirical models, which can be limited by their assumed, parametric formulations. This paper presents a density estimation framework that integrates information from empirical models, environment conditions, and satellite measurement data. Different from existing frameworks, the new integration mechanism is based on Gaussian Processes (GPs) which are nonlinear, non-parametric regression methods. Furthermore, the method will provide uncertainty quantifications in its estimates through GPs' underlying Bayesian inference. Simulations are designed to test the hypothesis that the new framework is valuable to improve the performance of the empirical models. Empirical models including NRLMSISR-00 and JB2008 and accelerometer-inferred densities from satellite CHAMP are used for the study. The new method is shown to increase Pearson correlation coefficient (R) and reduce root mean squared error (RMSE) from the empirical models when the density estimation is tested on both the missing data and future densities, which are, respectively, within and following the GP's training period. Together with providing quality uncertainty quantifications, the proposed framework has the great potential to reduce the estimation errors from the empirical models and provide an effective means to estimate density for a satellite.

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DEEP IMITATION LEARNING AND CLUSTERING IN ASTRODYNAMICS

Roberto Furfaro,* Kristofer Drozd,† Richard Linares,‡ Brian Gaudet§ and Andrea Scorsoglio**

This paper explores the use of deep-learning frameworks both for imitation learning (supervised) and unsupervised methods applied to structure classification and understanding in CR3BP dynamics typically arising in astrodynamics. More specifically, the goal is to explore the use of deep architectures such as Convolutional Neural Networks (CNN) and Variational Autoencoders (VAE) to classify families of periodic orbits within and across CR3BP dynamics (e.g. Earth-Sun, Jupiter-Sun). It is demonstrated that CNNs are capable of capturing non-linear decision boundaries that enable distinctions between family of orbits. Importantly, VAEs are designed to model the distribution of data comprising periodic orbits. The key distributions parameters (mean and variance) are modeled using neural networks. Such parameters are then plotted on 2-D graph to visually evaluate the clustering of the orbits which enables classification. VAEs are also compared with non-linear, statistically-based dimensionality reduction methods (e.g. t-Distributed Stochastic Neighbor Embedding or t-SNE) that project trajectory data in lower-dimensional embedding, while preserving distance metrics. It is shown that individual families generate clusters that can be easily and visually distinguished in a 2-D plane. This study is an initial attempt to employ the features learned by deep networks in a data-driven fashion to better understand and identify dynamical structure arising in astrodynamics.

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NEURAL NETWORK BASED OPTIMAL CONTROL: RESILIENCE TO MISSED THRUST EVENTS FOR LONG DURATION TRANSFERS

Ari Rubinsztejn,* Rohan Sood† and Frank E. Laipert‡

A growing number of spacecraft are adopting new and more efficient forms of in-space propulsion. One shared characteristic of these high efficiency propulsion techniques is their limited thrust capabilities. This requires the spacecraft to thrust continuously for long periods of time, making them susceptible to potential missed thrust events. This work demonstrates how neural networks can autonomously correct for missed thrust events during a long duration low-thrust transfer trajectory. The research applies and tests the developed method to autonomously correct a Mars return trajectory. Additionally, methods for improving the response of neural networks to missed thrust events are presented and further investigated.

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AAS 19-776

UNCERTAINTY CHARACTERIZATION AND SURROGATE MODELING FOR ANGLES ONLY INITIAL ORBIT DETERMINATION

David Schwab,[*] Puneet Singla[†] and Joseph Raquepas[‡]

Initial orbit determination may be used to initialize object tracking and associate observations with a tracked satellite, but only if uncertainty information exists for the approximated orbit. While classical initial orbit determination algorithms only provide a point solution, uncertainty information may be inferred using deterministic sampling techniques. Along with uncertainty characterization, two statistical learning techniques are tested in their ability to approximate the orbit determination mapping: first, a polynomial approximation built from the statistical moments in the state space and second, Gaussian Process Regression.

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ADAPTIVE ONLINE LEARNING STRATEGY FOR POST-CAPTURE ATTITUDE TAKEOVER CONTROL OF NONCOOPERATIVE SPACE TARGET

Yueyong Lyu,* Yuhan Liu,† Zhaowei Sun‡ and Guangfu Ma§

This paper investigates the problem of the post-capture attitude takeover control for partial constrained combined spacecraft, subject to the unknown dynamics of the noncooperative target. An online learning control strategy is developed for post-capture attitude stabilization and maneuvering based on adaptive dynamic programming. The real-time inertia identification is avoided, while only I/O data is utilized to generate the control strategy. It is capable to adjust its parameters online over time under various working conditions, which is very suitable for the combined spacecraft with complex time-varying dynamics. Theoretical analysis and simulations are exhibited to validate the effectiveness of the proposed strategy.

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AAS 19-813

DEEP LEARNING APPLICATIONS TO ASTRODYNAMICS PROBLEMS

Jordan Murphy[*] and Daniel Scheeres[†]

This paper investigates the ability of deep learning to characterize and predict solutions to common astrodynamics problems by using a number of machine learning techniques. Training sets are developed by conventionally solving the problems, and, from these sets, predictions of results on the trajectories are made into the future. The accuracy of these techniques are compared with traditional methods.

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COVARIANCE FUSION STRATEGY OF GAUSSIAN PROCESSES COVARIANCE AND ORBITAL PREDICTION UNCERTAINTY

Hao Peng* and Xiaoli Bai†

The previously proposed machine learning (ML) approach can use the hidden relationship between the orbit prediction error and the available data to improve satellite orbit prediction accuracy. Bayesian inference techniques not only generate the ML-correction to the orbit prediction but also the covariance information about this correction. Previously, Gaussian Process (GP) models have been examined and found with good performance on both its output mean and covariance. In this paper, a fusion strategy that can combine the information from GP models with that from the conventional extended Kalman filter (EKF) is proposed. Otherwise, the ML-correction is merely applied through replacing the EKF-predicted state and covariance, which is not reasonable because the information from EKF and physical models have been completely abandoned and thus wasted. In the new fusion strategy, the ML-correction could be combined with physical knowledge more rationally and confidently. Simulation results show that, for most cases, the fused orbit prediction state and covariance are more accurate than those of the EKF, but more conservative than a pure substitution with the ML-correction. Some issues are also noticed and discussed during analyzing.

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TOWARDS ROBUST LEARNING-BASED POSE ESTIMATION OF NONCOOPERATIVE SPACECRAFT

Tae Ha Park,[*] Sumant Sharma[*] and Simone D'Amico[†]

This work presents a novel Convolutional Neural Network (CNN) architecture and a training procedure to enable robust and accurate pose estimation of a noncooperative spacecraft. First, a new CNN architecture is introduced that has scored a fourth place in the recent Pose Estimation Challenge hosted by Stanford's Space Rendezvous Laboratory (SLAB) and the Advanced Concepts Team (ACT) of the European Space Agency (ESA). The proposed architecture first detects the object by regressing a 2D bounding box, then a separate network regresses the 2D locations of the known surface keypoints from an image of the target cropped around the detected Region-of-Interest (RoI). In a single-image pose estimation problem, the extracted 2D keypoints can be used in conjunction with corresponding 3D model coordinates to compute relative pose via the Perspective-n-Point (PnP) problem. These keypoint locations have known correspondences to those in the 3D model, since the CNN is trained to predict the corners in a pre-defined order, allowing for bypassing the computationally expensive feature matching processes. The proposed architecture also has significantly fewer parameters than conventional deep networks, allowing real-time inference on a desktop CPU. This work also introduces and explores the texture randomization to train a CNN for spaceborne applications. Specifically, Neural Style Transfer (NST) is applied to randomize the texture of the spacecraft in synthetically rendered images. It is shown that using the texture-randomized images of spacecraft for training improves the network's performance on spaceborne images without exposure to them during training. It is also shown that when using the texture-randomized spacecraft images during training, regressing 3D bounding box corners leads to better performance on spaceborne images than regressing surface keypoints, as NST inevitably distorts the spacecraft's geometric features to which the surface keypoints have closer relation.

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GAUSSIAN PROCESS MODELS FOR PRELIMINARY LOW-THRUST TRAJECTORY OPTIMIZATION

Lieve Bouwman,[*] Yuxin Liu[†] and Kevin Cowan[‡]

Low-thrust trajectories can benefit the search for propellant-optimal trajectories, but increases in modeling complexity and computational load remain a challenge for efficient mission design and optimization. In this paper, an approach for developing models utilizing Gaussian Process (GP) regression and classification is proposed to perform computationally efficient optimization while obtaining acceptable accuracies for trajectories based on exponential sinusoid shaping. The goal of this work is to predict a combination of values of input variables which corresponds to a shape-based trajectory with the smallest total velocity increment (ΔV) or propellant mass fraction (J_m). A GP classification model is constructed to assess whether a given combination of values of input variables corresponds to a feasible trajectory. GP regression models are developed to predict the total ΔV and J_m corresponding to a combination of shape parameters, which can replace the required integration along the shape. In addition, advanced regression models are developed to predict the target values while requiring only three input parameters, thereby replacing the entire shape computation. In order to develop a GP model that fits the problem at hand, the underlying functions and parameters should be selected rationally. In this work, a novel model development approach is proposed to ensure that the mean function, covariance function, likelihood function, inference method, and hyperparameters, which dominate the performance of the models, are chosen rationally in terms of mean absolute percentage error (MAPE) and prediction time. Using this approach, GP models are developed and tested on transfer trajectories from Earth to Mars and Ceres, and from Mars to Earth, and their performance, in terms of MAPE and prediction time, is compared to that of more common optimization techniques in combination with the exponential sinusoid and other shape-based methods. The results demonstrate that the computation time can significantly be reduced while achieving promising MAPE's, especially when the goal is to locate regions of feasible or near-optimal trajectories. The proposed model development procedure is tested for robustness, which provides confidence in the proposed approach. Furthermore, it is found that the models which map three input variables directly to a ΔV or J_m value perform better than the ones trained with shape information, which demonstrates the strength of GP models as applied to low-thrust trajectory optimization.

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SPECIAL SESSION – ARTIFICIAL INTELLIGENCE IN ASTRODYNAMICS II: REINFORCEMENT LEARNING

Session Chair:

Special Session: Artificial Intelligence in Astrodynamics II - Reinforcement Learning:

Roberto Furfaro, The University of Arizona

AAS 19-628

SEEKER-BASED ADAPTIVE GUIDANCE VIA REINFORCEMENT META-LEARNING APPLIED TO ASTEROID CLOSE PROXIMITY OPERATIONS

Brian Gaudet,* Richard Linares† and Roberto Furfaro‡

Current practice for asteroid close proximity maneuvers requires extremely accurate characterization of the environmental dynamics and precise spacecraft positioning prior to the maneuver. This creates a delay of several months between the spacecraft's arrival and the ability to safely complete close proximity maneuvers. In this work we develop an adaptive integrated guidance, navigation, and control system that can complete these maneuvers in environments with unknown dynamics, with initial conditions spanning a large deployment region, and without a shape model of the asteroid. The system is implemented as a policy optimized using reinforcement meta-learning. The spacecraft is equipped with an optical seeker that locks to either a terrain feature, reflected light from a targeting laser, or an active beacon, and the policy maps observations consisting of seeker angles and LIDAR range readings directly to engine thrust commands. The policy implements a recurrent network layer that allows the deployed policy to adapt real time to both environmental forces acting on the agent and internal disturbances such as actuator failure and center of mass variation. We validate the guidance system through simulated landing maneuvers in a six degrees-of-freedom simulator. The simulator randomizes the asteroid's characteristics such as solar radiation pressure, density, spin rate, and nutation angle, requiring the guidance and control system to adapt to the environment. We also demonstrate robustness to actuator failure, sensor bias, and changes in the spacecraft's center of mass and inertia tensor. Finally, we suggest a concept of operations for asteroid close proximity maneuvers that is compatible with the guidance system.

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AAS 19-640

VALUE ITERATION AND Q-LEARNING FOR OPTIMAL CONTROL BY HIGH DIMENSIONAL MODEL REPRESENTATION (HDMR)

Minh Q. Phan*

This paper describes how High Dimensional Model Representation (HDMR) can be used in Value Iteration for optimal control. Value Iteration is a reinforcement learning method that is closely related to Q-Learning. The relationship between Value Iteration, Q-Learning, model predictive control, and standard optimal control theory is explained. HDMR models a nonlinear function as a sum of dimensionally increasing functions. We employ a type of HDMR called cut-HDMR where the values of a function along multi-dimensional cuts are used to build the HDMR directly. Unlike other modeling methods such as artificial neural networks or basis functions, the representation is non-parametric and there are no parameters to learn. The cut-HDMR is used to model both the value function and the optimal controller.

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REINFORCEMENT LEARNING AND TOPOLOGY OF ORBIT MANIFOLDS FOR STATIONKEEPING OF UNSTABLE SYMMETRIC PERIODIC ORBITS

Davide Guzzetti*

This work investigates reinforcement learning (RL) as an algorithm for orbit stationkeeping within chaotic environments. We first consider maintenance of unstable symmetric periodic (USP) orbits within circular restricted three-body problem (CR3BP) dynamics. Because topology for USP orbit dynamics is largely understood, USP orbits may be a testing ground to explore maintenance strategies based on RL models. Existing stationkeeping algorithms, including Floquet mode and gradient-based optimal control, may also supply a reference for characterizing RL performance. Outlining fundamental RL mechanisms for orbit stationkeeping and describing their relation to existing orbit maintenance techniques will support similar applications within more complex scenarios.

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ELM-BASED ACTOR-CRITIC APPROACH TO LYAPUNOV VECTOR FIELDS RELATIVE MOTION GUIDANCE IN NEAR-RECTILINEAR ORBITS

Andrea Scorsoglio[*] and Roberto Furfaro[†]

In this paper, we present a new feedback guidance algorithm for autonomous docking maneuvers in the cislunar environment. In particular, we propose a closed-loop optimal guidance algorithm that is capable of taking path constraints and collision avoidance into account while being on a Near Rectilinear Orbit (NRO) around the L2 Lagrangian point in the Earth-Moon system. The algorithm is based on the Lyapunov vector field guidance where the acceleration command is derived from a desired velocity vector field. We use reinforcement learning to learn the shape of the field as a function of the state of the system, allowing for increased flexibility in terms of constraint shapes and better performance in terms of fuel consumption with respect to classical Lyapunov vector field guidance.

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PREDICTING SATELLITE CLOSE APPROACHES USING STATISTICAL PARAMETERS IN THE CONTEXT OF ARTIFICIAL INTELLIGENCE

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

In order to ensure a sustainable use of low earth orbit in particular and near Earth space in general, reliable and effective close approach prediction between space objects is key. Only this allows for efficient and timely collision avoidance. Space Situational Awareness (SSA) for commercial and government missions will be facing the rapidly growing amount of small and potentially less agile satellites as well as debris in the near Earth realm, such as the increase in CubeSat launches and upcoming large constellations. At the same time, space object detection capabilities are expected to increase significantly, allowing for the reliable detection of smaller objects, e.g. when the Air Force Space Fence radar becomes operational. In combination, the space object catalog is expected to increase tremendously in size, potentially challenging the use of current methods. In this paper, we introduce an investigative approach based on the latest capabilities in artificial intelligence in fostering the potential for fast and accurate close approach predictions. We consider the study of statistical and information theory parameters in contrast and complementary to the classical probability of collision computation alone, in order to determine the feasibility of reliably predicting close approaches.

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AAS 19-751

SPACECRAFT MANEUVER STRATEGY OPTIMIZATION FOR DETECTION AVOIDANCE USING REINFORCEMENT LEARNING

Jason A. Reiter,* David B. Spencer† and Richard Linares‡

Spacecraft maneuvers are planned with operational objectives in mind, usually ranging from making up for orbit perturbations to maneuvering to avoid a possible collision. Though these areas have been researched in depth, performing maneuvers to avoid detection by sensors hasn't been explored until recently. Reinforcement learning has been shown to be an effective method for optimizing a single detection avoidance maneuver for the purpose of avoiding detection. This work expands on that further by optimizing the maneuver strategy itself that will result in a spacecraft continually avoiding detection through-out a desired time period given a nominal tasking strategy for the opposed sensor.

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AAS 19-822

CONTINGENCY PLANNING IN COMPLEX DYNAMICAL ENVIRONMENTS VIA HEURISTICALLY ACCELERATED REINFORCEMENT LEARNING

Ashwati Das-Stuart[*] and Kathleen Howell[†]

Unexpected events can cause a spacecraft to significantly deviate from its nominal path, leading to undesirable impacts on the mission. In such scenarios, the capability for rapid trajectory re-design is key for mission success. This investigation leverages a reinforcement learning strategy to automate the search for a transfer route to restore the overall mission goals after a spacecraft experiences a deviance in its thrusting capabilities during nominal operations. The route is computed by exploiting natural dynamical flows and accommodating spacecraft propulsive capabilities to construct an initial guess that is then transitioned to a continuous solution via traditional optimization techniques.

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AAS 19-907

ON THE CHOICE OF FILTFILT, CIRCULANT, AND CLIFF FILTERS FOR ROBUSTIFICATION OF ITERATIVE LEARNING CONTROL

Tianyi Zhang* and Richard W. Longman†

Iterative learning control (ILC) aims to converge to zero tracking error in control systems that perform the same task repeatedly. Spacecraft applications include making sensors perform high accuracy repeated scanning motions. The original aim is perfect tracking at all frequencies up to Nyquist frequency. This is in contrast to classical feedback control design that aims and sometimes struggles to achieve a desired bandwidth, the upper limit of reasonable performance. Achieving zero tracking error at all frequencies pushes our ability to create sufficiently accurate models. High frequency parasitic poles or residual modes can destabilize the ILC learning process. Hence, a noncausal zero-phase frequency cut-off filter is needed for robustification to high frequency model error. The most obvious such filter Matlab filtfilt, uses a causal forward filter, then repeat the filtering backward in time on the result. Initial conditions both forward and backward are needed, producing transients at the start and the end of the filtered data set. These are unrelated to the frequency cutoff objective. A previous publication demonstrated that the Matlab initial condition choice at the time could cause instability of ILC. Two alternative filter approaches are presented here, a circulant filter, and a cliff filter. Various properties of the circulant filter are presented, and the appropriate initial conditions for use in forward-backward zero phase implementation are developed, solving the initial condition issue. What remains is a pure filter design implementing the chosen steady state frequency response profile. The cliff filter picks the chosen profile to be ideal, i.e. zero phase with gain of unity in the passband, and gain of zero in the stopband. This filter addresses only the frequencies visible in the number of time steps in the finite time ILC problem. When used on longer data sets it does not have ideal performance at additional frequencies. But it is concluded that this is not an issue for the ILC problem. Future work will investigate if the cliff filter allows one to have the highest possible cutoff of the learning in the presence of high frequency model error. The relationship to the FIR filter design used in repetitive control will also be investigated, as well as the relationship to frequency sampling filter designs.

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ATTITUDE DYNAMICS AND CONTROL

Session Chairs:

Attitude Dynamics and Control I: Atri Dutta, Wichita State University

Attitude Dynamics and Control II:
John Christian, Rensselaer Polytechnic Institute
Kenneth Horneman, Emergent Space Technologies, Inc.

AAS 19-607

MODELLING AND SIMULATION OF THE ADCS SUBSYSTEM FOR JY1-SAT

Ahmad Fares* and Ahmad Bani Younes†

In this paper, modelling and simulation of the attitude control subsystem for JY1Sat are presented. Three orthogonal magnetorquers with nominal dipole moment of 0.2 Am^2 are used. Detumbling of the satellite is achieved by two axes actuation, whereas actuating the third axis can align the satellite with the magnetic field of Earth. B-dot controller is used as the control law and three axes magnetometer is used to provide Earth magnetic field measurements. Performance of the control law with disturbance torques while maintaining low angular rates is verified by studying the implemented control algorithm. International Geomagnetic Reference Field (IGRF) model is considered to obtain the magnetic measurements for simulation purposes and J_6 orbit propagator is considered to calculate the satellite position and velocity in the inertial and fixed frames. A case study on the attitude regulation using Modified Rodrigues Parameters and Lyapunov control functions with reaction wheels as actuators for nanosatellites is also presented.

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RECURSIVE AND NON-DIMENSIONAL STAR-IDENTIFICATION

Carl Leake[*] and Daniele Mortari[†]

This paper describes two new algorithms to identify the stars observed by a wide field-of-view star tracker. The first algorithm, called *recursive*, is proposed to perform the star identification process when the attitude angular variation is slow enough so that a pure spin dynamics well approximates the attitude dynamics between two subsequent observations. This actually is the most common scenario of three-axis stabilized spacecraft, when the star fields slowly change in subsequent observations. The second algorithm, called *non-dimensional*, is proposed when both the recursive Star-ID algorithm and the lost-in-space algorithm (LISA)—used to initialize the recursive algorithm—fail because the star tracker focal length and optical axis offset values go beyond the nominal operational range. These variations may be caused by launch vibrations or orbital thermal transitions.

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AAS 19-615

PERFORMANCE IMPROVEMENTS FOR THE LUNAR RECONNAISSANCE ORBITER GYROLESS EXTENDED KALMAN FILTER

Julie Halverson (formerly Thienel),[*] Oscar Hsu,[†] Philip Calhoun[‡] and Yohannes Tedla[§]

In late 2017, the laser intensity monitor (LIM) current began to decline on the Lunar Reconnaissance Orbiter (LRO) miniature inertial measurement unit (MIMU). The MIMU was powered off in March 2018 and has only been used during extended eclipses, a pre-eclipse orbit phasing maneuver, and critical momentum unloads. Science slews were suspended, and the onboard extended Kalman filter (EKF) was disabled. A coarse rate was estimated through star tracker quaternion differentiation, and attitude was provided directly from a single star tracker. A complementary filter, combining the differentiated quaternions with the integrated acceleration derived from the attitude control torque, was developed, tested, and uploaded to the spacecraft in December 2018. The EKF has been enabled, using the complementary filter rate in place of the MIMU, and science slews are now being performed. This paper presents an overview of the complementary filter rate estimation and EKF changes, fault detection updates without the MIMU, and inflight performance improvements.

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AAS 19-620

NEW CONTROL SCHEMES AND FLIGHT RESULTS OF WORLD'S SMALLEST SS-520 NO.5 FOR MICRO-SATELLITE

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Yasuhiro Morita, Takahiro Ito, Takayuki Yamamoto and Hiroto Habu†

ISAS/JAXA has successfully launched the micro-satellite "TRICOM-1R" by the world's smallest orbit rocket "SS-520 No.5" from Uchinoura Space Center on February 3rd in 2018. ISAS modified the existing sounding rocket SS-520 adding a small 3rd-stage solid-motor and the attitude control system**.** It flies spinning for the attitude stabilization in the flight. Therefore, we devised the rhumb-line control system with a new scheme. This rhumb-line system has the high-performance functions; the high-preciseness, the high-maneuver rate and the suppression of the unnecessary nutation angle generated at the RCS injection. This paper reports the development of the G&C system and the flight results.

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AAS 19-629

ORTHOGONAL RANGE SEARCHING IN *N*-DIMENSIONAL SPACES USING *K*-VECTOR

David Arnas,[*] Carl Leake[†] and Daniele Mortari[‡]

This work focuses on the study of orthogonal range searching methodologies for static databases with multiple dimensions. To that end, a new algorithm is introduced, the *n*-dimensional *k*-vector. This algorithm represents the evolution of the *k*-vector, a range searching method originally devised to solve the Star-Identification problem in wide field-of-view star trackers. The *n*-dimensional *k*-vector methodology is based on first identifying the most convenient order in which the dimensions of the problem should be assessed, and later using this information in a modified projection method to perform the search. Additionally, and in order to speed up the process, the algorithm uses a set of auxiliary databases that obtains an approximation of the searching range, and assess which approach will be the best to solve that search. This work includes a description of the methodology as well as a study of the algorithm performance in terms of speed compared with other common algorithms from the literature.

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TIME-VARYING FEEDBACK FOR ATTITUDE REGULATION IN PRESCRIBED FINITE-TIME

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

This paper introduces a feedback-based control law capable of steering the attitude of a fully-actuated rigid-body into a desired state (or trajectory) in prescribed finite time. In contrast with other finite-time methods in the literature, the stabilizing control law presented in this work does not depends on any knowledge of the inertia properties of the controlled rigid body and does not require to cancel nonlinear terms from the equations of motion, fulfilling the so-called self-reduction property of attitude regulation in control systems. Toward meeting this objective, we introduce a carefully chosen Lyapunov-like storage function that, in conjunction with our proposed time-varying control law, can be used to prove that the limit of the attitude error converges to the origin as time approaches the convergence time. We also demonstrate that convergence is guaranteed even in the presence of unknown bounded disturbances torques, and we extend the controller to accommodate trajectory tracking by judicious addition of feed-forward terms.

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QUATERA: THE QUATERNION REGRESSION ALGORITHM

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

This work proposes a batch solution to the problem of estimating fixed angular velocity using orientation measurements. Provided that the angular velocity remains constant, we show that the orientation quaternion belongs to a constant plane of rotation as time evolves. Motivated by this fundamental property, we are able to determine the angular velocity's direction by estimating the quaternion plane of rotation. Under the small angle assumption on the attitude measurement noise, the plane of rotation is estimated by minimizing a constrained Total Least Squares cost function, and our algorithm produces a unique optimizing solution through a batch approach (no need for iterations). The angular velocity magnitude is estimated by projecting the measured quaternions onto the estimated plane of rotation, and then computing the least squares evolution of the quaternion angle in the plane. We derive certain important statistical properties of the problem, and draw parallels to the relatively straightforward problem of estimating constant translational velocity from position measurements. We also perform a Monte Carlo analysis of the proposed algorithm, validating our method.

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AAS 19-664

EFFICIENT MAGNETIC ATTITUDE REGULATION

Mohammed A. A. Desouky* **and Ossama Abdelkhalik†**

A magnetometer is an important component in most spacecraft magnetic attitude control systems due to the need for magnetic field strength data to compute the control command. An alternate magnetic attitude control algorithm that eliminates the need for magnetometers at some controller update cycles is proposed in this paper. By applying a magnetic torque on the spacecraft and measuring the resulting angular velocity, it is possible to estimate the ambient magnetic field strength that resulted in this response. The Tikhonov regularization approach is implemented to solve the singular magnetic torque system. The real test cases presented in this paper demonstrate the feasibility of using the proposed method in attitude change maneuvers.

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AAS 19-665

EFFICIENT B-DOT LAW FOR SPACECRAFT MAGNETIC DETUMBLING

Mohammed A. A. Desouky[*] and Ossama Abdelkhalik[†]

Magnetic detumbling using a B-dot control does not need angular velocity measurements. The magnetic dipole, however, is not guaranteed to be orthogonal to the magnetic field, especially as the angular velocity gets smaller during detumbling, resulting in a sub-optimal torque vector in the sense of minimum residual torque. This paper presents a new variant of the B-dot logic. By computing an equivalent angular velocity, based on the magnetic field data, it is possible to develop a control law that guarantees the magnetic dipole moment to remain in the plane orthogonal to the ambient magnetic field. Using Monte Carlo simulations, the proposed B-dot control is compared to one of the B-dot laws in the literature that is featured by its fast detumbling maneuver time. The results show better performance in terms of the detumbling time and power consumption of the magnetic rods.

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AAS 19-735

SINGULARITY-FREE EXTRACTION OF A DUAL QUATERNION FROM FEATURE-BASED REPRESENTATION OF MOTION

Daniel Condurache*

The parameterization of a rigid-body motion can be done using multiple algebraic entities. A very important criterion when choosing a parameterization method is the number of algebraic equations and variables. Recently, orthogonal dual tensors and dual quaternion proved to be a complete tool for computing rigid body displacement and motion parameters. The present research is focused on developing new methods for recovering kinematic data when the state of features attached to a body during a rigid displacement is available. The proof of concept is sustained by computational solutions both for the singularity-free extraction of a dual quaternion from feature-based representation of motion and for the recovery algorithms of the dual quaternion and the dual Rodrigues vector.

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AAS 19-741

OPTIMUM MOMENTUM BIAS FOR ZERO-FEEDBACK REACTION WHEEL SLEWS

Lara C. Magallanes[*] and Mark Karpenko[†]

Unscented guidance can reduce the open-loop sensitivity to parametric and other uncertainties and enable an accurate attitude maneuver to a target in the absence of feedback. The achievable open-loop sensitivity reduction depends on the magnitude and direction of the momentum bias of a reaction wheel attitude control system. In this paper, an unscented guidance problem is formulated for finding the optimum momentum bias to minimize the terminal pointing error for a large angle zero-feedback slew maneuver.

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AAS 19-765

OPPORTUNITIES AND LIMITATIONS OF ADAPTIVE AUGMENTED CONTROL FOR LAUNCH VEHICLE ATTITUDE CONTROL IN ATMOSPHERIC FLIGHT

Domenico Trotta,* Alessandro Zavoli,† Guido De Matteis‡ and Agostino Neri§

This paper investigates the benefits and the possible issues related to the use of an Adaptive Augmented Control system for launch vehicle attitude control in atmospheric flight. A time-frozen analysis is conducted, assuming a linear time-invariant model of the rocket rigid body dynamics plus flexibility and parasite TVC dynamics for two launch-vehicle configurations, representative of a small launch vehicle and a large one, whose data are available in literature. The AAC system architecture is recalled and critically analyzed. An automatic gain tuning procedure is devised for the AAC adaptation gains, while refined tuning guidelines are provided for spectral damper filters. Effects of the AAC on the stability and robustness with respect to the baseline, that is non-augmented, controlled system are discussed by means of numerical simulations carried out in the time domain as well as using tools from linear system analysis in the frequency domain.

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AAS 19-777

ICESAT-2 PRECISION POINTING DETERMINATION

Sungkoo Bae,[*] Ben Helgeson,[†] Michael James[†] and Jonathan Sipps[†]

The Precision Pointing Determination (PPD) is a crucial component for the success of the ICESat-2 mission. It must accurately determine the direction of the laser beams fired to the Earth. Due to the serious performance issues in one of the main instruments, the actual PPD is conducted by a contingency plan. Based on various assessments, the current PPD successfully meets the required accuracy goal. This paper describes ICESat-2 PPD at the University of Texas at Austin: preparation, adaptation, performance, and evaluation.

[View Full Paper]

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ATTITUDE DETERMINATION STRATEGY BASED ON KALMAN FILTER FOR THE SPORT CUBESAT SCIENCE MISSION

Kátia M. Santos,[*] André L. da Silva,[†] Willer G. Santos,[‡] Valdemir Carrara,[§] Charles Swenson,[**] Lidia H. S. Satok[††] and Luis E. V. L. Costa[‡‡]

In this work, an attitude determination algorithm was developed for the 6U CubeSat satellite model of the Scintillation Prediction Observation Research Task (SPORT) mission. The project is a cooperation among the US Space Agency (NASA), American universities, the National Institute for Space Research (INPE) and the Aeronautics Institute of Technology (ITA). The work includes obtaining data from star, solar, magnetometer and gyro sensors and, with them to carry out, the attitude estimation. One of the requirements of the mission is the accuracy of attitude determination, which is only satisfied by the star sensor. However, there are periods in which the star sensor does not have valid measures, therefore, there is a need to study methods to improve the attitude given by the solar sensor and magnetometer. Thus, the TRIAD algorithm, in addition to the Kalman Filter, were analyzed to achieve the most accurate result within the established requirement. It was concluded that when the star sensor does not present valid measures, the analyzed case that fulfilled the requirements was the Kalman Filter with the TRIAD algorithm.

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RELATIVE POSITIONING AND TRACKING OF TETHERED SMALL SPACECRAFT USING OPTICAL SENSORS

Yanjie Guo[*] and Brian C. Gunter[†]

This study analyzes the attitude dynamics and tracking control system for an object attached via tether to a primary small satellite using optical sensors. Requirements of the tracking system include body pointing of the main spacecraft to the tethered target, in addition to optimized sun pointing for maximum power generation from the primary spacecraft's solar panels. This study uses the Tethering And Ranging mission of the Georgia Institute of Technology (TARGIT) CubeSat mission as a case study, and presents results from a hardware-in-the-loop experimental simulation environment to show that a modified proportional-derivative controller with three reaction wheels can track the tethered object with a steady-state error of 4 degrees in 1 minute, given only relative position information, generated from an optical camera and sun sensor. The performance numbers given are directly dependent on the performance of the hardware such as the detecting camera, reaction wheels, and sun sensor. Additional experiments were designed to test the limitations and general performance of the algorithm under varying lighting conditions and target dynamics.

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REACTION WHEEL FRICTION ANALYSIS FOR THE FERMI SPACECRAFT

Ben Ellis,[*] Russell DeHart[†] and Julie Halverson[‡]

The Fermi Gamma-ray Space Telescope is a three-axis stabilized spacecraft in Low Earth Orbit. Responding to concerns about reaction wheel health raised by drag torque trending, this study calculates dry and viscous friction coefficients from Fermi's reaction wheel telemetry. This paper describes the methods used to obtain drag torques from telemetry and fit the resulting data to a friction model. Results obtained from 11 years of telemetry indicate that the reaction wheel friction has been slowly growing.

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AAS 19-877

RELATIVE ATTITUDE REGULATION CONTROL USING ELECTROSTATIC TORQUES AND CYLINDRICAL MODELS

John Galjanic,* Dongeun Seo† and Morad Nazari‡

A linear feedback control based on the minimum control energy approach is used to stabilize the relative attitude of two spacecraft using electrostatic torque. This study uses the multi-sphere method of Reference [1] to model two identical spacecraft and regulate their relative attitude in a one-dimensional rotation, thus synchronizing their attitude responses. The novelty of this study is the modelling of two cylindrical spacecraft, as opposed to earlier studies which used one cylinder and one sphere. The results show that both the proposed linear feedback control using the minimum control energy approach and the time-varying LQR control method can feasibly control the system. Future work will consider three-dimensional rotations and the optimal distribution of spacecraft charge to create the electrostatic torque.

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AAS 19-884

TWO NEW STABLE INVERSES OF DISCRETE TIME SYSTEMS

Xiaoqiang Ji* and Richard W. Longman†

The concept of bandwidth in feedback control systems is created to indicate up to what frequency the system will produce an output roughly the same as the command. One would like to have control laws that make the output of a control system actually do what is commanded. The needed command can be calculated as a mathematical inverse problem, given the desired output, find the command input to produce it. The inverse problems considered here consider a finite time command, and ask for an input history to produce this command. Such problems need to be digital in the world, and the inverse problem for digital systems using a zero order hold input to a plant transfer function, result in unstable control action for a majority of systems in the world. There is an existing theory for stable inverses. It appends pre- and post-actuation, control inputs that are applied before the start and after the end of the finite time problem. Stable inverses developed by the authors and co-workers, instead leave one or a few initial time steps free, and produce zero error at all later times using a stable control action. This paper develops two new stable inverses that leave slightly more time steps free at the start of the problem time interval. These eliminate all transients from the inverse problem solution. Numerical examples illustrate the inverse control laws.

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MAGNETORQUER-ONLY ATTITUDE CONTROL OF SMALL SATELLITES USING TRAJECTORY OPTIMIZATION

Andrew Gatherer[*] and Zac Manchester[*]

This paper presents a magnetorquer-only attitude control technique that utilizes trajectory optimization methods to circumvent the underactuated nature of satellite magnetic field interactions. Given a known orbit and desired attitude state, the method utilizes a nonlinear dynamics model and a fast constrained trajectory optimization solver based on differential dynamic programming to arrive at a nominal torque profile that respects the spacecraft's actuator limitations. This nominal maneuver is then tracked using a time-varying linear-quadratic regulator (LQR). To demonstrate the effectiveness and robustness of the proposed control technique, closed-loop Monte-Carlo simulations are performed from a variety of orbits and initial conditions. Our method is shown to significantly outperform previous magnetorquer-only control schemes by offering convergence from large initial errors and fast slew rates that exploit the full performance capabilities of the actuators. Computational complexity of the method and future implementation in flight software onboard a CubeSat are also discussed.

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SECOND ORDER REPETITIVE CONTROL: EVALUATION OF STABILITY BOUNDARY AND DEVELOPMENT OF SUFFICIENT CONDITIONS

Ayman F. Ismail,* Richard W. Longman,† Peiling Cui,‡ Zhiyuan Liu§ and Han Xu**

Spacecraft often have vibrations from slight imbalance in control moment gyros, reaction wheels, or momentum wheels. Repetitive Control (RC) is an effective method to eliminate the produced jitter, actively isolating fine pointing equipment from spacecraft vibrations. The period of the disturbances is known since these rotations are being commanded, and a first order RC adjusts the command of a closed loop isolation system during the current period based on the error observed at the corresponding times in the previous period, aiming to converge to zero tracking error. The frequency response of first order RC has narrow notches at the addressed frequencies having the given period, requiring accurate knowledge of the disturbance period. With imperfect knowledge, or with fluctuations in the period, the performance is compromised. Second order repetitive control is a design that can reduce the sensitivity to period fluctuations. A disadvantage is the added stability complications. This paper focuses on second order RC, initially including data from two periods back. The approach developed here makes use of a partial fraction expansion, developed by the third author and her research group, that allows second order RC to use data only from one period back, with equivalent results as if it were using data from two periods back. It also allows for parallel processing if desired. Several contributions are made here to address the stability complications. An algorithm to evaluate the true stability boundary is presented. A general sufficient stability condition from previous literature is reviewed for comparison purposes. And a new sufficient stability condition is derived and then simplified to make it much easier to use and independent of the number of time steps in a period. The paper evaluates how close the sufficient conditions are to the true stability boundary and confirms the effectiveness of using multiple sufficient stability conditions as a design tool for second order RC.

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ORBITAL DEBRIS
AND SPACE ENVIRONMENT

Session Chair:

Orbital Debris and Space Environment: Juan Arrieta, Nabla Zero Labs

AAS 19-616

SPACEFLIGHT HAZARDS OF ESCAPE-VELOCITY-DOMAIN IMPACT EJECTA IN THE CR3BP

M. M. Wittal[*] and R. J. Power[†]

As a consequence of planned/proposed human lunar activity, the long-term effects of lunar debris and ejecta resulting from large-body (> 1000 kg) impacts on the lunar surface is investigated. The Escape-Velocity-Domain (EVD) ejecta behavior is characterized in terms of destination, duration in lunar orbit, and total displaced mass. Likewise, the amount of mass sent into geocentric orbit is also characterized and assessed as a function of impact location in terms of time, lunar latitude & longitude, and impact angle. Finally, a threat analysis is performed on critical assets in Earth and Lunar orbit such as the ISS, artificial satellite infrastructure, prospective lunar surface structures & equipment, and the Deep Space Gateway now under construction.

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AAS 19-674

TRACKING OF LARGE SATELLITE CONSTELLATIONS USING A PARTITIONED GLMB FILTER

Benjamin L. Reifler* **and Brandon A. Jones†**

Previously, tracking of large satellite constellations with the Generalized Labeled Multi-Bernoulli (GLMB) filter was computationally intractable for myopic sensors, as the large number of unobserved targets at each step would lead to an exponentially increasing number of hypotheses. By partitioning the label space based on assumed independence between distant measurements, the overall tracking problem can be decomposed into smaller, tractable sub-problems. Using this technique, the GLMB filter is used to track a simulated constellation containing thousands of satellites and observed by a limited number of myopic sensors.

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AAS 19-707

REAL-TIME THERMOSPHERIC DENSITY ESTIMATION VIA TWO-LINE-ELEMENT DATA ASSIMILATION

David J. Gondelach* **and Richard Linares†**

Inaccurate estimates of the thermospheric density are a major source of error in low Earth orbit prediction. In this work, we develop a reduced-order dynamic model for the thermospheric density by computing the main spatial modes of the atmosphere and deriving a linear model for the dynamics. This model is then used to estimate the density using two-line element (TLE) data by simultaneously estimating the reduced-order modes and the orbits and ballistic coefficients of several objects using an unscented Kalman filter. Accurate density estimation using the TLEs of 15 objects is demonstrated and validated against CHAMP and GRACE accelerometer-derived densities. Finally, the use of the model for density forecasting is shown.

[View Full Paper]

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MULTIPLE SMALL-SATELLITE SALVAGE MISSION SEQUENCE PLANNING FOR DEBRIS MITIGATION

Guanwei He* and Robert G. Melton†

A new and efficient method, using a heuristic optimization algorithm, is presented to find the minimal propellant consumption solution for multiple dysfunctional-satellite salvage mission sequence planning. The two-burn impulsive maneuver strategy is applied to simulate the transfer of the spacecraft. A space station serves as the refueling station of the spacecraft and the collection center for the dysfunctional satellites. An improved version of a genetic algorithm (GA) is applied to determine the optimal visiting sequence of the target satellites by minimizing the propellant consumption of the servicing spacecraft which transports all the satellites to the maintenance station. The transfer between two targets is represented by a simple model that contains only the planar changes and orbital maneuvers. The validity of this method has been proved for different types of orbits, and their corresponding propellant consumption is provided.

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AAS 19-807

A TECHNIQUE FOR SPACE OBJECT CATALOG EVALUATION

**A. M. Segerman,[*] Z. J. Sibert,[*]
F. R. Hoots[†] and P. W. Schumacher, Jr.[‡]**

An ever-increasing number of non-U.S. governmental entities is collecting observations of orbiting objects, and constructing space object catalogs that are independent of the operational catalog maintained by Air Force Space Command. With this proliferation of cataloging, it becomes necessary to evaluate the performance of the resulting orbit catalogs. Using the operational U.S. military catalog as a baseline reference, a simple yet robust method of evaluating alternative space object catalogs has been developed, focusing on catalog completeness, accuracy, and timeliness. A full description of the evaluation methodology is presented, along with a prototypical set of results.

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AAS 19-841

SPACECRAFT CONSTELLATION TRACKING AND MANEUVER ESTIMATION USING A GENERALIZED LABELED MULTI-BERNOULLI FILTER

Nicholas Ravago* and Brandon A. Jones†

As organizations seek to deploy large constellations, methods that can track large populations of maneuvering objects will be needed to ensure the safety of these systems and to nearby satellites. Current methods in maneuvering target tracking are reasonably effective but inefficient, especially when considering the scale of the space object tracking problem. This paper presents a multiple-model generalized labeled multi-Bernoulli filter that can allow single-target adaptive maneuvering target tracking algorithms to be applied to multi-target tracking scenarios in a computationally efficient manner. This filter is applied to some simple test cases using an adaptive equivalent noise method to model maneuvers. The filter successfully tracks targets through maneuvers and provides informative estimates of the maneuver history.

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CHARACTERIZING THE INDIA ASAT DEBRIS EVOLUTION USING DIVERSE, COMPLEMENTARY TOOLS

Daniel L. Oltrogge,* T.S. Kelso† and Timothy Carrico‡

This paper details the types of spacecraft fragmentation and subsequent debris cloud evolution models in use today, using the recent India ASAT intercept as a sample case to model the kinetic engagement, build representative scenarios of the resulting debris cloud, and further characterize the likelihood of a debris fragment being present anywhere in three-dimensional space as a function of time. From such characterizations, additional derived data may be obtained, including an assessment of the "top 25" active satellites placed at highest temporal risk of secondary collision with debris fragments, the orbital lifetime expected for the fragment population, and the subsequently-affected orbital regimes.

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AAS 19-910

COLLISION PROBABILITY FOR PARALLELOGRAM CROSS SECTIONS

Ken Chan*

A closed-form analytical expression is obtained for computing the collision probability when the cross section is a parallelogram. It is based on the conversion of a parallelogram first to a rectangular and then into a circle, each with the same area and the same centroid. The approach involves using the concept of antipodal points so as to derive the analytical expressions expediently. The results so obtained agree to six or seven significant figures with detailed computations using realistic values of the covariance and miss distance of spacecraft encounters. The applications are for use with solar panels, solar sails and Composite CubeSats faces when their collision cross sections are general parallelograms when viewed obliquely.

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AAS 19-911

COLLISION PROBABILITY FOR POLYGONAL CROSS SECTIONS

Ken Chan*

This paper deals with the formulation of analytical expressions for computing the collision probability when the cross section is any polygon whether it is convex or concave, simply connected region or even a multiply connected region. The approach is based fundamentally on the conversion of a triangle into its equivalent parallelogram (defined as one having the same area and the same centroid). This conversion is especially interesting because it invokes concepts from group theory to enable the process and expedite the analysis. Since any polygon can be decomposed into a network of triangles, the totality of collision probabilities obtained from all of them will analytically yield the collision probability of the polygonal cross section. The intended application is for ambitiously deriving analytical expressions for the probability of an entire spacecraft colliding with space debris.

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EVALUATION OF THE 27 MARCH 2019 INDIAN ASAT DEMONSTRATION

Andrew J. Abraham*

On 27 March 2019 India announced the successful demonstration of a Direct Ascent Anti-Satellite (DA-ASAT) weapon. India claims their Kinetic Kill Vehicle hit Microsat-R and destroyed it in a responsible manner that limited the debris cloud lifetime to 45 days. The Aerospace Corporation's Debris Analysis Response Tool (DART) is a predictive model that can estimate the debris created from ASAT intercepts and other breakup events. The tool utilizes the target mass, projectile mass, and relative velocity to statistically model debris created from a fragmentation event. This report forensically evaluates India's claim that the debris cloud will disperse and reenter in the weeks following the intercept.

[View Full Paper]

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SPACE SITUATIONAL AWARENESS AND CONJUNCTION ANALYSIS

Session Chair:

Space Situational Awareness and Conjunction Analysis:
Matthew Wilkins, L3 Applied Defense Solutions

AAS 19-600

SPACE-BASED TARGET SEARCH METHODS USING AN OPTICAL SENSOR MODEL FOR SPACE SITUATIONAL AWARENESS

Ryne Beeson,[*] Kento Tomita,[†] Onalli Gunasekara,[†]
Andrew Sinclair[‡] and Koki Ho[§]

This paper develops a space-based, target search-to-tracking framework that incorporates an optical sensor model. The framework is used for analysis of dynamic steering of a space-based optical sensor to search, detect, and track unknown space objects that have highly uncertain states. The analysis with the target search framework compares derived information-theoretic and maximum probability target search algorithms to efficiently characterize a target with large uncertainty. The optical sensor model for the target search framework simulates a square, two-dimensional camera frame that provides measurements for the estimation process and includes a clutter model to represent false alarm. The target search framework is evaluated with Monte Carlo Simulations using estimated real-world case parameters and provides results that offer an efficient and optimized initial target search and estimation performance for SSA.

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AAS 19-603

DATA-DRIVEN FRAMEWORK FOR SPACE WEATHER MODELING WITH UNCERTAINTY TREATMENT TOWARDS SPACE SITUATIONAL AWARENESS AND SPACE TRAFFIC MANAGEMENT

Richard J. Licata,[*] Piyush M. Mehta[†] and Christina Kay[‡]

The Space Weather (SW) has a strong influence on satellite tracking, orbital decay, and collision avoidance in low Earth orbit (LEO). E.g., Satellite position Probability Density Functions (PDFs) essential for probability of collision, Pc, estimates are heavily dependent on drag. The uncertainty is caused mainly due to the state of the thermosphere which is a highly dynamic environment, strongly and readily influenced by SW. Therefore, accurate SW forecasts and associated uncertainty quantification are crucial for space situational awareness and space traffic management. This paper presents a new framework for the coupling of different SW dynamical systems that also accounts for uncertainty.

[View Full Paper]

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AAS 19-605

COVARIANCE REALISM IS NOT ENOUGH

J. Russell Carpenter*

A great deal of effort has been put into improving the practice of space situational awareness such that covariance data associated with predicted close approaches is more "realistic." However, "realistic" usually has meant "larger" and this presents a problem. In many cases, there exist multiple sources for predictive ephemerides, which may be fused to produce predictive states with smaller associated covariances. Ancillary to the fusion computation is the capability to assess consistency of the estimates. If actionable covariance information becomes available, interval estimates for the miss distance provide a more informative alternative to collision probability for risk assessment.

[View Full Paper]

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A NEW LOOK AT PREDICTIVE PROBABILITY OF COLLISION, PREDICTIVE MANEUVER TRADE SPACES AND THE PROBABILITY OF A MISSED MITIGATION*

Mark A. Vincent† and Theodore Sweetser‡

The methods for calculating the 2-D Probability of Collision (Pc) are reviewed and then applied to two new applications. The first application is a simplification of a previously developed tool to calculate the predicted Pc that would result from a new observation of the satellite states. The second application is for the probability of detection of an actual satellite collision. The latter application is discussed in the context of setting conjunction thresholds to meet lifetime risk requirements. Finally, progress on a new tool to produce predictive maneuver trade space plots incorporating the same algorithms used for predictive Pc is presented.

[View Full Paper]

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AAS 19-846

VERY LOW RESOLUTION SPACECRAFT RECOGNITION FOR CLOSE-RANGE RENDEZVOUS AND PROXIMITY OPERATIONS

William A. Bezouska,[*] [†] Daniel J. Hernandez[*] and Ryan S. Williams[*]

We present machine learning approaches for the identification of nearby spacecraft during proximity and rendezvous operations using very low resolution images. These images may include challenging illumination conditions such as shadowing or specular reflection. Spacecraft identification from a known set of spacecraft is conducted using convolutional neural networks trained on rendered low resolution images of the spacecraft. Both single-view and multi-view models are explored. Results indicate that identification can be successful for object as small as 20 pixels. Additionally, a simple super-resolution method is presented which exploits high accuracy attitude knowledge available on modern spacecraft.
[View Full Paper]

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AAS 19-858

THE YORP EFFECT FOR TUMBLING DEFUNCT GEO SATELLITES

Conor J. Benson[*] and Daniel J. Scheeres[*]

The long-term rotational dynamics of retired and otherwise defunct satellites in geosynchronous earth orbit (GEO) are not well understood. In this paper, we conduct a study of long-term defunct GEO satellite rotational dynamics in the non-principal axis (tumbling) regime, focusing particularly on the five well-documented GOES 8-12 satellites. Full dynamical models are developed using Euler's equations of motion that account for the Yarkovsky-O'Keefe-Radzievskii-Paddack (YORP) effect (spin state evolution due to solar radiation and thermal re-emission torques) and internal energy dissipation.

Overall, the dynamics simulations yielded a number of interesting behaviors. First of all, there is a strong tendency for the tumbling satellite's rotational angular momentum vector to track the sun. Also, it was found that the satellite can cycle between uniform rotation and tumbling with solar radiation torques alone, contrary to previous hypotheses that energy dissipation is also required. Long-term observations of the GOES 8 satellite suggest it is undergoing such tumbling cycles. Furthermore, the YORP modeling revealed transient resonant tumbling states where the satellite's two fundamental rotation periods are commensurate (e.g. 1:1, 2:1). GOES 8 was likely in a resonant tumbling state in April 2018. Accounting for internal energy dissipation, stable tumbling states with constant kinetic energy, angular momentum, and sun-tracking were found. In such states, the competing influences of YORP and energy dissipation balance. Long-term observations of GOES 9 suggest it may be in a stable, sun-tracking tumbling state.

Our findings have a number of significant implications. First of all, they indicate that defunct GEO satellite rotational dynamics have structure that is amenable to long-term prediction. Also, the ubiquitous sun-tracking behavior in simulations may facilitate initial attitude determination for space debris. In addition, by correctly setting the end of life configuration and spin state, it may be possible to place a satellite in a stable tumbling state for easier removal or servicing in the future. Finally, sun-tracking, resonant tumbling states, and stable tumbling states have been previously identified in asteroid YORP and comet outgassing simulations. This suggests that defunct satellites could provide insights about solar system small body dynamical evolution, which occurs on much longer timescales (months to years vs. 103 to > 109 years).

[View Full Paper]

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AAS 19-869

NO FEEDBACK MULTI-SENSOR TASKING

Bryan D. Little[*] and Carolin E. Frueh[†]

Observations of resident space objects generated by sensors are the primary method of maintaining knowledge of the object states. This requires the coordination of multiple sensors with different capabilities in an optimized manner. Information exchange and processing induces time delay in a multi-sensor system that is longer than the time available to plan and start the sensor tasking step. Sometimes no communication is available at all during the observation time span. This paper addresses the problem of optimizing in the absence of immediate feedback in a heterogeneous sensor network; an illustration is shown using TLE data in the geosynchronous region and two optical sensors with vastly different capabilities.

[View Full Paper]

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DESIGN & DEVELOPMENT OF AN OPTIMIZED SENSOR SCHEDULING & TASKING PROGRAM FOR TRACKING SPACE OBJECTS

David Shteinman,[*] Mark Yeo,[†] Alex Ryan,[‡] James Bennett,[§] Michael Lachut[**] and Scott Dorrington[††]

With a large and ever-growing number of resident space objects (RSOs) in orbit around the Earth, the efficient tasking of sensors is critical to track objects and maintain reliable state estimates of objects across a catalog. This paper describes a scheduler developed to task sensors in a way that maximizes the total utility of a sensor network, measured in terms of information gain, or the reduction in Rényi α-divergence of object state covariances. The program contains several features such as object prioritization, customizable propagators, and the capability to schedule both optical and laser sensors. The program has been fully implemented in C++ and can schedule a catalog containing over 20,000 objects (building up to 100,000 objects) with up to 6 sensors (building up to 72 sensors) in real-time. The scheduler is currently in use for catalog maintenance by the Space Environment Research Centre at its Mt Stromlo Facility in Canberra, Australia.

[View Full Paper]

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AAS 19-905

COLLISION PROBABILITY OF COMPOSITE CUBESATS HOVERING IN LEADER-FOLLOWER CONFIGURATION

Ken Chan,[*] Yuchen Xie[†] and Jingrui Zhang[‡]

Analytical expressions are obtained for computing the collision probability of a large Composite CubeSats hovering in the close vicinity of another large Composite CubeSats in a Leader-Follower configuration. The composite is constructed from a large number of Unitary CubeSats arranged in a cuboid volume. The study involves the modeling of the growth of a time-dependent probability density function over a period of time and the effects of that growth on the collision probability. Studies of collision probability as a function of time are performed in terms of the parameters: separation between neighboring orbiters, covariance size (different in three directions) and the size of the two cuboid CubeSat Composites. It was found that certain combinations of parameters resulted in collision probability curves which intersected and others did not. This curve-crossing phenomenon cannot be predicted in advance but must be demonstrated quantitatively by performing detailed computations. This knowledge may be used to advantage in the design of distributed systems and in the orbital maintenance of their configuration. Moreover, the Principle of Scaling is used to obtain collision probabilities using the results obtained from a relatively small number of case studies so as to circumvent the effort to perform copious computer runs when the input parameters are changed.

[View Full Paper]

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INDEX

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

It covers all articles that appear in the following:

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NUMERICAL INDEX*

VOLUME 171 I, II, III & IV

ADVANCES IN THE ASTRONAUTICAL SCIENCES, ASTRODYNAMICS 2019 (2020)
(AAS/AIAA Astrodynamics Specialist Conference, August 11–15, 2019, Portland, Maine, U.S.A.)

* Unless otherwise indicated all papers appear in Volume 171, *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 19-662 Constrained Energy-Optimal Guidance in Relative Motion Via Theory of Functional Connections and Rapidly-Explored Random Trees, Kristofer Drozd, Roberto Furfaro and Daniele Mortari (Part I)

AAS 19-663 Multi-Sensor Management Under Information Constraints, Kirsten Tuggle and Maruthi Akella (Part I)

AAS 19-664 Efficient Magnetic Attitude Regulation, Mohammed A. A. Desouky and Ossama Abdelkhalik (Part IV)

AAS 19-665 Efficient B-Dot Law for Spacecraft Magnetic Detumbling, Mohammed A. A. Desouky and Ossama Abdelkhalik (Part IV)

AAS 19-666 to -667 Not Assigned

AAS 19-668 NASA Conjunction Assessment Risk Analysis Updated Requirements Architecture, Lauri K. Newman, Alinda K. Mashiku, Matthew D. Hejduk, Megan R. Johnson and Joseph D. Rosa (Part IV)

AAS 19-669 An Operational Algorithm for Evaluating Satellite Collision Consequence, Travis F. Lechtenberg (Part IV)

AAS 19-670 Not Assigned

AAS 19-671 Multivariate Normality of Cartesian-Framed Covariances: Evaluation and Operational Significance, Travis F. Lechtenberg (Part IV)

AAS 19-672 to -673 Not Assigned

AAS 19-674 Tracking of Large Satellite Constellations Using a Partitioned GLMB Filter, Benjamin L. Reifler and Brandon A. Jones (Part IV)

AAS 19-675 Theory of Functional Connections Applied to Nonlinear Programming Under Equality Constraints, Daniele Mortari, Tina Mai and Yalchin Efendiev (Part II)

AAS 19-676 OSIRIS-REx Navigation Campaign Trajectory Design and Maneuver Performance, Daniel R. Wibben, Andrew Levine, Samantha Rieger, James V. McAdams, Peter Antreasian, Jason M. Leonard, Michael C. Moreau and Dante S. Lauretta (Part III)

AAS 19-677 OSIRIS-REx Frozen Orbit Design and Flight Experience, Daniel R. Wibben, Andrew Levine, Samantha Rieger, James V. McAdams, Peter G. Antreasian, Jason M. Leonard, Michael C. Moreau and Dante S. Lauretta (Part III)

AAS 19-678 Pose and Shape Estimation of a Small Body Via Extended Target Tracking, Enrico M. Zucchelli, Brandon A. Jones and Ryan P. Russell (Part III)

AAS 19-679 Geometric Formations Using Relative Orbital Elements and Artificial Potential Functions, Sylvain Renevey and David A. Spencer (Part I)

AAS 19-680 Reinforcement Learning and Topology of Orbit Manifolds for Stationkeeping of Unstable Symmetric Periodic Orbits, Davide Guzzetti (Part IV)

AAS 19-681 The Long-Term Forecast of Station View Periods for Elliptical Orbits, Andrew J. Graven and Martin W. Lo (Part I)

AAS 19-682 Aerobraking Trajectory Control Using Articulated Solar Panels, G. Falcone and Z. R. Putnam (Part III)

AAS 19-683 Not Assigned

AAS 19-684 Analytic Approximations of Orbit Geometry in a Rotating Higher Order Gravity Field, Ethan R. Burnett and Hanspeter Schaub (Part II)

AAS 19-746 A Study on Effective Initial Guess Finding Method Based on Bézier Curves: Orbit Determination Applications, Daegyun Choi, Sungwook Yang, Henzeh Leeghim and Donghoon Kim (Part III)

AAS 19-747 The First Commercial Lunar Lander Mission: Beresheet, Haim Shyldkrot, Eran Shmidt, Daniela Geron, Joseph Kronenfeld,Mike Loucks, John Carrico, Lisa Policastri and John Taylor (Part III)

AAS 19-748 A Survey of Mission Opportunities to Trans Neptunian Objects, Part VI: A Search for Multi-Target Missions, Daniel Johnson, Zackery Crum, Garrett Mitchell, Samuel Walters, Adam Dalton, Brandon Davis, Ben Dolmovich, Meghan Green, Amanda Williams, Gerald Wise and James Evans Lyne (Part I)

AAS 19-749 Spacecraft Maneuver Strategy Optimization for Detection Avoidance Using Reachability Sets, Connor N. Clary, Jason A. Reiter and David B. Spencer (Part II)

AAS 19-750 Optimization in Space-Based Pursuit-Evasion Games Through Competitive Coevolution, Jason A. Reiter and David B. Spencer (Part II)

AAS 19-751 Spacecraft Maneuver Strategy Optimization for Detection Avoidance Using Reinforcement Learning, Jason A. Reiter, David B. Spencer and Richard Linares (Part IV)

AAS 19-752 Implementing an Idan Speyer Cauchy Drag Estimator, Craig A. McLaughlin, Micaela Crispin and Frank J. Bonet (Part III)

AAS 19-753 Extended Phase-Space Realization for Attitude Dynamics of an Axisymmetric Body in Eccentric Orbit, Roshan T. Eapen, Manoranjan Majji and Kyle T. Alfriend (Part I)

AAS 19-754 An Estimation-Based Drag Coefficient Model for Tracking Variations Due to Attitude and Orbital Motion, Vishal Ray and Daniel J. Scheeres (Part III)

AAS 19-755 Not Assigned

AAS 19-756 Earth-Moon Halo Orbit – Gateway or Tollbooth?, David W. Dunham, Kjell Stakkestad, James V. McAdams, Anthony Genova and Jerry Horsewood (Part III)

AAS 19-757 Root Locus Method of Determining Sensitivity of Polynomial Systems to Error in Astrodynamics Applications, Alex Sizemore, Chris Ertl, Troy Henderson, David Zuehlke, Heidi Darsey and T. Alan Lovell (Part III)

AAS 19-758 Mission Feasibility from Trajectory Optimization and the State of Space Systems Research at the University of Auckland, Darcey R. Graham, Nicholas J. Rattenbury and John E. Cater (Part II)

AAS 19-759 to -760 Not Assigned

AAS 19-761 Fast Estimation Method for Trajectories to Near-Earth Asteroids, Lorenzo Casalino, Luigi Mascolo and Alessandro Bosa (Part III)

AAS 19-762 Design and Reconstruction of the Hayabusa2 Precision Landing on Ryugu, S. Kikuchi, F. Terui, N. Ogawa, T. Saiki, G. Ono, K. Yoshikawa, Y. Takei, Y. Mimasu, H. Ikeda, H. Sawada, T. Morota, N. Hirata, N. Hirata, T. Kouyama, S. Kameda and Y. Tsuda (Part III)

AAS 19-763 A Convex Optimization Approach for Finite-Thrust Time-Constrained Cooperative Rendezvous, Boris Benedikter, Alessandro Zavoli and Guido Colasurdo (Part II)

AAS 19-764 Precise Rendezvous Guidance in Cislunar Orbit Via Surrogate Modelling, Satoshi Ueda (Part I)

AAS 19-765 Opportunities and Limitations of Adaptive Augmented Control for Launch Vehicle Attitude Control in Atmospheric Flight, Domenico Trotta, Alessandro Zavoli, Guido De Matteis and Agostino Neri (Part IV)

AAS 19-766 Not Assigned

AAS 19-767 Missed Thrust Analysis for a Potential Mars Sample Return Orbiter, José M. Sánchez Pérez and Gábor I. Varga (Part II)

AAS 19-768 Dependent Variable Integration for Event Finding with Validation in Orbit Propagation, Anthony Iannuzzi (Part II)

AAS 19-769 Linking Low-to High-Energy Dynamics of Invariant Manifold Tubes, Transit Orbits, and Singular Collision Orbits, Kenta Oshima (Part I)

AAS 19-770 Accurate Low-Thrust Orbit Transfer Solutions in Equinoctial Elements Using an Analytic Representation of the Geopotential, Zachary J. Folcik and Paul J. Cefola (Part II)

AAS 19-771 to -772 Not Assigned

AAS 19-773 Neural Network Based Optimal Control: Resilience to Missed Thrust Events for Long Duration Transfers, Ari Rubinsztejn, Rohan Sood and Frank E. Laipert (Part IV)

AAS 19-774 Solar Sail Trajectories and Orbit Phasing of Modular Spacecraft for Segmented Telescope Assembly About Sun-Earth L2, Gabriel J. Soto, Erik Gustafson, Dmitry Savransky, Jacob Shapiro and Dean Keithly (Part II)

AAS 19-775 Optimal Quadrature-Based Filtering in Regularized Coordinates for Orbit Determination, David Ciliberto, Puneet Singla, Joe Raquepas and Manoranjan Majji (Part III)

AAS 19-776 Uncertainty Characterization and Surrogate Modeling for Angles Only Initial Orbit Determination, David Schwab, Puneet Singla and Joseph Raquepas (Part IV)

AAS 19-777 ICESat-2 Precision Pointing Determination, Sungkoo Bae, Ben Helgeson, Michael James and Jonathan Sipps (Part IV)

AAS 19-778 Not Assigned

AAS 19-779 Interplanetary Low-Thrust Design Using Proximal Policy Optimization, Daniel Miller, Jacob A. Englander and Richard Linares (Part II)

AAS 19-780 Quasi-Heliosynchronous Orbits, M. L. G. T. X. Costa, R. Vilhena de Moraes, A. F. B. A. Prado and J. P. S. Carvalho (Part II)

AAS 19-781 Analysis of Relative Merits of Unscented and Extended Kalman Filters in Orbit Determination, James Woodburn and Vincent Coppola (Part III)

AAS 19-782 Homo- And Heteroclinic Connections in the Spatial Solar-Sail Earth-Moon Three Body Problem, Jeannette Heiligers (Part II)

AAS 19-783 Validation of Simulation of Space Net Deployment Phase with Parabolic Flight Experiment Data, Rachael Gold and Eleonora M. Botta (Part III)

AAS 19-784 Adaptive Online Learning Strategy for Post-Capture Attitude Takeover Control of Noncooperative Space Target, Yueyong Lyu, Yuhan Liu, Zhaowei Sun and Guangfu Ma (Part IV)

AAS 19-785 Asteroid Deflection with Active Boulder Removal, Daniel N. Brack and Jay W. McMahon (Part I)

AAS 19-786 to -787 Not Assigned

AAS 19-810 Second-Order Solution for Relative Motion on Eccentric Orbits in Curvilinear Coordinates, Matthew Willis, Kyle T. Alfriend and Simone D'Amico (Part I)

AAS 19-811 A Unified Framework for Aerocapture Systems Analysis, Athul Pradeepkumar Girija, Sarag J. Saikia, James M. Longuski and James A. Cutts (Part II)

AAS 19-812 Attitude Determination Strategy Based on Kalman Filter for the Sport CubeSat Science Mission, Kátia M. Santos, André L. da Silva, Willer G. Santos, Valdemir Carrara, Charles Swenson, Lidia H. S. Satok and Luis E. V. L. Costa (Part IV)

AAS 19-813 Deep Learning Applications to Astrodynamics Problems, Jordan Murphy and Daniel Scheeres (Part IV)

AAS 19-814 Transfers from GTO to Sun-Earth Libration Orbits, Juan A. Ojeda Romero and Kathleen C. Howell (Part I)

AAS 19-815 Aerocapture Performance Analysis for a Neptune Mission Using a Heritage Blunt-Body Aeroshell, Athul Pradeepkumar Girija, Sarag J. Saikia, James M. Longuski, Shyam Bhaskaran, Matthew S. Smith and James A. Cutts (Part II)

AAS 19-816 Mid-Course Correction Contingency Analysis for the James Webb Space Telescope, Taabish Rashied, Benjamin Stringer, Jeremy Petersen and Karen Richon (Part II)

AAS 19-817 to -818 Not Assigned

AAS 19-819 NASA Goddard Independent Navigation Results for OSIRIS-REx Initial Encounter at Bennu, Dolan E. Highsmith, Jason C. Swenson, Benjamin W. Ashman, Jeffrey L. Small, Andrew J. Liounis, Kenneth M. Getzandanner, Josh Lyzhoft, Jennifer E. Donaldson, David D. Rowlands, Erwan M. Mazarico, Michael C. Moreau, Jason M. Leonard, Coralie D. Adam, Peter G. Antreasian, Dante S. Lauretta (Part III)

AAS 19-820 Not Assigned

AAS 19-821 Koopman Operator Theory Applied to the Motion of Satellites, Richard Linares (Part I)

AAS 19-822 Contingency Planning in Complex Dynamical Environments Via Heuristically Accelerated Reinforcement Learning, Ashwati Das-Stuart and Kathleen Howell (Part IV)

AAS 19-823 Not Assigned

AAS 19-824 Revisiting Trajectory Design with STK Astrogator Part 1, Cody Short, Pradipto Ghosh and Austin Claybrook (Part II)

AAS 19-825 Observability and Estimability Analysis of the Orbit Problem, Alex M. Friedman and Carolin Frueh (Part I)

AAS 19-826 Not Assigned

AAS 19-827 Uncertainty Analysis of a Generalized Coning Algorithm for Inertial Navigation, James D. Brouk and Kyle J. DeMars (Part I)

AAS 19-828 Not Assigned

AAS 19-829 Trajectory Design for a Solar Polar Observing Constellation, Thomas R. Smith, Natasha Bosanac, Thomas E. Berger, Nicole Duncan and Gordon Wu (Part II)

AAS 19-830 Covariance Fusion Strategy of Gaussian Processes Covariance and Orbital Prediction Uncertainty, Hao Peng and Xiaoli Bai (Part IV)

AAS 19-851 Low Thrust Transfers Between Halo Orbits in the Earth-Moon System, Mohammad S. Azhar and Robert G. Melton (Part II)

AAS 19-852 to -854 Not Assigned

AAS 19-855 Canonical Transformations Via a Sparse Approximation-Based Collocation Method for Dynamical Systems, Roshan T. Eapen, Manoranjan Majji, Kyle T. Alfriend and Puneet Singla (Part I)

AAS 19-856 Estimation of Entry Vehicle Parameters from Trajectory Data, Kevin Bonnet and Robert D. Braun (Part III)

AAS 19-857 Not Assigned

AAS 19-858 The YORP Effect for Tumbling Defunct GEO Satellites, Conor J. Benson and Daniel J. Scheeres (Part IV)

AAS 19-859 Not Assigned

AAS 19-860 Vehicle and Mission Design Options for Very Low Earth Orbit CubeSats, James W. Williams, Michael I. Gray and Zachary R. Putnam (Part I)

AAS 19-861 Not Assigned

AAS 19-862 Track Initiation for Cubesat Cluster Deployment Tracking, John A. Gaebler and Penina Axelrad (Part III)

AAS 19-863 Not Assigned

AAS 19-864 Design of a Distributed Modular Attitude Controller for Spacecraft Composed of Reconfigurable Joined Entities with Compliant Coupling, Deepti M. Kannapan (Part III)

AAS 19-865 Analysis of a Constrained Optimal Multiple-Phase Landing Trajectory for a Small Robotic Lunar Lander, J.P. Carrico III, Jae-ik Park, Alisa Hawkins and Dong-Young Rew (Part II)

AAS 19-866 Not Assigned

AAS 19-867 Heliocentric Escape and Lunar Impact from Near Rectilinear Halo Orbits, Diane C. Davis, Kenza K. Boudad, Rolfe J. Power and Kathleen C. Howell (Part II)

AAS 19-868 Variational Lambert's Problem with Uncertain Dynamics, Paolo Panicucci, Jay McMahon, Emmanuel Zenou and Michel Delpech (Part I)

AAS 19-869 No Feedback Multi-Sensor Tasking, Bryan D. Little and Carolin E. Frueh (Part IV)

AAS 19-870 Not Assigned

AAS 19-871 Optical Navigation for New Horizons' Flyby of Kuiper Belt Object (486958) 2014 MU_{69}, Derek S. Nelson, Erik J. Lessac-Chenen, John Y. Pelgrift, Coralie D. Adam, Frederic J. Pelletier, Jeremy A. Bauman, Michael J. Salinas, Dale R. Stanbridge, Joel T. Fischetti, Peter J. Wolff, John R. Spencer, Simon B. Porter, Marc W. Buie, Mark E. Holdridge, Harold A. Weaver, Catherine B. Olkin and S. Alan Stern (Part III)

AAS 19-872 Consider Filtering Applied to Maneuver Detection for Relative Orbit Determina tion, Peter C. Scarcella, Kirk W. Johnson and Joshuah A. Hess (Part III)

AAS 19-873 Gaussian Process Models for Preliminary Low-Thrust Trajectory Optimization, Lieve Bouwman, Yuxin Liu and Kevin Cowan (Part IV)

AAS 19-874 Cloud Computing Methods for Near Rectilinear Halo Orbit Trajectory Design, Sean M. Phillips and Diane C. Davis (Part III)

AAS 19-875 Maximum A Posteriori Estimation of Hamiltonian Systems with High Order Series Expansions, Simone Servadio, Renato Zanetti and Roberto Armellin (Part III)

AAS 19-876 Experimental Field Testing and Confirmation of Particle Swarm Optimization for Autonomous Extraterrestrial Surface Search and Exploration, Gregory D. Hatfield, Alexander E. Cook and May-Win Thein (Part III)

AAS 19-877 Relative Attitude Regulation Control Using Electrostatic Torques and Cylindrical Models, John Galjanic, Dongeun Seo and Morad Nazari (Part IV)

AAS 19-878 Selecting Planning Horizon Length for Sequential Low-Thrust Orbit-Raising Optimization Problem, Pardhasai Chadalavada and Atri Dutta (Part II)

AAS 19-879 Design & Development of an Optimized Sensor Scheduling & Tasking Program for Tracking Space Objects, David Shteinman, Mark Yeo, Alex Ryan, James Bennett, Michael Lachut and Scott Dorrington (Part IV)

AAS 19-880 Not Assigned

AAS 19-881 Onboard Optical Navigation for Asteroid Explorer by Asteroid Shape Model, Shuya Kashioka, Genki Ohira, Yuki Takao, Takatoshi Iyota and Yuichi Tsuda (Part I)

AAS 19-882 Not Assigned

AAS 19-883 Missed-Thrust Analysis of Bepicolombo's Interplanetary Transfer to Mercury Orbit, Pablo Muñoz (Part II)

AAS 19-884 Two New Stable Inverses of Discrete Time Systems, Xiaoqiang Ji and Richard W. Longman (Part IV)

AAS 19-885 Automated Navigation Analysis for the Lucy Mission, Jeremy Knittel, Dale Stanbridge and Kenneth Williams (Part III)

AAS 19-886 Navigation Preparations for a Possible Binary System During the New Horizons Extended Mission, Joel T. Fischetti, John Y. Pelgrift, Erik J. Lessac-Chenen, Jeremy A. Bauman, Derek S. Nelson, Fred J. Pelletier, Dale R. Stanbridge, Michael J. Salinas, Peter J. Wolff, Bobby G. Williams, Mark E. Holdridge, Harold A. Weaver, John R. Spencer, Simon B. Porter, Marc W. Buie, Catherine B. Olkin, and S. Alan Stern (Part III)

AAS 19-887 Spacecraft Trajectory Tracking and Parameter Estimation around a Splitting Contact Binary Asteroid, Tiago M. Silva, Jean-Baptiste Bouvier, Kathleen Xu, Masatoshi Hirabayashi and Koki Ho (Part III)

AAS 19-888 Not Assigned

AAS 19-889 Characterizing the India ASAT Debris Evolution Using Diverse, Complementary Tools, Daniel L. Oltrogge, T.S. Kelso and Timothy Carrico (Part IV)

AAS 19-890 Orbit Determination and Tests of General Relativity in the Cruise Phase of BepiColombo, Luciano Iess, Ivan di Stefano, Paolo Cappuccio and Gael Cascioli (Part III)

AAS 19-891 GTOC X: Settlers of the Galaxy Problem Description and Summary of the Results, Anastassios E. Petropoulos, Eric D. Gustafson, Gregory J. Whiffen and Brian D. Anderson (Part III)

AAS 19-892 Not Assigned

AAS 19-893 Risk-Aware Trajectory Design with Impulsive Maneuvers: Convex Optimization Approach, Kenshiro Oguri and Jay W. McMahon (Part II)

AUTHOR INDEX

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