SPACEFLIGHT MECHANICS 2015

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This mosaic comprises four individual NAVCAM images taken from 31.8 km from the center of Comet 67P/Churyumov-Gerasimenko on 4 November 2014. The image resolution is 2.7 m/pixel and thus each original 1024 x 1024 pixel frame measured 2.8 km across. The mosaic has been slightly rotated and cropped, and measures roughly 4.6 x 3.8 km.
Credit: ESA/Rosetta/NAVCAM

SPACEFLIGHT MECHANICS 2015

Volume 155

ADVANCES IN THE ASTRONAUTICAL SCIENCES

Edited by
Roberto Furfaro
Stefano Cassotto
Aaron Trask
Scott Zimmer

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FOREWORD

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

Spaceflight Mechanics 2015, Volume 155, Advances in the Astronautical Sciences, consists of three parts totaling about 3,600 pages, plus a CD ROM which contains all the available papers in digital format. Papers which were not available for publication are listed on the divider pages of each section in the hard copy volume. A chronological index and an author index appear at the end of the main linking file, and are appended to the third part of the volume.

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

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

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

AAS/AIAA SPACEFLIGHT MECHANICS VOLUMES

Spaceflight Mechanics 2015 appears as Volume 155, *Advances in the Astronautical Sciences*. This publication presents the complete proceedings of the 25th AAS/AIAA Space Flight Mechanics Meeting 2015.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

AAS/AIAA ASTRODYNAMICS VOLUMES

Astrodynamics 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

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 2015 Space Flight Mechanics Meeting was held at the Williamsburg Lodge in Williamsburg, Virginia from January 11th to 15th, 2015. The meeting was sponsored by the American Astronautical Society (AAS) Space Flight Mechanics Technical Committee and co-sponsored by the American Institute of Aeronautics and Astronautics (AIAA) Astrodynamics Technical Committee. The 219 people who registered for the meeting included 93 students, as well as professional engineers, scientists, and mathematicians representing the government, industry, and academic sectors of the United States and 13 other countries. There were 213 papers presented in 28 sessions on topics spanning the breadth of current research in astrodynamics and space-flight mechanics.

On Tuesday evening, the Brouwer Award Lecture was given by Dr. Srinivas Rao Vadali, the 2014 AAS Dirk Brouwer Award Honoree. Dr. Vadali is a Professor of Aerospace Engineering at Texas A&M University. He has made significant contributions in the areas of satellite attitude control and orbital mechanics. He has served as an Associate Editor of the AIAA Journal of Guidance, Control, and Dynamics and is currently an Associate Editor of the International Journal of Aerospace Engineering. He is a Fellow of the AAS and an AIAA Associate Fellow. His lecture was entitled “Problems in Satellite Attitude Control and Formation Flying.” Under attitude control, it covered optimal rotational maneuvers with reaction wheels and CMGs, Lyapunov function-based quaternion feedback and sliding mode attitude control, and implementation of control laws on the AFRL ASTREX test structure. Under formation flying, it covered the use of mean differential elements for analysis and establishment of formations, the no-along-track drift condition, a novel concept for formation maintenance with fuel balancing, an explanation for the existence of special inclinations for which in-plane and cross-track frequencies match, and a robust formation design for the NASA MMS mission.

The editors would like extend their sincerest gratitude to each of the Session Chairs that helped make this meeting a success: Felix Hoots, Terry Alfriend, Moriba Jah, Roby Wilson, Jill Seubert, Nathan Strange, John Seago, Bob Melton, Kathleen Howell, Fu-Yuen Hsiao, David Dunham, Renato Zanetti, Laureano Cangahuala, Carolin Frueh, Ryan Russell, Thomas Starchville, Angela Bowes, Russell Carpenter, Eric Butcher, Martin Ozimek, Lisa Policastri, Kyle DeMars, Jeff Parker, Brandon Jones; and double thanks to Francesco Topputo and Maruthi Akella for chairing two sessions each. We would also like to thank the numerous volunteers who staffed the registration and information tables during the conference. Your help is much appreciated. Lastly, we would like to thank the authors for their efforts in performing world-class research and their dedication to present their work to our astrodynamics community. We are all richer for your service and commitment to excellence.

Dr. Roberto Furfaro
AAS Technical Chair

Dr. Aaron Trask
AAS General Chair

Dr. Stefano Cassoto
AIAA Technical Chair

Dr. Scott Zimmer
AIAA General Chair

CONTENTS

Part II

Part III

Page

SPACE SITUATIONAL AWARENESS I

SESSION 1

Chair: Moriba Jah
Air Force Research Laboratory

The following papers were not available for publication:

AAS 15-243
(Paper Withdrawn)

AAS 15-261
(Paper Withdrawn)

AAS 15-348
(Paper Withdrawn)

AAS 15-231

IMPROVED MODELS FOR ATTITUDE ESTIMATION OF AGILE SPACE OBJECTS

Ryan D. Coder,* Richard Linares† and Marcus J. Holzinger‡

Several innovations are introduced to ameliorate error in space object attitude estimation. A radiometric measurement noise model is developed to define the observation uncertainty in terms of optical, environmental, and sensor parameters. This reduces biases in the space objects' posterior state distributions. Additionally, a correlated angular rate dynamics model is adopted to decouple the effects of inertia and body torques for agile space objects. This novel dynamics model requires the adoption of marginalized particle filters to preserve computational tractability. The software framework is outlined, and simulated results are presented to demonstrate resultant reductions in agile space object attitude estimation error.

[View Full Paper]

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‡ Assistant Professor, School of Aerospace Engineering, Georgia Institute of Technology, holzinger@gatech.edu, AIAA Senior Member

AAS 15-233

FORMULATION OF COLLISION PROBABILITY WITH TIME-DEPENDENT PROBABILITY DENSITY FUNCTIONS

Ken Chan[*]

This paper is primarily concerned with the formulation of the probability of collision between two space orbiting objects when their probability density functions (pdfs) are time-dependent. Some recent papers addressing this problem have dealt with the concept of integrating the flux of time-dependent pdfs through a hemispherical surface over a period of time. This latter approach is permissible only for the relatively simple case of time-independent pdfs and relative motion which does not lead to self-intersection of the cylindrical tube. However, it is not even valid for time-independent pdfs and self-intersecting integration volumes. It is definitely not consistent with the basic tenets of probability theory for the case of time-dependent pdfs. Several concrete examples are provided to illustrate this point.

[View Full Paper]

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AAS 15-234

HOVERING COLLISION PROBABILITY

Ken Chan*

This paper is concerned with an orbiting (secondary) object hovering in the close vicinity of another (primary) object, whether deliberately or accidentally. It is assumed that measurements are made of the secondary object either from the ground or from the primary object at various times. During the periods between successive ground-tracking or inter-satellite ranging, the probability of collision is of grave concern. This paper deals with the computation of that probability. It 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.

[View Full Paper]

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AAS 15-262

ON MUTUAL INFORMATION FOR OBSERVATION-TO-OBSERVATION ASSOCIATION

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

In this paper, we build on recent work to further investigate the use of mutual information to tackle the observation-to-observation association (OTOA) problem where we are given a set of observations at different time instances and wish to determine which of these observations were generated by the same RSO. The approach relies on using an appropriate initial orbit determination (IOD) method in addition to the notion of mutual information within an unscented transform framework. We assert that, because the underlying initial orbit determination algorithm is deterministic, we can introduce an approximate correction factor to the IOD methodology. The correction is a function represented by a constant bias for this work but can be expanded to other parametrizations. The application of this correction results in an order of magnitude improvement in performance for our mutual information data association technique over the previous results. The correction can be used in conjunction with other information theoretic discriminators for data association; however it was found in previous work that mutual information is the most precise discriminator. The information theoretic solution described in this paper can be adjusted to address the other (OTTA and TTTA) association problems, which will be the focus of future research. We will demonstrate the main result in simulation for LEO, MEO, GTO, and GEO orbit regimes to show general applicability.

[View Full Paper]

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RENDEZVOUS AND PROXIMITY OPERATIONS

SESSION 2

Chair: Russell Carpenter
NASA Goddard
Space Flight Center

The following paper was not available for publication:

AAS 15-245
(Paper Withdrawn)

AAS 15-213

OPTIMAL SINGLE IMPULSE MANEUVER ENSURING MULTIPLE SPACECRAFTS PERIODIC RELATIVE MOTION

Wei Wang,* Jianping Yuan,† Jianjun Luo‡ and Zhanxia Zhu§

In this paper, a single impulse maneuver strategy is presented to ensure multiple spacecraft periodic relative motion, without specifying a predetermined reference orbit. The optimal velocity impulse in the sense of the l^2-norm and the reference semimajor axis after the maneuver are derived from the analytical point of view to eliminate relative drifts caused by the initialization errors. The problems are classified into three cases: 1) Maneuver moment is fixed. 2) Maneuver moment is unfixed and spacecraft maneuver separately. 3) Maneuver moment is unfixed and spacecraft maneuver simultaneously. After the maneuver, the value of each semimajor turns to be identical, and the relative motion exhibits periodicity.

[View Full Paper]

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AAS 15-247

SIMILAR ANALYSIS FOR GROUND-BASED ASTRODYNAMICAL EXPERIMENT OF SPACE RELATIVE MANEUVER

Yu Qi,* Peng Shi† and Yushan Zhao‡

In order to make out more reliable spacecraft's ground-based experiment schedule, the confident coefficient of experimental results must be studied thoroughly, as which will be significant in proving the results reliable and credible. After building bond graph for relative motion between satellites, a similar function, based on similitude process and activity analysis, is figured out to measure the similar degree for ground-based astrodynamical experimental results. With the benefit brought by similar function, it's convenient to compute the errors resulted from disturbances, such as resistance and control thrust error. Also it is easy to work out the reliable degree of ground-based experimental results, and then the shortcomings of ground-based experiment system can be found, which will be helpful for the improving of ground-based astrodynamical experiment system, especially at the beginning of experiment facilities' building. In addition of the confidence interval for similar function values of experiments affected by disturbances, the conclusion could point out a method for the choosing of experiment facilities.

[View Full Paper]

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AAS 15-266

MIXED PRIMAL/DUAL ALGORITHM FOR DEVELOPING LINEAR FUEL-OPTIMAL IMPULSIVE-CONTROL TRAJECTORY

Youngkwang Kim,[*] Sang-Young Park[†] and Chandeok Park[‡]

This paper addresses a linear impulsive-control trajectory optimization problem for minimizing total characteristic velocity. To solve the optimization problem, a mixed primal/dual algorithm is developed to take advantage of the primal and dual formulations at once. The dual optimization problem is a convex problem with a nonlinear dual constraint on the primer vector's maximum magnitude. While the dual solution is globally optimal, there exist two difficulties: the dual constraint itself is another optimization problem and the accuracy of the primal constraint is not directly controllable in dual space. On the other hand, though the primal problem has multiple local minima, its solution converges faster than that of the dual problem, and the accuracy of the primal constraints is directly controllable. With a nonlinear programming solver, the proposed algorithm first finds an approximate global optimal solution in dual space by applying the dual constraints on the primer vector's maximum magnitude only at finite points instead of the whole time domain. Solving the approximated dual problem reduces computational cost significantly rather than solving the original dual problem. Then, the algorithm completes the optimization process in primal space by further refining the approximate global optimal solution with a root-finding algorithm so that the final solution precisely satisfies the first-order necessary conditions of the primal problem. The overall process is illustrated and validated by an impulsive-thrust rendezvous problem near an elliptical reference orbit. It is shown that the proposed algorithm successfully generates an accurate global optimal solution.

[View Full Paper]

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AAS 15-324

PRECISE RELATIVE NAVIGATION FOR SJ-9 MISSION USING REDUCED-DYNAMIC TECHNIQUE

Shu Leizheng,[*] Chen Pei[†] and Han Chao[‡]

Shi Jian-9 Formation Flight Mission (SJ-9) was carried out in 2012 by China Academy of Space Technology (CAST) to develop and validate key technologies required for autonomous formation flying. This paper develops a real-time estimate algorithm to perform precision relative navigation for this mission. Double-difference GPS carrier phase and reduced-dynamic techniques are utilized to calculate the relative position and velocity. Actual flight data from SJ-9 is used to assess the algorithm performance. Results show that the relative position of the two satellites can be reconstructed with accuracies at the few millimeter to centimeter level.

[View Full Paper]

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AAS 15-334

SURVEY OF SPACECRAFT RENDEZVOUS AND PROXIMITY GUIDANCE ALGORITHMS FOR ON-BOARD IMPLEMENTATION

Costantinos Zagaris,[*] Morgan Baldwin,[†] Christopher Jewison[‡] and Christopher Petersen[§]

Over the last several years the topic of autonomous spacecraft rendezvous and proximity operations (RPO) has been rapidly gaining interest. Several methods have been presented in literature that enable autonomous RPO trajectory planning. The purpose of this paper is to survey those methods and assess their suitability for on-board implementation. Factors such as optimality, algorithm convergence rate, convergence guarantees, complexity, and computational efficiency will be used to determine which algorithms are best suited for on-board implementation. Finally, the paper will present simulation results of algorithms that have been implemented, and provide recommendations for future work.

[View Full Paper]

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[‡] Graduate Student, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA

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AAS 15-460

A GREEDY RANDOM ADAPTIVE SEARCH PROCEDURE FOR MULTI-RENDEZVOUS MISSION PLANNING

Atri Dutta*

The paper proposes a new algorithm to optimize a sequence of rendezvous maneuvers by a spacecraft with multiple targets. The algorithm consists of two phases: the first phase generates feasible solutions of the problem using a greedy randomized adaptive search procedure, and the second phase performs local search about the constructed solution. The performance of the algorithm is evaluated by considering different cases of complexity for each rendezvous problem. The first case considers C-W equations, the second case considers multi-revolution Lambert's problem, and the third case considers a Non-Linear Programming problem to determine the cost of a rendezvous maneuver. Numerical examples demonstrate the proposed algorithm for cases when the targets are on a circular orbit.

[View Full Paper]

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DYNAMICAL SYSTEMS
AND TRAJECTORY DESIGN

SESSION 3

Chair: Kathleen Howell
Purdue University

The following paper was not available for publication:

AAS 15-289
(Paper Withdrawn)

A NATURAL AUTONOMOUS FORCE ADDED IN THE RESTRICTED PROBLEM AND EXPLORED VIA STABILITY ANALYSIS AND DISCRETE VARIATIONAL MECHANICS

Natasha Bosanac,[*] Kathleen C. Howell[†] and Ephraim Fischbach[‡]

With improved observational capabilities, an increasing number of binary systems have been discovered both within the solar system and beyond. In this investigation, stability analysis is employed to examine the structure of selected families of periodic orbits near a large mass ratio binary in two dynamical models: the circular restricted three-body problem and an expanded model that incorporates an additional autonomous force. Discrete variational mechanics is employed to determine the natural parameters corresponding to a given reference orbit, facilitating exploration of the effect of an additional three-body interaction and the conditions for reproducibility in the natural gravitational environment.

[View Full Paper]

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AAS 15-282

DESIGN OF OPTIMAL TRAJECTORY FOR EARTH-L1-MOON TRANSFER

Jin Haeng Choi,[*] Tae Soo No,[†] Ok-chul Jung[‡] and Gyeong Eon Jeon[§]

The design of transfer trajectories from the Earth to the Moon via the Libration L1 point is often broken into two phases, wherein Earth-L1 and L1-Moon transfers are considered separately. In this paper, we present a method of designing an optimal "one-shot" transfer trajectory from the Earth to the Moon via L1 point. As a way of enforcing natural transit through the L1 point from the Earth's gravitational field to the Moon's sphere of gravitation, the Jacobi energy during the transfer is constrained to remain between L1 and L2 energy levels. By this way, we prevent the spacecraft from crossing over the zero-velocity curve (or boundary) and force it to move through the L1 neck and arrive at the final Moon-centered mission orbit. This paper presents and analyzes the results for some preliminary design examples

[View Full Paper]

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AAS 15-287

LOW-ENERGY TRANSFERS TO AN EARTH-MOON MULTI-REVOLUTION ELLIPTIC HALO ORBIT

Hao Peng,[*] Shijie Xu[†] and Leizheng Shu[‡]

The Sun-Earth/Moon Patched Elliptic and Circular Restricted three-body Problem model is utilized to construct low-energy transfers to a strictly periodic orbit in the ERTBP, the Multi-revolution Elliptic Halo (ME-Halo). The ME-Halo orbit can keep its special configuration in the ephemeris model. The low-energy transfers are defined by eight parameters. The ME-Halo orbit in this paper has a three-dimensional stable manifold. A survey of all feasible low-energy transfers is presented, and the impact of the redundant dimension of the stable manifold is considered. It reveals that the redundant stable manifold affects the probability of feasible transfers in the whole parameter space.

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AAS 15-297

WEAK STABILITY BOUNDARY AND TRAJECTORY DESIGN

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

The Weak Stability Boundary (WSB) is a region of space where the gravitational attraction of the Earth, Moon and Sun tend to cancel. Since these bodies move as a function of time, the WSB also moves as a function of time. For the restricted three-body problem, rotating coordinates can be defined such that the Jacobi integral and Lagrange points are static surfaces or points. When the restricted four-body problem is considered, there are no convenient static surfaces or singular points that can be defined. At least, the authors are not aware of any. A restricted three-body problem can be defined for the Earth/Sun system and another one for the Earth/Moon system. Trajectory design for the restricted four-body problem may be accomplished by patching together these two three-body problems in a manner similar to patched conics that are used for the two-body problem. Another approach is to target the trajectory directly, using constrained parameter optimization theory. The latter approach was used in May of 1991 when a ballistic trajectory from low Earth orbit to capture by the Moon was discovered. At the time, there was no theory that would predict this result, but it could be explained by the existing WSB theory of Ed Belbruno of the Jet Propulsion Laboratory and Carlos Simo of the University of Barcelona. The discovery of a restricted four-body trajectory was the result of attempting to target a bielliptic transfer from Earth to lunar orbit and was somewhat accidental. Since the initial discovery, many missions have been proposed that use this WSB trajectory and at least three have been flown. The Japanese Hiten Mission, the Genesis Mission and the Grail Mission all use the same inertial trajectory with small variations.

[View Full Paper]

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AAS 15-302

BALLISTIC CAPTURE INTO DISTANT RETROGRADE ORBITS FROM INTERPLANETARY SPACE

Collin Bezrouk[*] and Jeffrey Parker[†]

This paper presents an method for generating a set of ballistic capture trajectories (BCTs) from interplanetary space that target a specific distant retrograde orbit (DRO) around the Moon. This set of trajectories is then analyzed for trends and limitations that can allow mission designers to construct specific BCTs to meet their mission requirements. This analysis is demonstrated using two stable DROs: the 70,000 km DRO for the Asteroid Robotic Redirect Mission (ARRM) and a 50,000 km DRO. This investigation shows the boundaries at which these trajectories exist in terms of energy and approach direction, and identifies flyby options upon arrival and prior to DRO capture. These results provide a trade space for missions that intend to place a spacecraft into a stable or semi-stable DRO while using as little fuel as possible.

[View Full Paper]

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AAS 15-311

LOW-ENERGY TRANSFERS TO DISTANT RETROGRADE ORBITS

Jeffrey S. Parker,* Collin J. Bezrouk† and Kathryn E. Davis‡

This paper presents an examination of low-energy transfers to Distant Retrograde Orbits (DROs) about the Moon. Large DROs become unstable with very little out-of-plane motion; smaller DROs become unstable with more out-of-plane motion. Many unstable DROs, big and small, may be targeted from Earth using very little fuel, if any. This paper examines the trade space of low-energy transfers to DROs using dynamical systems theory and evaluates their costs and benefits compared with conventional orbit transfers.

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AUTOMATED TRAJECTORY REFINEMENT OF THREE-BODY ORBITS IN THE REAL SOLAR SYSTEM MODEL

Diogene A. Dei-Tos[*] and Francesco Topputo[†]

In this paper, an automatic algorithm for the correction of orbits in the real solar system model is described. The differential equations governing the dynamics of a massless particle in the *n*-body problem are written as perturbation of the restricted three-body problem in a non-uniformly rotating, pulsating frame by using a Lagrangian formalism. The refinement is carried out by means of a multiple shooting technique, and the problem is solved for a finite set of variables. Results are given for the dynamical substitutes of the collinear points of several gravitational systems, as well as for periodic three-body orbits.

[View Full Paper]

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AAS 15-322

APPROXIMATION OF INVARIANT MANIFOLDS BY CUBIC CONVOLUTION INTERPOLATION

F. Topputo* and R. Y. Zhang†

In this paper a two-step approach to approximate the invariant manifolds in the circular restricted three-body problem is presented. The method consists in a two-dimensional interpolation, followed by a nonlinear correction. A two-dimensional cubic convolution interpolation is implemented to reduce the computational effort. A nonlinear correction is applied to enforce the energy level of the approximated state. The manifolds are parameterized by using two scalars. Results show efficiency and moderate accuracy. The present method fits the needs of trajectory optimization algorithms, where a great number of manifold insertion points has to be evaluated.

[View Full Paper]

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AAS 15-342

BALLISTIC CAPTURE TRANSFERS FROM THE EARTH TO MARS

E. Belbruno[*] and F. Topputo[†]

We construct a new type of transfer from the Earth to Mars, which ends in ballistic capture. This results in a substantial savings in capture Δv from that of a classical Hohmann transfer under certain conditions as well as an alternate way for spacecraft to transfer to Mars, with a flexible launch window. This is accomplished by first becoming captured at Mars, very distant from the planet, and then from there, following a ballistic capture transfer to a desired altitude within a ballistic capture set. This is achieved by manipulating the stable sets, or sets of initial conditions whose orbits satisfy a simple definition of stability. This transfer type may be of interest for Mars missions because of lower capture Δv, moderate flight time, and flexibility of launch period from the Earth.

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SOLAR SAIL EQUILIBRIA POINTS IN THE CIRCULAR RESTRICTED THREE BODY PROBLEM OF A RIGID SPACECRAFT OVER AN ASTEROID

Mariusz E. Grøtte* and Marcus J. Holzinger†

The Circular Restricted Three Body Problem (CR3BP) is investigated together with the effects of solar radiation pressure (SRP) and albedo radiation pressure acting on a solar sail spacecraft in a Sun-Asteroid system. Due to the significant albedo effects experienced close to an asteroid with highly reflective surfaces, the solar sail dynamics change considerably as compared to models investigated in previous work. For approximation purposes in establishing the albedo radiation, the asteroid is treated as a Lambertian diffuse model with characteristics from bidirectional reflectance distribution function (BRDF). As a result of both solar and albedo radiation, a wide range of artificial equilibrium solutions are generated in addition to the classical Lagrange points. Particular attention is given to the solutions around L_1 and L_2 with varying solar sail lightness numbers and orientation angles. The inclusion of albedo radiation effects indicates that the equilibrium points shift considerably as opposed to the model with SRP only, an important fact to address for any potential missions to bright objects such as asteroids and comets. Stability and controllability are investigated at the equilibrium points of interest, which are found to be unstable but controllable.

Keywords: Asteroids, Solar Sail, Circular Restricted Three Body Problem, Albedo Radiation, Lambertian Diffuse Models

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ORBITAL DYNAMICS AND ESTIMATION

SESSION 4

Chair: Jill Seubert
Jet Propulsion Laboratory

A GENERAL PERTURBATIONS METHOD FOR SPACECRAFT LIFETIME ANALYSIS

Emma Kerr* **and Malcolm Macdonald†**

An analytical atmospheric density model, including solar activity effects, is applied to an analytical spacecraft trajectory model for use in orbit decay analysis. Previously presented theory is developed into an engineering solution for practical use, whilst also providing the first step towards validation. The model is found to have an average error of 3.46% with standard deviation 3.25% when compared with historical data. The method is compared to other analytical solutions and AGI's Systems Toolkit software, STK. STK provided the second best results, with an average error of 11.39% and standard deviation 10.69%. The developed method allows users to perform rapid Monte-Carlo analysis of the problem, such as varying launch date, initial orbit, spacecraft characteristics, and so forth, in fractions of a second. This method could be used in many practical applications such as in initial mission design to analyze the effects of changes in parameters such as mass or drag coefficient on the lifetime of the mission. The method could also be used to ensure regulatory compliance with the 25-year end-of-life removal period set out by debris guidelines.

[View Full Paper]

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AAS 15-241

HELIUM DISCREPANCY IN NRLMSISE-2000 DENSITY MODEL DETECTED VIA CHAMP/GRACE DATA AND DECAYING SPHERES

Chia-Chun Chao,* James R. Wilson,†
John P. McVey‡ and Richard L. Walterscheid**

The authors performed an investigation of a helium discrepancy in the NRLMSISE-2000 density model (MSIS00) with two parallel analyses. One analysis focused on processing data from the CHAMP and GRACE spacecraft, and the other analysis estimated the area-to-mass (A/m) ratio of ten decaying spheres with known diameter and mass. Results show that MSIS00 predicts temperatures that are too high, which leads to density estimates that are about 35% too high for the solar minimum of 2008. During this solar minimum year, the estimated A/m ratio values in the CHAMP/GRACE altitude range, 385 km to 415 km, are consistently lower by 15% to 26%, which clearly supports the early finding by Thayer et al.[1] The errors in the estimated A/m ratio reflect both MSIS00 temperature and helium errors. When the temperature errors for December 2008 are corrected following a procedure established by Thayer et al., the estimated A/m ratios are too high, which indicates that MSIS00 is under-estimating the amount of helium at these altitudes. This is consistent with the findings of Thayer et al. The significant deviations in the A/m ratios from the truth at higher altitudes suggest that the MSIS00 density model requires updates or enhancements at altitudes above 800 km in addition to correcting the helium modeling error. In this study, a methodology was developed to correct the helium modeling error without modifying the MSIS00 density model.

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AAS 15-244

UTILIZATION OF THE DEEP SPACE ATOMIC CLOCK FOR EUROPA GRAVITATIONAL TIDE RECOVERY

Jill Seubert[*] and Todd Ely[†]

Estimation of Europa's gravitational tide can provide strong evidence of the existence of a subsurface liquid ocean. Due to limited close approach tracking data, a Europa flyby mission suffers strong coupling between the gravity solution quality and tracking data quantity and quality. This work explores utilizing Low Gain Antennas with the Deep Space Atomic Clock (DSAC) to provide abundant high accuracy uplink-only radiometric tracking data. DSAC's performance, expected to exhibit an Allan Deviation of less than 3e-15 at one day, provides long-term stability and accuracy on par with the Deep Space Network ground clocks, enabling one-way radiometric tracking data with accuracy equivalent to that of its two-way counterpart. The feasibility of uplink-only Doppler tracking via the coupling of LGAs and DSAC and the expected Doppler data quality are presented. Violations of the Kalman filter's linearization assumptions when state perturbations are included in the flyby analysis results in poor determination of the Europa gravitational tide parameters. B-plane targeting constraints are statistically determined, and a solution to the linearization issues via pre-flyby approach orbit determination is proposed and demonstrated.

[View Full Paper]

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AAS 15-267

EFFECTS OF ORBITAL ELLIPTICITY ON DYNAMIC EVOLUTION OF ASTEROID IMPACT EJECTA

Yun Zhang,* Hexi Baoyin,† Junfeng Li‡ and Yanyan Li§

The behavior of the debris ejected from asteroids after collisional disruptions has significant implications for asteroid evolution, which will be influenced by the structure and motion state of asteroid as well as the gravitational perturbation forces from other celestial bodies. For nonzero heliocentric eccentricity asteroids, the effect of the perturbative force will lead to a mass-loss enhancement effect on the collision outcomes. In this paper, the three-body dynamical environment is analyzed to study the eccentric effects on the evolution of asteroid impact ejecta, which indicates that the behavior of ejecta will discriminatively vary with the true anomaly at impact position. As comparison, a series of impact simulations are conducted with various orbital eccentricities and impact site, which consist with the analyses.

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AAS 15-286

SOLAR RADIATION PRESSURE END-OF-LIFE DISPOSAL FOR LIBRATION-POINT ORBITS IN THE ELLIPTIC RESTRICTED THREE-BODY PROBLEM

Stefania Soldini,* Camilla Colombo† and Scott J. I. Walker‡

This paper proposes an end-of-life propellant-free disposal strategy for Libration-point orbits in the elliptic restricted three-body problem as an extension of a preliminary study performed in the circular problem. The spacecraft is initially disposed into the unstable manifold leaving the Libration-point orbit, before a reflective sun-pointing surface is deployed to enhance the effect of solar radiation pressure. This allows closing the pulsating zero-velocity curves at the pseudo Libration-point, SL_2 such that, the consequent increase in energy prevents the spacecraft returning to Earth. An energy approach is used to compute the required area for the Hill's curves closure at the pseudo Libration-point SL_2, via numerical optimisation. The Gaia mission is selected as an example scenario since a low deployable area is required in the circular case. Guidelines for the end-of-life disposal of future Libration-point orbit missions are proposed.

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AAS 15-294

NUMERICAL ENERGY ANALYSIS OF THE ESCAPE MOTION IN THE ELLIPTIC RESTRICTED THREE-BODY PROBLEM

Hao Peng,[*] Yi Qi,[†] Shijie Xu[‡] and Yanyan Li[§]

The Elliptic Restricted Three-Body Problem (ERTBP) is non-autonomous and periodic. The energy of the third body in the ERTBP is not conservative, and where does not exist a constant integral as in the Circular Restricted Three-Body Problem (CRTBP). In this paper, a numerical survey on the escaping trajectories under the planar ERTBP model of the Earth-Moon system is carried out. The energy variation map of the orbital plane is demonstrated. The escaping motions are then analyzed by observing both their energy variation and pulsating of instantaneous zero velocity curves.

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EFFICIENT COMPUTATION OF SHORT-PERIOD ANALYTICAL CORRECTIONS DUE TO THIRD-BODY EFFECTS

M. Lara,[*] R. Vilhena de Moraes,[†] D. M. Sanchez[†] and A. F. B. de A. Prado[†]

Efficient evaluation of short-period corrections is a key point in the semi-analytical integration of the artificial satellite problem. This is particularly important when second-order corrections of the geopotential or third-body effects are taken into account. For the latter we show that the use of polar-nodal variables allows to cast the periodic corrections in a very simple form of straightforward evaluation which is valid for any eccentricity below one.

[View Full Paper]

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[*]http://logiciels.cnes.fr/STELA/en/logiciel.htm

AAS 15-385

NUMERICAL ACCURACY OF SATELLITE ORBIT PROPAGATION AND GRAVITY FIELD DETERMINATION FOR GRACE AND FUTURE GEODETIC MISSIONS

Christopher McCullough,[*] Srinivas Bettadpur[†] and Karl McDonald[‡]

The orbit determination process, such as that used for the Gravity Recovery and Climate Experiment (GRACE), is highly dependent upon the comparison of measured observables with computed values, derived from mathematical models relating the satellites' numerically integrated state to the observable. Significant errors in the computed state corrupt this comparison and induce errors in the least squares estimate of the satellites' states, as well as the gravity field. Due to the high accuracy of the inter-satellite ranging measurements from GRACE, numerical computations must mitigate errors to maintain a similar level of accuracy. One error source is the presence of round off errors in the computed inter-satellite range-rate when integrating continuous, smoothly varying accelerations with double precision arithmetic. These errors occur at approximately 8 pm/s RMS and limit the accuracy of numerically integrating background gravity field models to degree/order 260 and 410, for satellite pairs flying at altitudes of 500 and 300 kilometers respectively. In addition, errors due to inaccurate modeling of transient accelerations, which occur on time scales much smaller than the integration step size, may contaminate computed satellite trajectories. For GRACE, these errors arise due to minute inaccuracies in the firing of the spacecrafts' attitude thrusters. Mis-modeling of these accelerations induce errors at approximately 10 nm/s in range-rate; becoming a limitation as more advanced inter-satellite measurement techniques approach this level of accuracy.

[View Full Paper]

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ANALYTICAL MODEL OF VAN ALLEN PROTON RADIATION FLUX FOR TRAJECTORY OPTIMIZATION SOLVERS

Alexander T. Foster* and Atri Dutta†

Radiation damage is a concern for electric orbit-raising of spacecraft to the Geostationary orbit because the spacecraft spends a lot of time in the Van Allen radiation belts. Trajectory optimization solvers are required to compute the solar array degradation during orbit-raising because the loss of power generation capability of the solar array impacts the thrust generated by the electric propulsion devices. Considering that the charged protons in the Van Allen belts cause the majority of damage to the spacecraft solar array, this paper proposes to develop approximate analytical models of the flux of protons in the radiation belts using the recently released AP-9 data. The analytical functions can be used within optimization solvers for improving convergence characteristics and computational time for generating low-thrust trajectories. This paper compares different approximate analytical models for the proton radiation flux.

[View Full Paper]

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LAUNCH AND REENTRY OPERATIONS

SESSION 5

Chair: Angela Bowes
NASA Langley Research Center

The following papers were not available for publication:

AAS 15-290
(Paper Withdrawn)

AAS 15-340
(Paper Withdrawn)

AAS 15-218

SFDT-1 CAMERA POINTING AND SUN-EXPOSURE ANALYSIS AND FLIGHT PERFORMANCE

Joseph White,* Soumyo Dutta† and Scott Striepe‡

The Supersonic Flight Dynamics Test (SFDT) vehicle was developed to advance and test technologies of NASA's Low Density Supersonic Decelerator (LDSD) Technology Demonstration Mission. The first flight test (SFDT-1) occurred on June 28, 2014. In order to optimize the usefulness of the camera data, analysis was performed to optimize parachute visibility in the camera field of view during deployment and inflation and to determine the probability of sun-exposure issues with the cameras given the vehicle heading and launch time. This paper documents the analysis, results and comparison with flight video of SFDT-1.

[View Full Paper]

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SUPERSONIC FLIGHT DYNAMICS TEST 1 - POST-FLIGHT ASSESSMENT OF SIMULATION PERFORMANCE

Soumyo Dutta,[*] Angela L. Bowes,[†] Scott A. Striepe,[‡] Jody L. Davis,[§] Eric M. Queen,[**] Eric M. Blood[††] and Mark C. Ivanov[‡‡]

NASA's Low Density Supersonic Decelerator (LDSD) project conducted its first Supersonic Flight Dynamics Test (SFDT-1) on June 28, 2014. Program to Optimize Simulated Trajectories II (POST2) was one of the flight dynamics codes used to simulate and predict the flight performance and Monte Carlo analysis was used to characterize the potential flight conditions experienced by the test vehicle. This paper compares the simulation predictions with the reconstructed trajectory of SFDT-1. Additionally, off-nominal conditions seen during flight are modeled in post-flight simulations to find the primary contributors that reconcile the simulation with flight data. The results of these analyses are beneficial for the pre-flight simulation and targeting of the follow-on SFDT flights currently scheduled for summer 2015.

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AAS 15-224

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

Prasad Kutty,[*] Christopher D. Karlgaard,[†] Eric M. Blood,[‡] Clara O'Farrell,[§] Jason M. Ginn,[**] Mark Schoenenberger[††] and Soumyo Dutta[‡‡]

The Supersonic Flight Dynamics Test is a full-scale flight test of a Supersonic Inflatable Aerodynamic Decelerator, which is part of the Low Density Supersonic Decelerator technology development project. The purpose of the project is to develop and mature aerodynamic decelerator technologies for landing large mass payloads on the surface of Mars. The technologies include a Supersonic Inflatable Aerodynamic Decelerator and Supersonic Parachutes. The first Supersonic Flight Dynamics Test occurred on June 28th, 2014 at the Pacific Missile Range Facility. This test was used to validate the test architecture for future missions. The flight was a success and, in addition, was able to acquire data on the aerodynamic performance of the supersonic inflatable decelerator. This paper describes the instrumentation, analysis techniques, and acquired flight test data utilized to reconstruct the vehicle trajectory, atmosphere, and aerodynamics. The results of the reconstruction show significantly higher lofting of the trajectory, which can partially be explained by off-nominal booster motor performance. The reconstructed vehicle force and moment coefficients fall well within pre-flight predictions. A parameter identification analysis indicates that the vehicle displayed greater aerodynamic static stability than seen in pre-flight computational predictions and ballistic range tests.

[View Full Paper]

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LDSD POST2 SIMULATION AND SFDT-1 PRE-FLIGHT LAUNCH OPERATIONS ANALYSES

Angela L. Bowes,* Jody L. Davis,† Soumyo Dutta,‡ Scott A. Striepe,§ Mark C. Ivanov, Richard W. Powell†† and Joseph White‡‡**

The Low-Density Supersonic Decelerator (LDSD) Project's first Supersonic Flight Dynamics Test (SFDT-1) occurred June 28, 2014. Program to Optimize Simulated Trajectories II (POST2) was utilized to develop trajectory simulations characterizing all SFDT-1 flight phases from drop to splashdown. These POST2 simulations were used to validate the targeting parameters developed for SFDT-1, predict performance and understand the sensitivity of the vehicle and nominal mission designs, and to support flight test operations with trajectory performance and splashdown location predictions for vehicle recovery. This paper provides an overview of the POST2 simulations developed for LDSD and presents the POST2 simulation flight dynamics support during the SFDT-1 launch, operations, and recovery.

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AAS 15-291

THE GENERATION OF REENTRY LANDING FOOTPRINT WITH ROBUSTNESS

Kai Jin,[*] Jianjun Luo,[†] Jianping Yuan[‡] and Baichun Gong[§]

In this paper, a novel method to obtain the footprint with robustness of entry vehicles is presented. Aiming at eliminating the deficiencies of traditional optimization method in robustness, a robust reentry guidance law is presented using the model predictive static programming. The presented guidance essentially shapes the trajectory of the vehicle by computing the necessary angle of attack and bank angle that the vehicle should execute. Then use an innovative performance index to generate the footprint. The simulations show that the method can generate an accurate landing footprint with reduced sensitivity to uncertainty for more robust performance

[View Full Paper]

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SPACECRAFT FORMATION FLIGHT

SESSION 6

Chair: Eric Butcher
University of Arizona

The following paper was not available for publication:

AAS 15-367
(Paper Withdrawn)

AAS 15-277

DISTRIBUTED COOPERATIVE ATTITUDE TRACKING CONTROL FOR MULTIPLE SPACECRAFT

Xiaoyu. Liu,[*] Yushan Zhao[†] and Peng Shi[‡]

Distributed cooperative control laws for multiple spacecraft attitude tracking are abundant in the related literature. However, most of them are designed based on the availability of both attitude and angular velocity. Since the failure of sensors or the unequipped cases, it is of significant interest to take account of the common occurrence that some spacecraft's angular velocity measurements are unavailable. In this paper, utilizing the feedback from the auxiliary system, a kind of distributed cooperative control method is proposed to handle the attitude tracking control problem of the multiple spacecraft in inertial space, taking account of this kind of common occasion. The asymptotic stability is demonstrated by the Lyapunov theory. Furthermore, the numerical simulations are provided for a four-spacecraft formation experiencing the failure of angular velocity sensors in sequence to highlight the effectiveness of this method.

[View Full Paper]

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AAS 15-362

SPACE-BASED RELATIVE MULTITARGET TRACKING

Keith A. LeGrand[*] and Kyle J. DeMars[†]

As satellite proximity operations involving multiple neighbors, such as a nearby debris cloud or a cooperative swarm, become more common, satellite on-board relative navigation schemes must be augmented to be able to track more than one target. Multitarget intensity filter approaches have shown promise as tractable methods to track single or multiple targets using measurement data which is subject to noise, misdetections, and false alarms. One such filter, known as the cardinalized probability hypothesis density filter, is applied to the space-based tracking problem. The necessary models are developed and discussed, and simulation results from synthetic data are provided for two potential applications.

[View Full Paper]

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RAPID COLLECTION OF LARGE AREAS FOR IMAGING SPACECRAFT

Jeffery T. King,[*] Mark Karpenko[†] and I. Michael Ross[‡]

Imaging a large contiguous area of the Earth's surface involves a continuous succession of alternating image collection and maneuvering operations that must be seamlessly stitched together into an operational mission plan. Even though the change in look angle between adjacent scan swaths may be small, the time for maneuvering between scans may be large. This is because the satellite boresight is in motion at the beginning and at the end of each scan operation so it is necessary to reverse the motion of the satellite in addition to re-pointing the boresight in order to begin the next scan. To facilitate rapid collection of large areas, a class of shortest-time, non-rest, maneuvers is developed in this paper to reduce the waste time between scans and improve the overall image collection rate. The maneuvers are solved as a series of multi-point optimal control problems which are complicated by the fact that the boundary conditions on the satellite attitude, rate and momentum state are time varying due to the relative motion between the satellite and the Earth. A set of nonlinear equations describing the kinematics of the boresight line-of-sight during scanning are therefore developed and integrated as part of the optimal control problem formulation. The results show that maneuver times can be reduced by up to 34% leading to an improvement in collection rate of up to 28%. The relationship between the reduction in maneuver time and the resulting improvement in image collection rate is shown to be dependent on the ratio of total maneuver time to total imaging time, creating a *lever arm effect* which amplifies the improvement in image collection rate as the maneuver time becomes larger in proportion to the imaging time.

[View Full Paper]

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AAS 15-401

DECENTRALIZED RELATIVE POSITION AND ATTITUDE CONSENSUS CONTROL OF A SPACECRAFT FORMATION WITH COMMUNICATION DELAY

Eric A. Butcher[*] and Morad Nazari[†]

The decentralized consensus control of a formation of rigid body spacecraft is studied in the framework of geometric mechanics while accounting for a constant communication time delay between spacecraft. The relative position and attitude dynamics are modeled in the framework of the Lie group $SE(3)$ while the communication topology is modeled as a digraph. The consensus problem is converted into a local stabilization problem of the error dynamics associated with the Lie algebra $\mathfrak{se}(3)$ in the form of an LTI delay differential equation (DDE) with a single discrete delay in the case of a circular orbit and it is in the form of a time periodic DDE in the case of an elliptic orbit.

[View Full Paper]

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AAS 15-402

STATE DEPENDENT RICCATI EQUATION CONTROL OF COLLINEAR SPINNING THREE-CRAFT COULOMB FORMATIONS

Mohammad Mehdi Gomroki* and Ozan Tekinalp†

The relative position control of a collinear spinning three-spacecraft Coulomb formation with set charges is addressed. Such a formation is assumed to be in deep space without relevant gravitational forces present. The nonlinear control is realized through state dependent Riccati equation (SDRE) control method. Relative position control is used to keep a three-craft Coulomb formation about a desired equilibrium collinear configuration. The equations of motion of the formation are properly manipulated to obtain a suitable form for SDRE control. The state-dependent coefficient (SDC) form is then formulated to include the non-linearities in the relative dynamics. Numerical simulations illustrate effectiveness of the controllers.

[View Full Paper]

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PROPAGATION OF CHIP-SCALE SPACECRAFT SWARMS WITH UNCERTAINTIES USING THE KUSTAANHEIMO-STIEFEL TRANSFORMATION

Lorraine Weis[*] and Mason Peck[†]

Chip-scale spacecraft swarms trade the conventional highly reliable and well-characterized strategy of monolithic spacecraft for inexpensive, mass producible, and simple designs. Rather than guarantee a behavior from a single spacecraft, we can instead ensure that the swarm in aggregate will fulfill the mission criteria. The KS transform provides a straightforward way to propagate a chipsat swarm as a whole, including its uncertainties, enabling quantitative evaluation of the swarm's dynamics.

[View Full Paper]

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AAS 15-441

SPACECRAFT ATTITUDE FORMATION STABILIZATION USING LINES-OF-SIGHT WITHOUT ANGULAR VELOCITY MEASUREMENTS

Tse-Huai Wu[*] and Taeyoung Lee[†]

Based on line-of-sight measurements between an arbitrary number of spacecraft in formation, velocity-free attitude formation control systems are developed. The proposed control systems are unique in the sense that spacecraft do not need to have possibly expensive, inertial measurement units, as attitude formation is directly controlled by lines-of-sight that can be measured by low-cost optical sensors. This paper generalizes the previous results of vision-based attitude formation control by making it velocity-free, thereby removing the need for gyros as well. Another distinct feature is that control systems are developed on the nonlinear configuration manifold to avoid singularities and complexities that are inherent to local parameterizations.

[View Full Paper]

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COLLISION AVOIDANCE FOR ELECTROMAGNETIC SPACECRAFT FORMATION FLYING WITH CONSENSUS ALGORITHMS

Xu Zengwen,[*] Shu Leizheng,[†] Shi Peng[‡] and Zhao Yushan[§]

The far-field approximate model used to calculate forces for electromagnetic spacecraft formations is not accurate if the distance between components is small. In order to deal with the inaccuracy, a collision avoidance problem of electromagnetic spacecraft formations was discussed based on the multi-agent control theory. A distributed cooperative controller of the collision avoidance for electromagnetic spacecraft formations was developed by a state-based consensus algorithm. Variable weights were obtained to avoid collisions by the artificial potential function method. An example of a four-craft electromagnetic formation in low earth circular orbit was provided to demonstrate the algorithms' performance. Results show that component spacecrafts do not collide with each other in the process of orbit transferring. Simulations indicate that electromagnetic forces can be used in the collision avoidance control of spacecraft formations.

[View Full Paper]

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TRAJECTORY DESIGN

SESSION 7

Chair: Francesco Topputo
Politecnico di Milano, Italy

The following paper was not available for publication:

AAS 15-306
(Paper Withdrawn)

AAS 15-201

MARS DOUBLE-FLYBY FREE RETURNS

Mark Jesick*

A subset of Earth-originating Mars double-flyby ballistic trajectories is documented. The subset consists of those trajectories that, after the first Mars flyby, perform a half-revolution transfer with Mars before returning to Earth. This class of free returns is useful for both human and robotic Mars missions because of its low geocentric energy at departure and arrival, and because of its extended stay time in the vicinity of Mars. Ballistic opportunities are documented over Earth departure dates ranging from 2015 through 2100. The mission is viable over three or four consecutive Mars synodic periods and unavailable for the next four, with the pattern repeating approximately every 15 years. Over the remainder of the century, a minimum Earth departure hyperbolic excess speed of 3.16 km/s, a minimum Earth atmospheric entry speed of 11.47 km/s, and a minimum flight time of 904 days are observed. The algorithm used to construct these trajectories is presented along with several examples.

[View Full Paper]

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† Data available at `http://nssdc.gsfc.nasa.gov/planetary/chronology_mars.html` [accessed 10 October 2014]

THE REBOOT OF THE INTERNATIONAL SUN/EARTH EXPLORER 3: THE ORBIT DETERMINATION AND TRAJECTORY DESIGN OPTION ANALYSIS

Timothy Craychee,[*] Craig Nickel,[†] Lisa Policastri[**] and Michel Loucks[‡]

In late spring 2014, a team of engineers investigated the feasibility of potentially recapturing the International Sun/Earth Explorer 3 (ISEE-3) also known as the Interstellar Cometary Explorer (ICE) spacecraft. This effort is known as the ISEE-3 Reboot Project. This paper reports on the flight dynamics team's efforts to accurately determine the ISEE-3 orbit and design trajectory options that were evaluated for the ISEE-3 spacecraft upon successful recapture into the Earth-Moon system.

[View Full Paper]

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AAS 15-223

HIGH ALTITUDE VENUS OPERATIONS CONCEPT TRAJECTORY DESIGN, MODELING, AND SIMULATION

Rafael A. Lugo,[*] Thomas A. Ozoroski,[†] John W. Van Norman,[†] Dale C. Arney,[‡] John A. Dec,[§] Christopher A. Jones[‡] and Carlie H. Zumwalt[**]

A trajectory design and analysis that describes aerocapture, entry, descent, and inflation of manned and unmanned High Altitude Venus Operation Concept (HAVOC) lighter-than-air missions is presented. Mission motivation, concept of operations, and notional entry vehicle designs are presented. The initial trajectory design space is analyzed and discussed before investigating specific trajectories that are deemed representative of a feasible Venus mission. Under the project assumptions, while the high-mass crewed mission will require further research into aerodynamic decelerator technology, it was determined that the unmanned robotic mission is feasible using current technology.

[View Full Paper]

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AAS 15-255

DESIGNING TRANSFERS TO GEOSTATIONARY ORBIT USING COMBINED CHEMICAL-ELECTRIC PROPULSION

Craig A. Kluever*

While it is clear that electric propulsion can deliver more payload mass when compared to conventional chemical propulsion, near-term transfers to geostationary-equatorial orbit will likely use both propulsion modes in order to reduce the transfer time. Determining the best starting orbit for the subsequent electric-propulsion phase is the key to computing time-constrained, maximum-payload transfers to geostationary orbit. Numerical optimization methods are used to determine the unique optimal starting orbit for a given low-thrust velocity increment (ΔV) to be performed by the electric-propulsion stage. This approach yields a purely analytical algorithm that can determine spacecraft mass requirements for a desired electric propulsion system and desired transfer time. Numerical examples are presented in order to demonstrate how this tool can be used to rapidly perform trade studies for transfers that utilize chemical and electric propulsion stages.

[View Full Paper]

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AAS 15-416

LOW THRUST ORBIT-RAISING USING NON-SINGULAR ORBITAL ELEMENTS AND PROXIMITY QUOTIENT APPROACH

Sainath Vijayan[*] and Atri Dutta[†]

Recent years have shown a growing interest in the space industry in all-electric satellites. Mission designers analyzing the optimal deployment options for all-electric satellites need to consider three important metrics: transfer time, fuel expenditure and radiation damage. This paper proposes a proximity quotient type approach based guidance-scheme using modified equinoctial elements to determine a low-thrust trajectory that minimizes other objectives during electric orbit-raising. The use of the equinoctial elements help in avoidance of singularity of the orbital elements at GEO, thereby enabling the final orbit to be precisely GEO at the end of the transfer. We present numerical examples to illustrate our methodology when the objective function to be minimized is different from time.

[View Full Paper]

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AERO-GRAVITY ASSIST MISSION DESIGN

Jeremy M. Knittel,[*] Mark J. Lewis[†] and Ken Yu[‡]

A method for the design of spacecraft missions requiring the use of an aero-gravity assist maneuver is presented. Interplanetary paths are created by connecting Lambert arcs based on maximum aero-gravity assist performance estimations and C_3 matching for non-atmospheric gravity assist fly-bys. A route is defined by a launch date and C_3, a list of planetary fly-bys, and requisite aero-gravity assist performance. Next, the overall trajectory is optimized using an n-body simulator and modeling of atmospheric entry, hypersonic cruise, and ascent. Genetic algorithms are used to design an aeroshell capable of delivering the needed aerodynamic performance to complete the maneuver, while optimizing for other figures of merit such as: heat load, internal volume, and structural load. The overall method is demonstrated with the step-by-step design of a mission to send a spacecraft out of the solar system in the shortest time possible, a revival of the so-called interstellar probe concept. It is shown that for the example given, using two consecutive aero-gravity assist maneuvers in sequence is not beneficial. However, single AGA trajectories are found which save twenty-one years over a gravity assist only route. Further, by optimizing the vehicle shape along with the interplanetary trajectory, a heating minimum vehicle was found while saving an additional two years of flight time to interstellar space.

[View Full Paper]

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TRAJECTORY DESIGN FROM GTO TO NEAR-EQUATORIAL LUNAR ORBIT FOR THE DARK AGES RADIO EXPLORER (DARE) SPACECRAFT

Anthony L. Genova,* Fan Yang Yang,† Andres Dono Perez,‡ Ken F. Galal,§ Nicolas T. Faber,¶ Scott Mitchell,# Brett Landin,** Abhirup Datta†† and Jack O. Burns‡‡, §§

The trajectory design for the Dark Ages Radio Explorer (DARE) mission concept involves launching the DARE spacecraft into a geosynchronous transfer orbit (GTO) as a secondary payload. From GTO, the spacecraft then transfers to a lunar orbit that is stable (i.e., no station-keeping maneuvers are required with minimum perilune altitude always above 40 km) and allows for more than 1,000 cumulative hours for science measurements in the radio-quiet region located on the lunar farside.

[View Full Paper]

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AAS 15-464

THE PHASING PROBLEM FOR SUN-EARTH HALO ORBIT TO LUNAR ENCOUNTER TRANSFERS

Hongru Chen,* Yasuhiro Kawakatsu† and Toshiya Hanada‡

Halo orbit missions are of many applications and become popular. An investigation on the extended mission following halo orbit missions would be worthwhile. In a previous study, the strategy of using the unstable manifolds associated with the Sun-Earth L_1/L_2 halo orbit and lunar gravity assists for Earth escape was analyzed to be advantageous for extending the mission. However, in an extension mission where the halo orbit mission is not pre-phased for a lunar swingby, the fuel cost for phasing the halo-to-Moon transfers should be investigated. The current paper aims to give the insight of the minimum phasing ΔV to encounter the Moon for various lunar phases with respect to the halo orbit. Efforts are made to tackle the problem of multiple optimization directions. The phasing planning is briefly discussed as well.

[View Full Paper]

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ASTEROID AND COMETARY MISSIONS

SESSION 8

Chair: Nathan Strange
Jet Propulsion Laboratory

The following papers were not available for publication:

AAS 15-225
(Paper Withdrawn)

AAS 15-310
(Paper Withdrawn)

AAS 15-283

STUDY ON THE REQUIRED ELECTRIC SAIL PROPERTIES FOR KINETIC IMPACTOR TO DEFLECT NEAR-EARTH ASTEROIDS

Kouhei Yamaguchi* and Hiroshi Yamakawa†

The electric sail is a next-generation propulsion system which enables a spacecraft to produce thrust without consuming any reaction mass. It uses a interaction between many charged long thin tethers and the solar wind to produce the propulsive force. This paper discussed the required propertied of the electric sail for kinetic impactor to deflect the near earth asteroids. As fundamental contents, solar wind force model, equations of motion, and orbital maneuvering technique are provided. In addition, more practical theory as the way to calculate the optimal mass model of electric sail and terminal guidance technique are also provided. Those contents are combined into one simulation tool to investigate the efficiency of the electric sail kinetic impactor and required electric sail properties. Through the case study based on real parameters of a near Earth asteroid, required properties of the electric sail and the usability of the developed tool are shown. The relation between the achievable deflection distance and resources of the electric sail are also provided.

[View Full Paper]

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AAS 15-299

OPTIMIZED LOW-TRUST MISSION TO THE ATIRA ASTEROIDS

Marilena Di Carlo,[*] Natalia Ortiz Gómez,[†] Juan Manuel Romero Martín,[*] Chiara Tardioli,[*] Fabien Gachet,[‡] Kartik Kumar[§] and Massimilano Vasile[¶]

Atira asteroids are recently-discovered celestial bodies characterized by orbits lying completely inside the Earth's. The study of these objects is difficult due to the limitations of ground-based observations: objects can only be detected when the Sun is not in the field of view of the telescope. However, many asteroids are expected to exist in the inner region of the Solar System, many of which could pose a significant threat to our planet. In this paper, a mission to improve knowledge of the known Atira asteroids in terms of ephemerides and composition and to observe inner-Earth asteroids is presented. The mission is realized using electric propulsion, which in recent years has proven to be a viable option for interplanetary flight. The trajectory is optimized in such a way as to visit the maximum possible number of asteroids of the Atira group with the minimum propellant consumption; the mission ends with a transfer to an orbit with perigee equal to Venus's orbit radius, to maximize the observations of asteroids in the inner part of the Solar System.

[View Full Paper]

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AAS 15-333

RAPID PROTOTYPING OF ASTEROID DEFLECTION CAMPAIGNS WITH SPATIALLY AND TEMPORALLY DISTRIBUTED PHASES

Sung Wook Paek,[*] Patricia Egger[†] and Olivier de Weck[‡]

This paper discusses a framework to design asteroid deflection campaigns consisting of multiple phases that are temporally or spatially distributed. A precursor mission prior to actual deflection can reduce uncertainties in asteroid properties in order to improve deflection accuracy and reduce impact probability. Also, spatially distributed, multiple impactors can increase the upper bound of achievable total deflection. An open-source Propagator for Asteroid Trajectories Tool (PAT2) is used to rapidly prototype and evaluate the resulting large tradespace of deflection campaigns for both exploration and mitigation purposes.

[View Full Paper]

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AAS 15-336

CONTINUOUS LOW-THRUSTING TRAJECTORY DESIGN FOR EARTH-CROSSING ASTEROID DEFLECTION

Chong Sun,[*] Jian-ping Yuan[†] and Qun Fang[‡]

An analytical approach for continuous low thrusting trajectory design for earth crossing asteroid deflection is proposed in this paper. The performance measure is to minimize fuel consumption required to achieve target separation distance. The displacement of the asteroid at the minimum orbit interception distance from the earth's orbit is parameterized using proposed method. With Practical Swarm Optimization algorithm, optimization parameters can be found to satisfy astro-dynamical constraints and optimize the transfer trajectory. The simulation results show that proposed method can provide a significant saving in computational time and maintain a good accuracy.

[View Full Paper]

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AAS 15-337

DESIGN AND OPERATION OF A MICRO-SPACECRAFT ASTEROID FLYBY MISSION: PROCYON

Yoshihide Sugimoto,* Stefano Campagnola,† Chit Hong Yam,* Bruno Sarli,‡ Hongru Chen,§ Naoya Ozaki,§ Yasuhiro Kawakatsu and Ryu Funase††**

PROCYON (PRoximate Object Close flYby with Optical Navigation) is a 50kg-class micro-spacecraft developed by the University of Tokyo and the Japan Aerospace Exploration Agency (JAXA), to be launched in an Earth resonant trajectory at the end of 2014 as a secondary payload with Hayabusa 2 mission. The mission objective is to demonstrate low cost and applicability of a micro-spacecraft bus technology for deep space exploration and proximity flyby to asteroids performing optical navigation. This paper introduces the spacecraft and mission design for PROCYON, as well as, the operation strategy mainly for the deep-space cruising period

[View Full Paper]

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APPLICATION OF THE JUMPING MECHANISM OF TROJAN ASTEROIDS TO THE DESIGN OF A TOUR TRAJECTORY THROUGH THE COLLINEAR AND TRIANGULAR LAGRANGE POINTS

Kenta Oshima[*] and Tomohiro Yanao[†]

We develop and optimize a low-thrust sample return trajectory touring the vicinities of the collinear (L_1 and L_3) and triangular (L_4 and L_5) Lagrange points in the Earth-Moon planar circular restricted three-body problem. For the purposes of looping around L_4 and L_5 many times and reducing the transfer cost between them, we utilize a natural transfer trajectory of a Trojan asteroid between L_4 and L_5 through L_3, which is dynamically mediated by the invariant manifolds associated with L_3. We then connect the two ends of this natural transfer trajectory with a Lyapunov orbit around L_1 and with the Earth respectively via fuel-efficient low-thrust trajectories utilizing lunar gravity assists. These connecting trajectories are globally optimized through a recently developed interior search algorithm combined with the indirect approach, and are locally optimized to satisfy all the boundary conditions as well as the first order necessary conditions for optimality using the Matlab functions "fmincon" and "minimize". We thus obtain an overall trajectory that starts from an L_1 Lyapunov orbit, transfers to the vicinity of L_5 utilizing lunar gravity assist and low-thrust maneuvers, loops around L_5 many times, then transfers to the vicinity of L_4 through L_3 without fuel consumption as a natural transport, loops around L_4 many times, and finally returns to the Earth utilizing lunar gravity assist and low-thrust maneuvers.

[View Full Paper]

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AAS 15-462

REDIRECTION OF ASTEROIDS ONTO EARTH-MARS CYCLERS

Nathan Strange,* Damon Landau* and James Longuski†

NASA is currently studying an Asteroid Redirect Mission (ARM) that would capture either an entire small asteroid or a boulder from a larger asteroid and place it in orbit around the Moon using a Solar Electric Propulsion (SEP) vehicle. This asteroid redirection capability could also be used in future missions to redirect asteroids onto Earth-Mars cyclers where the asteroidal material could be used to provide water, propellant, structural material, and radiation shielding material. This last application is especially interesting as it may provide an economical solution to the problem of protecting astronauts from radiation on journeys to Mars.

[View Full Paper]

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ORBIT DETERMINATION I

SESSION 9

Chair: John H. Seago
Analytical Graphics, Inc.

AAS 15-258

GENERATION OF INITIAL ORBIT ERROR COVARIANCE

James Woodburn[*] and Jens Ramrath[†]

Higher order methods of propagating orbit error uncertainty show promise for cases where the uncertainty is large enough to violate linear assumptions. While large orbit uncertainty is possible in many circumstances, the perception of large uncertainties based on the propagation of ill-formed initial error covariance functions can unnecessarily implicate the need for higher order methods when more traditional methods would suffice. The effect of commonly used initial error covariance selection practices on the predicted history of the covariance is examined through numerical examples covering several classes of orbits. The results show that the propagation of ad-hoc initial error covariance matrices should not be considered to be indicative of how orbit uncertainty will propagate when operational orbit determination is performed and therefore do not provide a valid basis for decision making.

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UPDATING TRACK DATA FROM PARTIAL SERENDIPITOUS SATELLITE STREAKS

Charlie T. Bellows,[*] Jonathan T. Black,[†] Richard G. Cobb[‡] and Alan L. Jennings[§]

Reliable Space Situational Awareness (SSA) is a recognized requirement in the current congested, contested, and competitive environment of space operations. A shortage of available sensors and reliable data sources are some current limiting factors for maintaining SSA. Alternative methods are sought to enhance current SSA, including utilizing non-traditional data sources to perform basic SSA catalog maintenance functions. This work examines the feasibility and utility of performing positional updates for a Resident Space Object (RSO) catalog using metric data obtained from RSO streaks gathered by astronomical telescopes. The focus of this work is on processing data from three possible streak categories: streaks that only enter, only exit, or cross completely through the astronomical image. The methodology developed can also be applied to dedicated SSA sensors to extract data from serendipitous streaks gathered while observing other RSOs.

[View Full Paper]

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

AAS 15-329

CONTROL METRIC MANEUVER DETECTION WITH GAUSSIAN MIXTURES AND REAL DATA

Andris D. Jaunzemis,[*] Midhun Mathew[†] and Marcus J. Holzinger[‡]

The minimum-fuel distance metric provides a natural tool with which to associate space object observation data. A trajectory optimization and anomaly hypothesis testing algorithm is developed based on the minimum-fuel distance metric to address observation correlation under the assumption of optimally maneuvering spacecraft. The algorithm is tested using inclination-change scenarios with both synthetic and real data gathered from the Wide Area Augmentation System (WAAS). Comparisons to other commonly-used association metrics such as Mahalanobis distance reveal less sensitivity in anomaly detection but improved consistency with respect to observation cadence, while providing added data through the reconstruction of the optimal maneuver. Non-Gaussian boundary conditions are also approached through an analytical approximation method, yielding significant computational complexity improvements.

[View Full Paper]

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AAS 15-355

MITIGATION OF PROPAGATION ERROR IN INTERPLANETARY TRAJECTORIES

Davide Amato,[*] Claudio Bombardelli[†] and Giulio Baù[‡]

The reliable and accurate propagation of interplanetary orbits is of crucial importance in several applications in celestial mechanics and astrodynamics, for example asteroid impact monitoring and mitigation, and interplanetary mission analysis and design. When planetary close encounters are involved, numerical propagation is complicated by the amplification of the numerical error in the position and velocity after the encounter. Therefore, the presence of subsequent encounters (for example resonant returns) makes accurate orbit computation a difficult and challenging task. In this work, we investigate the possibility of reducing global numerical error by employing regularized formulations of orbital dynamics, such as the Dromo formulation. Test cases are performed both for geocentric hyperbolic trajectories and for whole interplanetary trajectories with a resonant close encounter. Results show that Dromo, along with the Kustaanheimo-Stiefel formulation, is able to significantly reduce the propagation error with respect to Cowell's method. In particular, the addition of a time element to Dromo is highly beneficial in containing the error produced by the integration of time.

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AAS 15-359

AN RBF-COLLOCATION ALGORITHM FOR ORBIT PROPAGATION

Tarek A. Elgohary,* John L. Junkins† and Satya N. Atluri‡

Several analytical and numerical methods exist to solve the orbit propagation of the two-body problem. Analytic solutions are mainly implemented for the unperturbed/classical two-body problem. Numerical methods can handle both the unperturbed and the perturbed two-body problem. The literature is rich with numerical methods addressing orbit propagation problems such as, Gauss-Jackson, Higher order adaptive Runge-Kutta and Taylor series based methods. More recently, iterative methods have been introduced for orbit propagation based on the Chebyshev-Picard methods. In this work, Radial Basis Functions, RBFs, are used with time collocation to introduce a fast, accurate integrator that can readily handle orbit propagation problems. Optimizing the shape parameter of the RBFs is also introduced for more accurate results. The algorithm is also applied to Lambert's problem. Two types of orbits for the unperturbed two-body problem are presented; (1) a Low Earth Orbit (LEO) and (2) a High Eccentricity Orbit (HEO). The initial conditions for each orbit are numerically integrated for 5, 10 and 20 full orbits and the results are compared against the Lagrange/Gibbs F&G analytic solution, *Matlab ode45* and the higher order *rkn12(10)*. An Lambert's orbit transfer numerical example is also introduced and the results are compared against the *F&G* solution. The algorithm is shown to be capable of taking large time steps while maintaining high accuracy which is very significant in long-term orbit propagation problems.

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INTEGRATED DETECTION AND TRACKING FOR MULTIPLE SPACE OBJECTS

James S. McCabe,* Kyle J. DeMars† and Carolin Frueh‡

The tracking of multiple objects in the space environment contains many complications, including ambiguity in the number of tracked objects, an unknown association between objects and observations, and sensor injected uncertainty in the form of false returns, measurement noise, and missed detections. While the topics of initial orbit determination (IOD) and target tracking are well studied in the field, the complexities of the problem demand a method for detection and tracking in a single, unified framework capable of performing maintenance of tracking solutions already in the catalog, instantiating new objects into the catalog. FISST-based filtering, modern IOD methods, and high-fidelity sensor modeling are presented in an integrated framework to accomplish this.

[View Full Paper]

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AAS 15-368

GAUSSIAN INITIAL ORBIT DETERMINATION IN UNIVERSAL VARIABLES

Stefano Casotto*

Gaussian IOD is based on the sector-to-triangle ratio, which incorporates the dynamical information associated with Keplerian motion. It has already been shown that this method leads to a system of six highly nonlinear equations in terms of Keplerian elements. Here we show how by switching to the universal formulation based on Stumpff functions the minimal set of five equations can be derived. As in the method of Gauss, the basis of the present method is still the Bouguer complanarity condition. However, the subsequent development relies on the direct transcription of the unknown Bouguer coefficients in terms of the Lagrange coefficients, which brings the Two-Body dynamics into the formulation. The minimal set of equations is thus obtained, which can be solved in a variety of ways, all requiring initial guesses as a starter. These are provided for the new pair of variables introduced in the universal algorithm which differ from the strictly Gaussian approach. An analysis of the impact of measurement precision on the final result, i.e., on the dynamical state vector, either Cartesian or Keplerian, by mapping the covariance matrix of the three raw observations by a sequence of similarity transformations.

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AAS 15-413

A LABELED MULTI-BERNOULLI FILTER FOR SPACE OBJECT TRACKING

Brandon A. Jones[*] and Ba-Ngu Vo[†]

To maintain custody of the increasing number of detectable objects in Earth orbit, tracking systems require robust methods of multi-target state estimation and prediction. One alternative to the classic multiple hypothesis and probabilistic data association methods uses a random finite set for modeling the multi-target state. The common forms of such filters sacrifice knowledge of specific targets for the sake of tractability. This paper presents a labeled multi-Bernoulli filter for tracking space objects, which allows for the identification of individual targets. This version of the filter includes a new-target birth model based on the admissible region and non-Gaussian propagation of the single-target state probability density function. The benefits of the filter are then demonstrated for the tracking of both previously known and newly detected objects near geosynchronous orbit.

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AAS 15-418

COLLABORATIVE MULTI-SENSOR TRACKING AND DATA FUSION

Kyle J. DeMars,[*] James S. McCabe[†] and Jacob E. Darling[‡]

Multi-sensor networks can alleviate the need for high-cost, high-accuracy, single-sensor tracking in favor of an abundance of lower-cost and lower-accuracy sensors to perform multi-sensor tracking. The use of a multi-sensor network gives rise to the need for a fusion step that combines the outputs of all sensor nodes into a single probabilistic state description. Broadly speaking, multi-sensor networks may be classified as cooperative or collaborative, where cooperative networks share single-sensor tracking solutions but do not use other solutions to inform their tracking directives. Collaborative networks, on the other hand, enable tip-off tracking paradigms, where the tracking solution from one sensor is used to queue another sensor in the network. This paper investigates efficient methods for achieving multi-sensor data fusion in a collaborative network of disparate sensors. Simulation results are presented for the tracking of a low-Earth orbit object using both optical telescope and radar systems.

[View Full Paper]

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AAS 15-423

GENERALIZED GAUSSIAN CUBATURE FOR NONLINEAR FILTERING

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

A novel method for nonlinear filtering based on a generalized Gaussian cubature approach is shown. Specifically, a new point-based nonlinear filter is developed which is not based on one-dimensional quadrature rules, but rather uses multi-dimensional cubature rules for Gaussian distributions. The new generalized Gaussian cubature filter is not in general limited to odd-order degrees of accuracy, and provides a wider range of order of accuracy. The method requires the solution of a set of nonlinear equations for finding optimal cubature points, but these equations are only required to be solved once for each state dimensional and order of accuracy. This rule is also extended to anisotropic cases where the order of accuracy is not isotropic in dimension. This method allows for tuning of the cubature rules to develop problem-specific rules that are optimal for the given problem. The generalized Gaussian cubature filter is applied to benchmark problems in astrodynamics, and it is compared against existing nonlinear filtering methods.

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ATTITUDE DETERMINATION AND SENSORS

SESSION 10

Chair: Fu-Yuen Hsiao
Tamkang University

AAS 15-211

OBSERVABILITY ANALYSIS AND FILTER DESIGN FOR THE ORION EARTH-MOON ATTITUDE FILTER

Renato Zanetti[*] and Christopher N. D'Souza[†]

The Orion attitude navigation design is presented, together with justification of the choice of states in the filter and an analysis of the observability of its states while processing star tracker measurements. The analysis shows that when the gyro biases and scale factors drift at different rates and are modeled as first-order Gauss-Markov processes, the states are observable so long as the time constants are not the same for both sets of states. These results are used to finalize the design of the attitude estimation algorithm and the attitude calibration maneuvers.

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AAS 15-254

DISCRETE AND CONTINUOUS TIME ADAPTIVE ANGULAR VELOCITY ESTIMATORS

Daniele Mortari[*] and Maruthi R. Akella[†]

Two filtering techniques to estimate the angular velocity are presented for rigid-spacecraft with no gyros. The primary motivation for this work arises from the possibility of estimating angular velocity using estimated quaternions when the spacecraft is performing slew maneuvers, and/or to provide on-board Kalman filter implementations with good initial angular velocity estimates. Both discrete-time and continuous-time formulations are presented. For the discrete-time case, the basic idea for the estimator relies on the fact that, as long as the angular rate does not change direction, the quaternion kinematics describing the attitude evolution constraints the quaternion itself on an 2-D plane on a 4-D space. Using the properties of Ortho-skew matrices and the decomposition of orientation into rotations in 4-D space, this paper shows how to identify this plane and how to extract the angular velocity vector from a matrix containing a series of subsequent quaternion measurements. Specifically, the angular velocity direction is derived from the instantaneous quaternion's plane of rotation. The magnitude of the angular velocity is then estimated by a simple linear weighted equation using angles between quaternions. The resulting algorithm allows to adjusts the size of a sliding window over which possibly noise corrupted attitude measurements are processed. The size of this window is adapted according to the angular rate variations (fast v/s slow maneuvers). A salient feature is that no prior knowledge of the inertia tensor is required which is an extremely attractive feature for implementation onboard spacecraft with poorly characterized mass properties. For the continuous-time formulation, a new nonlinear angular velocity observer is established that once again uses only attitude measurements albeit under the assumption of perfectly modeled inertia properties. Noisy measurements and possible unknown bounded disturbance torques are accommodated within this formulation while ensuring signal boundedness for the estimated angular velocities. Moreover, the state estimates are guaranteed to be continuously differentiable functions of time and the convergence properties of the observer are established for all possible rotational motions subject to bounded angular rates.

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AAS 15-319

COARSE SUN ACQUISITION ONLY WITH SUN SENSORS FOR MICRO SATELLITES

Fu-Yuen Hsiao,* Wei-Ting Chou,† Trendon Cato‡ and Carla Rebelo§

This paper discusses the algorithm of coarse sun acquisition with sun sensors only for micro satellites. The developing FormoSat 7 constellation is employed as the application and example of this algorithm. Unlike a larger satellite, the power in a micro satellite is limited. Therefore, an attitude estimator is usually not functioned at the launching stage. After the stage of detumbling, the micro satellite has to acquire sun as soon as possible with the designated algorithm. In this paper, an algorithm to perform blind search of sun is developed only with coarse sun sensors. We also consider the eclipse of the sun. A 6DOF model is developed and Monte Carlo simulation method is employed to verify the developed algorithm. The developed algorithm will later be applied to the FormoSat 7 constellation, and can be used in any micro satellites with similar equipment.

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AAS 15-341

BILINEAR SYSTEM IDENTIFICATION BY MINIMAL-ORDER STATE OBSERVERS

Francesco Vicario,[*] Minh Q. Phan,[†] Richard W. Longman[‡] and Raimondo Betti[§]

Bilinear systems offer a promising approach for nonlinear control because a broad class of nonlinear problems can be reformulated and approximated in bilinear form. System identification is a technique to obtain such a bilinear approximation for a nonlinear system from input-output data. Recent discrete-time bilinear model identification methods rely on Input-Output-to-State Representations (IOSRs) derived via the interaction matrix technique. A new formulation of these methods is given by establishing a correspondence between interaction matrices and the gains of full-order bilinear state observers. The new interpretation of the identification methods highlights the possibility of utilizing minimal-order bilinear state observers to derive new IOSRs. The existence of such observers is discussed and shown to be guaranteed for special classes of bilinear systems. New bilinear system identification algorithms are developed and the corresponding computational advantages are illustrated via numerical examples.

[View Full Paper]

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GYRO ACCURACY AND FAILURE SENSITIVITY OF UNDERDETERMINED COARSE SUN-DIRECTION ESTIMATION

Stephen A. O'Keefe[*] and Hanspeter Schaub[†]

Coarse sun sensors are commonly used to perform coarse attitude estimation and point a spacecraft's solar arrays at the Sun. These sensors are attractive due to their relative inexpensiveness, small size, and minimal power consumption. While, traditionally, these sensors are used in large quantities to ensure redundant sensor coverage over the entire attitude sphere, this research examines underdetermined configurations where not enough sensors are available to uniquely determine the sun-direction vector at any one time. The sensitivities of two coarse sun sensor based sun-direction estimation techniques, using underdetermined sensor configurations, to rate gyroscope noise and sensor failure are presented. The relative performance of these schemes when using the spectrum of rate accuracy between inertial grade and MEMS gyroscopes is examined. In addition, the sensitivity of these methods to sensor failure is examined along with a method of improving estimation accuracy when sensor failure occurs.

[View Full Paper]

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AAS 15-380

ESTIMATION OF OPTIMAL CONTROL BENEFITS USING THE AGILITY ENVELOPE CONCEPT

Jeffery T. King* and Mark Karpenko†

The capability of space-based sensors to collect images is directly related to the agility of the sensor. Increasing the sensor agility, without changing the attitude control hardware, can be accomplished by using optimal control to design shortest-time maneuvers. The performance improvement that can be obtained using optimal control is tied to the specific configuration of the satellite, e.g., mass properties, reaction wheel array geometry, etc. Therefore, it is generally difficult to predict performance without extensive simulation. This paper presents a simple idea for estimating the agility enhancement that can be obtained using optimal control without the need to solve the optimal control problem. The approach is based on the concept of the agility envelope, which expresses the capability of a spacecraft in terms of a three-dimensional agility volume.

[View Full Paper]

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ON-ORBIT COARSE SUN SENSOR CALIBRATION SENSITIVITY TO SENSOR AND MODEL ERROR

Stephen A. O'Keefe* and Hanspeter Schaub†

The size and budgetary limitations of increasingly popular smaller satellites as a lower cost alternative to traditional satellites are a driving factor for making the most of inexpensive components and sensors. One example of an attractive, inexpensive sensor is the coarse cosine-type sun sensor (CSS) that outputs a voltage relative to the input irradiance. CSS are often used, in combination with other sensors, to perform attitude determination. The accuracy of these estimation techniques can be greatly improved by on-orbit calibration of the CSS. However, the requirements for achieving high-accuracy on-orbit calibration can often necessitate significant ground-based support. A Modified Rodrigues Parameter calibration filter, based on an extended consider Kalman filter, that uses an albedo model is presented along with a second filter in which the CSS input due to albedo is treated as a bias. The accuracy of these two methods and their relative computational cost is evaluated. It is found that the estimation schemes are minimally impacted by reduced orbit reference sun-direction accuracy, and that a lower resolution albedo model can significantly reduce computation time without overly sacrificing accuracy.

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AAS 15-425

ASSESSING GOES-R MAGNETOMETER ACCURACY

Craig Babiarz,[*] Delano Carter,[†] Douglas Freesland,[‡] Monica Todirita,[§]
Jeff Kronenwetter,[**] Kevin Kim,[††] Kumar Tadikonda[‡‡] and Donald Chu[§§]

The Geostationary Operational Environmental Satellite (GOES-R) will have two magnetometers on a long boom to monitor the geomagnetic field and space weather. There are several sources of measurement error including spacecraft field, bias, misalignment, scale factor and sensor non-orthogonality. This paper is a first attempt at estimating overall system accuracy using simulation and covariance analyses. It also proposes calibration procedures for post-launch test and routine operations. The results suggest that small annual maneuvers would be highly advantageous for maintaining accuracy.

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LOW-THRUST TRAJECTORY DESIGN

SESSION 11

Chair: Jeffrey Parker
University of Colorado at Boulder

The following paper was not available for publication:

AAS 15-323
(Paper Withdrawn)

AAS 15-227

MULTI-OBJECTIVE HYBRID OPTIMAL CONTROL FOR MULTIPLE-FLYBY LOW-THRUST MISSION DESIGN

Jacob A. Englander,* Matthew A. Vavrina† and Alexander R. Ghosh‡

Preliminary design of low-thrust interplanetary missions is a highly complex process. The mission designer must choose discrete parameters such as the number of flybys, the bodies at which those flybys are performed, and in some cases the final destination. In addition, a time-history of control variables must be chosen that defines the trajectory. There are often many thousands, if not millions, of possible trajectories to be evaluated. The customer who commissions a trajectory design is not usually interested in a point solution, but rather the exploration of the trade space of trajectories between several different objective functions. This can be a very expensive process in terms of the number of human analyst hours required. An automated approach is therefore very desirable. This work presents such an approach by posing the mission design problem as a multi-objective hybrid optimal control problem. The method is demonstrated on a hypothetical mission to the main asteroid belt.

[View Full Paper]

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AAS 15-273

EARTH-TO-HALO LOW-THRUST MINIMUM FUEL OPTIMIZATION WITH OPTIMIZED LAUNCH CONDITIONS

C. Zhang* and F. Topputo†

Transfer time and fuel consumption are two major performance indexes in trajectory optimization. In this paper, low-thrust propulsion is applied after an impulsive maneuver. Both phases are optimized, and trajectory optimization with optimized launch conditions in the Earth–Moon restricted three-body model is performed. The total fuel consumption is minimized, and the first-order necessary condition for optimality as well as their analytic Jacobians are derived. Homotopy method is used to link the related and easier minimum-energy problem to the corresponding minimum-fuel problem. The combination of these methods stated above are applied to minimum-fuel Earth–Halo transfer. Simulation show that this method can afford various combinations of time of flight and total mass consumption, which gives a great flexibility in mission design.

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AAS 15-278

AN AUTOMATIC MEDIUM TO HIGH FIDELITY LOW-THRUST GLOBAL TRAJECTORY TOOL-CHAIN; EMTG-GMAT

Ryne Beeson,* Jacob A. Englander,†
Steven P. Hughes‡ and Maximilian Schadegg§

Solving the global optimization, low-thrust, multiple-flyby interplanetary trajectory problem with high-fidelity dynamical models requires an unreasonable amount of computational resources. A better approach, and one that is demonstrated in this paper, is a multi-step process whereby the solution of the aforementioned problem is solved at a medium-fidelity and this solution is used as an initial guess for a higher-fidelity solver. The framework presented in this work uses two tools developed by NASA Goddard Space Flight Center (GSFC): the Evolutionary Mission Trajectory Generator (EMTG) and the General Mission Analysis Tool (GMAT). EMTG is a medium to medium-high fidelity low-thrust interplanetary global optimization solver, which now has the capability to automatically generate GMAT script files for seeding a high-fidelity solution using GMAT's local optimization capabilities. An overview of the analysis tools is presented along with a discussion of the autonomy of the tool-chain. Current capabilities are highlighted with increasingly difficult problems; the final problem being the recreation of the interplanetary trajectory for the DAWN mission.

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AAS 15-281

LOW-THRUST ORBIT TRANSFER OPTIMIZATION USING UNSCENTED KALMAN FILTER PARAMETER ESTIMATION

Zhang Ran,[*] Li Jian[†] and Han Chao[‡]

It is considered optimization of low-thrust transfer from a low and eccentric initial orbit toward a high geostationary orbit. The optimal control problem is reduced to the two-point boundary value problem (TPBVP) by means of Pontryagin Maximum Principle. Unscented Kalman filter (UKF) parameter estimation algorithms are applied in solving TPBVP. The algorithms are simple, efficient and robust to overcome the difficulties of guessing the initial values of the costate variables. Environmental constraints such as Earth oblateness and shadow effect are included in both minimum-time and fuel-saving cases. Several numerical simulations are presented to demonstrate the effectiveness of those proposed methods.

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AAS 15-397

COUPLED LOW-THRUST TRAJECTORY AND SYSTEMS OPTIMIZATION VIA MULTI-OBJECTIVE HYBRID OPTIMAL CONTROL

Matthew A. Vavrina,[*] Jacob A. Englander[†] and Alexander R. Ghosh[‡]

The optimization of low-thrust trajectories is tightly coupled with the spacecraft hardware. Trading trajectory characteristics with system parameters to identify viable solutions and determine mission sensitivities across discrete hardware configurations is labor intensive. Local, independent optimization runs can sample the design space, but a global exploration that resolves the relationships between the system variables across multiple objectives enables a full mapping of the optimal solution space. A multi-objective, hybrid optimal control algorithm is formulated using a multi-objective genetic algorithm as an outer-loop systems optimizer around a global trajectory optimizer. The coupled problem is solved simultaneously to generate Pareto-optimal solutions in a single execution. The automated approach is demonstrated on two interplanetary boulder return missions.

[View Full Paper]

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AAS 15-431

LOW-THRUST ORBIT-RAISING TRAJECTORIES CONSIDERING ECLIPSE CONSTRAINTS

Suwat Sreesawet[*] and Atri Dutta[†]

Many-revolution electric orbit-raising trajectories make numerous passages through the shadow of the Earth. The paper presents a new algorithm to determine the minimum-time trajectory of the spacecraft during orbit-raising. Standard two-body problem and cylindrical shadow model are assumed. The proposed methodology breaks the minimum-time orbit-raising problem into a series of optimization sub-problems, with each sub-problem attempting to maximize the proximity to the Geostationary orbit at the end of the time horizon. We present results for planar and non-planar orbit-raising scenarios and demonstrate the benefits of the algorithm.

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AAS 15-434

A PRELIMINARY APPROACH TO MESH GENERATION FOR LOW-THRUST TRAJECTORY OPTIMIZATION OF EARTH-ORBIT TRANSFERS

Kathryn F. Graham[*] and Anil V. Rao[†]

A mesh generation method is described for solving low-thrust orbit transfer optimal control problems using collocation at Legendre-Gauss-Radau points. The method generates an appropriate mesh based on a given relative error estimate and the size, shape, and orientation of each orbital revolution of a transfer trajectory. The mesh is constructed by first dividing each orbital revolution into a specific number of segments based on the geometry of the revolution. Then, using the arc length of each segment, an appropriate number of collocation points is assigned to each segment. Three examples highlight various features of the mesh generation and show that the approach is more computationally efficient than a variable-order mesh refinement method.

[View Full Paper]

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AAS 15-438

LOW-THRUST TRAJECTORY OPTIMIZATION OF EARTH-ORBIT TRANSFERS WITH ECLIPSE CONSTRAINTS

Kathryn F. Graham* and Anil V. Rao†

An approach for solving low-thrust orbit transfer problems with eclipse constraints is described. The orbit transfer problem is posed as a multi-phase optimal control problem consisting of burn phases with linkage constraints between the phases. The linkage constraints are formulated based on the geometry of the shadow regions. The initial guess and the number of phases are determined by solving a series of single-phase optimal control problems. The multi-phase optimal control problem is solved using a variable-order Legendre-Gauss-Radau orthogonal collocation method. To demonstrate the approach developed in this research, optimal transfer trajectories are computed for a variety of launch dates.

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ORBITAL DEBRIS

SESSION 12

Chair: Thomas Starchville
The Aerospace Corporation

AAS 15-204

METHODOLOGY FOR CHARACTERIZING HIGH-RISK ORBITAL DEBRIS IN THE GEOSYNCHRONOUS ORBIT REGIME

Paul V. Anderson* **and Hanspeter Schaub†**

Forecasting of localized debris congestion in the geostationary (GEO) ring is performed to formulate and investigate methodology for identifying the debris objects that pose the highest risk to operational satellites in this ring. Proximity and speed relative to GEO during near-miss events detected under a torus intersection metric are translated into a combined risk factor that is accumulated during propagation. This accumulated risk is then used to identify the objects that have the highest risk contributions, either globally or in the vicinity of one of the two gravitational wells at 75°E and 105°W. Results show that nearly 60% of the total risk surrounding the Western well is attributed to 10 derelicts alone, which has critical implications for active debris removal (ADR) target selection for attenuating risk levels in this ring.

[View Full Paper]

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AAS 15-205

CONJUNCTION CHALLENGES OF LOW-THRUST GEOSYNCHRONOUS DEBRIS REMOVAL MANEUVERS

Paul V. Anderson* and Hanspeter Schaub†

The conjunction challenges of low-thrust engines for continuous thrust re-orbiting of geosynchronous (GEO) objects to super-synchronous disposal orbits are evaluated, with applications to end-of-life mitigation and active debris removal (ADR) technologies. In particular, the low maneuverability of low-thrust systems renders collision avoidance a challenging task. This study assesses the number of conjunction events that a low-thrust system could encounter with the current GEO debris population during a typical re-orbit to 300 km above the GEO altitude. Sensitivity to thrust level and initial longitude and inclination are evaluated, and the effect of delaying the start time of the re-orbit maneuver is investigated. Results dictate that the mean number of conjunctions rises hyperbolically as the thrust level decreases, but timing the re-orbit start appropriately can reduce the average conjunction rate.

[View Full Paper]

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AAS 15-236

ANALYSIS OF THE EVOLUTION OF SPACE DEBRIS THROUGH A SYNTHETIC POPULATION

Daniel Casanova,* Anne Lemaitre† and Alexis Petit‡

Space debris are all man-made objects orbiting the Earth which no longer serve a useful function. Space debris have increased substantially in the last decades and can be counted in millions. This paper deals with the idea of the creation of a synthetic population of space debris, which preserves as accurate as possible the characteristics of the real one. All the individuals of the synthetic population will be propagated by powerful numerical integrators, becoming into an excellent tool for global predictions or simulations, useful for the future ADR actions, and for the location of parking orbits.

[View Full Paper]

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AAS 15-260

ON THE MODELING AND SIMULATION OF TETHER-NETS FOR SPACE DEBRIS CAPTURE

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

A proposed method for containing the growth of space debris, which jeopardizes operation of spacecraft, is the active debris removal of massive derelict spacecraft and launcher upper stages by means of tether-nets. The behavior of such systems in space is not well-known; therefore, numerical simulation is needed to gain understanding of deployment and capture dynamics. In this paper, a lumped parameter approach for modeling the net, and different continuous compliant models of contact dynamics are presented. The ability of the tool developed to simulate multiple dynamic conditions is demonstrated in this paper, and the results of a deployment dynamics simulation are discussed. A contact dynamics simulation of a net falling on the ground is presented, in which linear and non-linear continuous compliant models for the normal contact force are compared.

[View Full Paper]

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SHORT PERIOD VARIATIONS IN ANGULAR VELOCITY AND OBLIQUITY OF INACTIVE SATELLITES DUE TO THE YORP EFFECT

Antonella A. Albuja* and Daniel J. Scheeres†

he Yarkovsky-O'Keefe-Radzievskii-Paddack (YORP) effect is a proposed explanation for observed variations in the rotational period of inactive satellites. This paper analyzes the short period variations of the angular velocity and obliquity of a defunct satellite as a result of the YORP effect. These variations are used to find limits for the expected behavior of the rotational period of inactive satellites over short time frames. These bounds can be used to better compare simulation results to observed changes in rotational period.

[View Full Paper]

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2D CONTINUITY EQUATION METHOD FOR SPACE DEBRIS CLOUD COLLISION ANALYSIS

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

Small fragments are rarely included in the evolution of the debris population as their number is so large that the computational time would become prohibitive. However, they also can be dangerous to operational satellites, so it is important to study their contribution to the collision probability. This work proposes an analytical method to propagate fragment clouds, whose evolution under the effect of drag is studied on the space defined by the semi-major axis and the eccentricity. This approach provides an analytical expression of the cloud density that can be translated into a quick estimation of the collision probability.

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AAS 15-335

INTEGRATION OF COUPLED ORBIT AND ATTITUDE DYNAMICS AND IMPACT ON ORBITAL EVOLUTION OF SPACE DEBRIS

**Clémence Le Fèvre, Vincent Morand, Michel Delpech,*
Clément Gazzino and Yannick Henriquel†**

This paper deals with the integration of coupled orbit and attitude dynamics over the long term for uncontrolled space objects. In the objective of space debris mitigation, orbital propagation is required to evaluate the evolution of orbital elements over long time scales – up to more than 100 years. In many cases, the hypothesis of "cannonball model" is applied. Assuming a randomly averaged attitude, it enables to perform orbit propagation, uncoupled from the attitude motion. Yet, modelling the attitude dynamics and evaluating attitude dependent forces may be needed to obtain a more representative orbit evolution. The aim of this paper is two-fold: first, analyzing the coupled orbit and attitude propagation for a low area-to-mass ratio in Low Earth Orbits and compare the induced orbital evolution with uncoupled propagation; second, investigating the efficiency of integration techniques.

Based on 6-Degrees-of-Freedom (6-DoF, position and attitude) numerical simulations, this paper highlights the strong sensitivity of the attitude dynamics to initial conditions. The chaoticity of the coupled system is analyzed and some situations of temporary stable attitudes are shown. Then, the impact of the coupling is studied in terms of orbital evolution and lifetime. Finally, an Encke-type correction algorithm is applied for the coupled numerical integration, paving the way for improved computational efficiency.

[View Full Paper]

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DENSITY OF THE BUILT ORBITAL ENVIRONMENT FROM AN OBJECT CATALOG

Liam Healy,[*] Kevin Reich[*] and Christopher Binz[*]

A density function in orbital element space provides a prior for a Bayesian computation of probability density. The orbital catalog can provide this initial density function. A histogram with wide bins is poorly resolved, and gives little information; one with narrow bins has either zero or one object in each bin, and also gives little information. Kernel density estimation methods have been developed and applied in a variety of fields and are presented here applied to orbital density estimation to resolve this conundrum. Clustering techniques and knowledge of orbital purpose to determine orbital neighborhoods are used to help refine these estimates.

[View Full Paper]

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AAS 15-403

EFFECTS OF THERMAL RE-RADIATION USING ON ORBIT AND ATTITUDE OF HIGH AREA-TO-MASS RATIO OBJECTS USING DIFFERENT MODELS: YORP AND YARKOWSKI

Carolin Frueh*

Commonly used models for the thermal re-radiation of space objects are mathematically very simple but also insufficient. The radiation transport through the objects is either neglected or semi-empirically fitted with so-called lag parameters. The simplified models without lag parameters assume no thermal radiation if the two sides of the object have identical thermal radiation parameters and temperature drops to zero immediately when shadow is reached. This is not realistic and leads to a wrong determination of the effects of thermal radiation, so-called YORP and YARKOWSKI effects on the orbit and attitude of uncontrolled objects. This paper suggests an improved thermal model, which is still computationally inexpensive. The effects of using different models on the attitude and orbit dynamics of objects with high area-to-mass ratios (YORP and YARKOWSKI) is shown. The differences are significant even for only a couple of hours of propagation time.

[View Full Paper]

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SPACE SITUATIONAL AWARENESS II

SESSION 13

Chair: Carolin Frueh
Purdue University

The following paper was not available for publication:

AAS 15-404
(Paper Withdrawn)

AAS 15-360

VISUALIZING THE DISSIPATION OF HIGH-RISK REGIONS IN BREAKUP DEBRIS CLOUDS

Brian W. Hansen,[*] Jeffrey A. Cummings[*] and Felix R. Hoots[†]

When satellite breakups are caused by hypervelocity impacts or explosions, it is important to assess and communicate the long-term environmental impact of the resulting debris clouds. Existing methods for visualizing long-term evolution of the debris environment tend to over-represent the persistence of dangerous risk regions. We present a new method that more accurately assesses and communicates the dissipation of these high-risk regions, highlighting the evolution of peak density as a function of altitude, inertial location, and time. Included is a discussion of how this method was enabled by efficient memory management techniques and particle binning algorithms.

[View Full Paper]

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AAS 15-366

DEBRIS CATALOG MANAGEMENT AND SELECTION FOR CONJUNCTION ANALYSIS USING K-VECTOR

Daniele Mortari[*] and Roberto Furfaro[†]

This paper presents a methodology to perform a fast selection of the subset of the known space debris who may collide with a spacecraft in an assigned orbit. This is done for a limited time range, $T_{\max}$, within which the SGP4 (or linear J_2) propagation is sufficiently accurate. The selection is performed in two distinct phases using the k-vector range searching technique. The first phase discards the set of debris that do not intersect the volume between the spheres with perigee and apogee radii. In the second phase a simple analysis is performed about the two locations where conjunction may occur: at the node line between spacecraft and debris orbits. This second phase is split is two serial checks. The first evaluates the angular distance of the debris when the spacecraft passes through the node line while the second is related to the physical distance between spacecraft at node line and debris position. If all these safe checks fail then the debris ID and the node line transition time(s) are recorded for subsequent very accurate conjunction analysis. The accurate conjunction analysis is usually computationally very expensive. This motivates this study, aiming to reduce the number of cases (spacecraft + debris + time ranges) for which an accurate conjunction analysis is needed.

[View Full Paper]

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DENSITY OF DEBRIS FRAGMENTS THROUGH DIFFERENTIAL ALGEBRA AND AVERAGED DYNAMICS

Camilla Colombo,[*] Alexander Wittig,[†]
Francesca Letizia[‡] and Roberto Armellin[§]

The modeling of space debris objects is a difficult task. In this work Differential Algebra (DA) techniques are coupled with semi-analytical averaged dynamics to describe the density evolution of debris fragments in the space of orbital elements. Given an initial probability density function, DA is used to propagate the probability density function to any given time by means of a high order polynomial expansion. The effect of orbit perturbations is described through averaged dynamics. We use the proposed DA+average dynamics approach to represent the time evolution of a cloud of debris fragments in Medium Earth Orbit and their density in time. This allows to assess the consequent risk of intersection between the cloud of resulting orbit and a target orbit.

[View Full Paper]

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AAS 15-394

COLLISION PROBABILITY USING MULTIDIRECTIONAL GAUSSIAN MIXTURE MODELS

Vivek Vittaldev[*] and Ryan P. Russell[†]

The number of tracked space objects is trending upwards, raising the need for accurate and fast collision probability computations. Gaussian Mixture Models (GMMs) provide a compromise between accuracy and runtime by better approximating the true non-Gaussian distributions during conjunction. In this study, the use of Multidirectional GMMs (MGMMs) to improve the collision probability accuracy in cases that are highly non-Gaussian is proposed. A method for identifying important splitting directions using the second order divided difference is presented. The selection of the directions and number of splits along relevant direction provides a dial that spans from Monte Carlo to the classic Gaussian approximation. The MGMM method is formulated and successfully demonstrated using several test cases with non-Gaussian uncertainty distributions for both short and long duration encounters.

[View Full Paper]

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AAS 15-409

GEODETICA: A GENERAL SOFTWARE PLATFORM FOR PROCESSING CONTINUOUS SPACE-BASED IMAGERY

Brad Sease* **and Brien Flewelling†**

In this paper we describe a general tool for detection, tracking, and discrimination of objects in continuous sequences of unresolved space-based imagery. Through the use of Phase Congruency edge detection and a Kalman filter based, multi-hypothesis point tracking framework, this software provides an automated data processing suite for ground- and space-based observers. The architecture is capable of detecting and discriminating space objects from the stellar background with minimal knowledge of the optical system. Here we detail the some of the key algorithms which comprise the GEODETICA pipeline, present simulated verification scenarios, and discuss limitations.

[View Full Paper]

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AAS 15-410

MULTI-OBSERVER RESIDENT SPACE OBJECT DISCRIMINATION AND RANGING

Brad Sease,* Kevin Schmittle† and Brien Flewelling‡

In this paper we propose a method for using multi-view epipolar geometry to simultaneously discriminate and range resident space objects (RSOs) in the overlapping fields of view of a multi-observer system. This method can be used to identify RSOs from ground- or space-based optical systems. We use the relative location and attitude of the observers to compute the epipolar geometry. The intersections of epipolar lines in each image can then be used to probabilistically associate objects of interest in the set of images. The probability of false associations is quantifiable for multi-sensor configurations, and high certainties can be achieved.

[View Full Paper]

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AAS 15-412

POLAR AND SPHERICAL IMAGE TRANSFORMATIONS FOR STAR LOCALIZATION AND RSO DISCRIMINATION

Brad Sease[*] and Brien Flewelling[†]

Detection and discrimination of resident space objects during long exposures is often complicated by field rotation during the exposure time. This produces "streaked" images, in which an object's size and shape is often dependent on its location in the image. By resampling the original image about the axis of rotation, it is possible to remove the curvature from star streaks and produce an image wherein all star streaks have a uniform geometry. Additionally, streak lengths in the resampled image correspond directly to the magnitude of the field rotation during the exposure. Further, resident space objects (RSOs) in the original image become clearly differentiated from the stellar background.

[View Full Paper]

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SENSOR RESOURCE MANAGEMENT FOR SUB-ORBITAL MULTI-TARGET TRACKING AND DISCRIMINATION

Ajay Verma,* Maruthi Akella,† John Freeze‡ and Kalyan Vadakkeveedu§

In this paper we address a problem where limited sensor resources must be used in an efficient manner during short-duration events for situational assessment and mitigation of threats arising from a cluster of unknown sub-orbital space objects. Many of these target space objects may be too small to survive atmosphere entry. Additionally, many other objects may be on a path to hit remote locations, too far from population centers to pose any threat. The sensor resource management (SRM) goal is to allocate sensor resources to i) track various targets, ii) make a determination of threat targets vs non-threat targets, and iii) support a threat engagement by ground-based interceptors by providing required quality of track estimation within a time bound. The SRM approach presented in this paper includes prioritization of sensor tasks based on situation awareness analysis. Information-theory-based sensor allocation is implemented to maximize expected information gain under the measurement constraints, defined by finite sensor capabilities and sensor-target geometry.

[View Full Paper]

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ASTRODYNAMICS INNOVATION AND DATA SHARING

SESSION 14

Chair: Felix Hoots
The Aerospace Corporation

The following paper was not available for publication:

AAS 15-374
(Paper Withdrawn)

AAS 15-332

PROPAGATION OF UNCERTAINTY IN SUPPORT OF SSA MISSIONS

Jeffrey M. Aristoff,[*] Joshua T. Horwood[†] and Aubrey B. Poore[‡]

The achievement of covariance/uncertainty realism is needed for several SSA mission areas and encompasses the quantification of uncertainty in sensor level processing, dynamics and space environment modeling, inverse problems such as statistical orbit determination, and the propagation of uncertainty. After outlining some of the sources of uncertainty in astrodynamics, this presentation surveys some of the many methods being developed by the astrodynamics community for propagating uncertainty. To assist with a comparison of methods, we propose a set of metrics and an initial list of benchmark test cases. In particular, the performance of the UKF is demonstrated using the averaged uncertainty realism test, the Pearson goodness-of-fit test, and the Cramér-von Mises test.

[View Full Paper]

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AAS 15-349

SATELLITE BREAKUP PROCESSING

Robert F. Morris,[*] Felix R. Hoots,[†]
Larry Cuthbert[‡] and Thomas F. Starchville[§]

The breakup of a satellite presents an immediate challenge to the Space Surveillance Network (SSN). Each new piece will generate an uncorrelated track (UCT) when it passes through radar coverage. These UCTs must be grouped together to form self-consistent orbits. We apply a previously unpublished method first developed in the 1960's to recently released SSN tracking data to demonstrate the ability of an automated method to quickly process breakup UCTs. We also apply a recently published method to determine the breakup time and key characterization parameters of the breakup event.

[View Full Paper]

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AAS 15-420

TRACKING OF THE LANDSAT 2 ROCKET BODY PRIMARY BREAKUP

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

The tracking of multiple space objects is a problem of vital importance in providing the capability to realistically predict the forward behavior of space objects. Beyond the fact that there already exist a large number of space objects in orbit, new objects can be introduced into the environment through launches of new objects, separations of existing on-orbit objects, and fragmentation or delamination of existing on-orbit objects. This paper investigates the application of an approximate Bayesian multiple object tracking algorithm to data collected on the primary breakup event associated with the Landsat 2 rocket body. Results are presented for estimating the number of total objects stemming from the event as well as localization estimates on each of the objects.

[View Full Paper]

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ASTRODYNAMICS COLLABORATIVE ENVIRONMENT: A STEP TOWARD DATA SHARING AND COLLABORATION VIA THE AIR FORCE RESEARCH LABORATORY

Moriba K. Jah[*]

As a result of the National Research Council's "Continuing Kepler's Quest" study, the Air Force Space Command (AFSPC) reinvigorated what is now called the Astrodynamics Innovation Committee (AIC). One of the activities of the AIC is to create and maintain an environment where the global astrodynamics community can have access to various data sets, algorithms, and tools called the Astrodynamics Collaborative Environment (ACE). The Air Force Research Laboratory has been explicitly invoked to create and maintain ACE for AFSPC. A survey was sent to the larger astrodynamics community asking for input into the requirements for ACE. One of the major responses was a desire for actual data to be made available. To this end, an actual data set from a break-up event has been provided and its analyses are the subject of this session. On February 9, 1976, the Landsat 2 Rocket Body (international designator 1975-004B) broke up and eventually 207 separate debris pieces were cataloged. This paper will briefly provide a description of and motivation for the AIC, ACE, and a vision moving forward with what these will be.

[View Full Paper]

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AAS 15-465

TECHNICAL RESEARCH AREA IDENTIFICATION WORKING GROUP PROCESS

Michele Gaudreault,[*] Timothy K. Roberts[†] and Moriba Jah[‡]

This paper outlines the purpose of the Technical Research Area Identification (TRAI) Working Group (WG) and how it attempts to identify those areas of astrodynamics research that the Astrodynamics Innovation Committee (AIC) should champion and promote. The TRAI WG provides recommendations on technical areas of work that AIC members should participate in and verifies that research is linked to the Air Force Space Command (AFSPC) Science and Technology (S&T) process and the Core Function Support Plan (CFSP).

[View Full Paper]

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TRAJECTORY OPTIMIZATION

SESSION 15

Chair: Robert Melton
Pennsylvania State University

The following paper was not available for publication:

AAS 15-216
(Paper Withdrawn)

AAS 15-237

OPTIMIZATION OF MANY-REVOLUTION, ELECTRIC-PROPULSION TRAJECTORIES WITH ENGINE SHUTOFF CONSTRAINTS

Jason A. Reiter,[*] Austin K. Nicholas[†] and David B. Spencer[‡]

Many-revolution, solar-electric-propulsion trajectories are difficult to computationally optimize. One of the most significant, unsolved problems with optimizing low-orbit trajectories using feedback control is eclipse constraints. Employing a new forward-looking feedback control technique, however, allows for an optimization of the trajectory including the effects of eclipses or any other arbitrary engine shutoff periods. The control law applies weightings to the optimal thrusting angles based on the spacecraft's relative instantaneous efficiency over one revolution, which includes the effect of the engine shutoffs. This method also facilitates simple exploration of the propellant versus time trade space in the presence of engine shutoff constraints.

[View Full Paper]

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AAS 15-246

A STUDY ON THE TRAJECTORY OPTIMIZATION OF A KOREAN LUNAR ORBITER USING PATTERN SEARCH METHOD

Su-Jin Choi,[*] Sang-Cher Lee[†] and Hae-Dong Kim[‡]

The Republic of Korea has a plan to launch a lunar orbiter and a lander by 2020. There are several ways to enter lunar orbit such as direct transfer trajectory, phasing loop transfer trajectory, WSB and spiral transfer trajectory. This paper performed the trajectory optimization research of lunar orbiter using Pattern Search method to minimize required ΔV regarding direct transfer trajectory. This method generates neighborhood points near initial condition of control variable and then searches if there is a new point that can reduce objective function value. Although classical method requires gradient and acceleration of objective function, Pattern Search doesn't need them. I choose 6 poll methods and 9 search methods so that 54 combinations can be selected. Optimization results such as ΔV, time of flight and numbers of function call by combinations of poll and search methods are plotted. As a result of simulation, 'MADSNp1' poll method showed minimum ΔV up to few m/s among 6 poll methods.

[View Full Paper]

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AAS 15-298

HIGH-SPEED, HIGH-FIDELITY LOW-THRUST TRAJECTORY OPTIMIZATION THROUGH PARALLEL COMPUTING AND COLLOCATION METHODS

Jonathan F. C. Herman,[*] Jeffrey S. Parker,[†] Brandon A. Jones[‡] and George H. Born[§]

This study develops a parallel implementation of a collocation-based low-thrust trajectory optimization method. It compares serial performance to parallel performance on both the Central Processing Unit (CPU) and the Graphical Processing Unit (GPU) for Gauss-Lobatto collocation schemes. The parallelized elements of the problem formulation execute up to 11 times faster, depending on what force model is used and when evaluated by themselves. When accounting for the operations of the nonlinear programming (NLP) solver, this translates to up to 3.7 times faster performance for solving a complete trajectory optimization problem, also depending on the force model that is used. The presented results have greatest impact for problems which rely on force models that are computationally expensive, but in the future these results may be extended to lower-cost force models as well.

[View Full Paper]

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VERTICAL TAKEOFF VERTICAL LANDING SPACECRAFT TRAJECTORY OPTIMIZATION VIA DIRECT COLLOCATION AND NONLINEAR PROGRAMMING

Michael J. Policelli[*] and David B. Spencer[†]

Optimal rocket-powered translational Vertical Takeoff Vertical Landing (VTVL) trajectories are analyzed. Such a vehicle would take off vertically under rocket propulsion, translate a specified horizontal distance, and vertically return softly to the surface. The trajectory optimization model developed was found to be robust and able to handle a wide range of various spacecraft and mission parameters. Results were compared against the required propellant use and nominal time of flight determined via the ballistic-impulse burn-coast-burn analysis. For the finite model developed herein, the required propellant use and optimal flight times exceeded the ideal impulsive case by 5-30% depending on the specific spacecraft and mission parameters and constraints implemented.

[View Full Paper]

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OPTIMAL LOW-THRUST-BASED RENDEZVOUS MANEUVERS

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

The minimum-time, low-constant-thrust, same circular orbit rendezvous problem is studied using a relative motion description of the system dynamics. The resulting Optimal Control Problem in the thrust orientation angle is formulated using both the Direct and Indirect methods. An extensive set of test cases is numerically solved with the former, while perturbation techniques applied to the later allow to obtain several approximate solutions and provide a greater insight on the underlying physics. These results show that the structure of the solutions undergoes fundamental changes depending on the value of the non-dimensional thrust parameter.

[View Full Paper]

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AAS 15-370

LOW-THRUST TRAJECTORY OPTIMIZATION IN DROMO VARIABLES

Juan L. Gonzalo* and Claudio Bombardelli†

The Dromo orbital propagator was recently introduced by Peláez et al., and has been under active development. It has proven to be an excellent propagation tool, both in terms of accuracy and computational cost. In this article, we explore its applicability to the solution of optimal control problem in low-thrust missions. To this end, an optimal control formulation based in Dromo and a direct transcription method is used to solve several LEO-GEO and escape from Earth problems; the obtained results clearly show the suitability of this orbital propagator for such purposes.

[View Full Paper]

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AAS 15-372

A CREWED MARS EXPLORATION ARCHITECTURE USING FLY-BY AND RETURN TRAJECTORIES

Andrew S. W. Thomas,* Cesar A. Ocampo† and Damon F. Landau‡

Sustainable human Mars exploration strategies are presented that use Mars fly-by and return trajectories. Three mission models are considered that differ in the number of transit habitats and the type of fly-by and return trajectories used. Earth-Mars-Earth and Earth-Mars-Mars-Earth fly-by and return trajectories form the basis for these architectures. The strategies assume the existence and operation of the Space Launch System and the Orion spacecraft with no reliance or requirement for new technology development. The capability for hyperbolic rendezvous and complex orbital operations at Mars is needed. Advantages of the proposed strategies include, smaller transit habitats since they are only occupied for fractions of the overall mission time, lower propellant requirements since the interplanetary transit habitats need not be inserted into or taken out of Mars orbit, and some limited abort opportunities. The strategies can be used in a stair step approach that facilitates a logical sequence of fly-by, orbital, Mars moons or surface missions. Representative solutions and selected mission performance data are presented for missions in the 2020-2050 time frame bracketing 15 complete Earth-Mars synodic cycles.

[View Full Paper]

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AAS 15-393

MASSIVELY PARALLEL OPTIMIZATION OF TARGET SEQUENCES FOR MULTIPLE-RENDEZVOUS LOW-THRUST MISSIONS ON GPUS

Mauro Massari[*] and Alexander Wittig[†]

In this work a massively parallel method for identification of optimal sequences of targets in multiple-rendezvous low-thrust missions using GPU processors is presented. Given a list of possible targets, an exhaustive search of sequences compatible with mission requirements is performed. To estimate feasibility of each transfer, a heuristic model based on Lambert transfers is evaluated in parallel. The resulting sequences are ranked by user-specified criteria such as length or fuel consumption. The algorithm has been used to compute asteroid sequences for GTOC7. The efficiency of the GPU implementation is demonstrated by comparing it with a traditional CPU based branch and bound method.

[View Full Paper]

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SMALL BODY PROXIMITY OPERATIONS

SESSION 16

Chair: Laureano Cangahuala
Jet Propulsion Laboratory

AAS 15-296

PHILAE LANDING SITE SELECTION AND DESCENT TRAJECTORY DESIGN

Eric Jurado,[*] Alejandro Blazquez, Thierry Martin, Elisabet Canalias, Julien Laurent-Varin, Romain Garmier,[†] Thierry Ceolin, Jens Biele,[‡] Laurent Jorda,[§] Jean-Baptiste Vincent,[**] Vladimir Zakharov,[††] Jean-François Crifo[‡‡] and Alexander Rodionov[§§]

Philae, the Lander of the Rosetta mission, has finally landed on 67P/Churyumov-Gerasimenko surface on the 12th November 2014 at 15h34 UT. Even if the first touchdown point was very close from the targeted landing site (around 100m), the landing was not nominal. The harpoons did not fire causing the lander to bounce when hitting comet surface. After two hours, it finally came to rest in a poorly illuminated area, preventing it from using power from its solar arrays. Yet it was able to execute most of its main mission using its primary battery. During 64 hours it performed in-situ measurements of the comet environment with its payload consisting in 10 scientific instruments. Before that, after a successful wake-up on 20th January 2014 and a rendez-vous with the comet in August 2014, the Orbiter instruments (the OSIRIS cameras, VIRTIS, MIRO, ALICE and ROSINA) had characterized the target comet and its environment to allow landing site selection and the definition of the Separation, Descent and Landing (SDL) strategy for the Lander. This paper addresses the flight dynamics studies that were done between August and November 2014 in the scope of the landing site selection process and landing operations preparation. It also reports about the Philae landing itself.

[View Full Paper]

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AAS 15-330

ORBITAL PERTURBATION ANALYSIS NEAR BINARY ASTEROID SYSTEMS

Loic Chappaz,[*] Stephen B. Broschart,[†] Gregory Lantoine[†] and Kathleen Howell[‡]

Current estimates indicate that approximately sixteen percent of the known near-Earth asteroid population may be binaries. Within the context of exploring the dynamical behavior of a spacecraft orbiting or moving near such systems, a first step in the analysis is an assessment of the perturbing effect that dominates the dynamics of the spacecraft. The relative strength of several perturbations, including the perturbation that arises from the existence of a binary system, rather than a single body system, is compared by exploiting 'zonal maps'. Such a map is useful in determining the type of orbit that is practical in support of a given mission scenario.

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AAS 15-363

SPIN STATE ESTIMATION OF TUMBLING SMALL BODIES

Corwin Olson,[*] Ryan P. Russell[†] and Shyam Bhaskaran[‡]

It is expected that a non-trivial percentage of small bodies that future missions may visit are tumbling in non-principal axis rotation. An Extended Kalman Filter (EKF) Simultaneous Localization and Mapping (SLAM) method is used to estimate the small body spin state with optical landmark measurements, as well as the spacecraft position, velocity, attitude, and surface landmark locations. An example scenario based on the Rosetta mission is used, with a tumbling small body. The SLAM method proves effective, with order of magnitude decreases in the spacecraft and small body spin state errors after less than a quarter of the comet characterization phase. Initial small body angular velocity errors can be several times larger than the true rates, and the SLAM method will still converge (effectively having no apriori knowledge of the angular velocity). It is also observed that higher levels of tumbling in the small body increase the spin state angular velocity estimation errors and decrease the moments of inertia error, as expected.

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AAS 15-389

QUANTIFYING MAPPING ORBIT PERFORMANCE IN THE VICINITY OF PRIMITIVE BODIES

Thomas A. Pavlak,* Stephen B. Broschart* and Gregory Lantoine*

Predicting and quantifying the capability of mapping orbits in the vicinity of primitive bodies is challenging given the complex orbit geometries that exist and the irregular shape of the bodies themselves. This paper employs various quantitative metrics to characterize the performance and relative effectiveness of various types of mapping orbits including terminator, quasi-terminator, hovering, ping-pong, and conic-like trajectories. Metrics of interest include surface area coverage, lighting conditions, and the variety of viewing angles achieved. The metrics discussed in this investigation are intended to enable mission designers and project stakeholders to better understand the implications of candidate mapping orbits during preliminary mission formulation activities.

[View Full Paper]

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AAS 15-424

ACCURATE DEPLOYMENT OF LANDERS TO DYNAMICALLY CHALLENGING ASTEROIDS

Simon Tardivel* and Daniel J. Scheeres†

This paper investigates the ballistic deployment of landers to dynamically challenging asteroids, in the context of the current NASA Discovery mission proposal BASiX. Dynamically challenging asteroids are fast rotators, where the amended gravitational acceleration almost vanishes near the equator. In the studied architecture, a mothership flies-by the asteroid at high altitude and releases the lander on a ballistic trajectory towards its landing site. Given fixed constraints and GNC capabilities, the landing time and spread can be reduced manyfold with fine adjustments of the lander's orbit parameters such as the radius of periapse, the inclination, or the argument of periapse.

Keywords: Asteroid; Astrodynamics; Lander

[View Full Paper]

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AAS 15-427

DIVERGENCE CHARACTERISTIC OF THE EXTERIOR SPHERICAL HARMONIC GRAVITY POTENTIAL

Kiichiro J. DeLuca[*] and Daniel J. Scheeres[†]

In order to quantify the divergence characteristic of the classical exterior spherical harmonic expansion for the gravitational potential field modeling of non-spherical mass distributions, a simplified small body model consisting of just two point masses is introduced. Using the simplified model, tractable closed form solutions of the true, exterior spherical harmonic, and interior spherical harmonic gravity potentials are derived to investigate the divergence characteristic. Result from this investigation show that some regions within the Brillouin sphere show asymptotic series behavior. A method for approximating the error of the exterior spherical harmonic potential is presented and demonstrated. Key results from this investigation are applied to practical example scenarios such as a boulder on an asteroid and Mt. Everest on Earth and the accuracy of the exterior spherical harmonic expansion in estimating the surface gravitational acceleration is quantified.

[View Full Paper]

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AAS 15-430

ASTEROID LANDING GUIDANCE DESIGN IN THE FRAMEWORK OF COUPLED ORBIT-ATTITUDE SPACECRAFT DYNAMICS

Gaurav Misra,[*] Amit Sanyal[†] and Ehsan Samiei[‡]

This paper addresses the asteroid landing guidance and control problem for a rigid body spacecraft. The traditional approach for close proximity operations around small bodies considers the translational motion to be described a point mass while the attitude motion is considered to be decoupled from the translational motion. While, in this paper we consider a fully coupled spacecraft dynamics model for guidance and control design to ensure soft landing on a tumbling asteroid. A nonlinear continuous time feedback guidance scheme is implemented to guarantee that the spacecraft reaches the desired point on the asteroid surface in finite time. The almost global stability of this closed-loop system is shown via a Lyapunov-based technique.

[View Full Paper]

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AAS 15-445

HELIOTROPIC ORBITS AT ASTEROIDS: ZONAL GRAVITY PERTURBATIONS AND APPLICATION AT BENNU

Demyan Lantukh,[*] Ryan P. Russell[†] and Stephen B. Broschart[‡]

Analytical inclusion of high degree zonal gravity harmonics and solar radiation pressure enables heliotropic orbits to be found at irregular primitive bodies like Bennu, the target of the OSIRIS-REx mission. Heliotropic orbits provide long-lifetime, low-altitude orbits in the presence of these significant perturbations. Using a constrained, doubly-averaged disturbing potential in the Lagrange Planetary Equations yields inclined heliotropic orbits as well as a method for assessing the likelihood of a heliotropic orbit existing in an uncertain environment. The existence of heliotropic orbits is shown to be robust to uncertainty in the gravity parameters of a model of Bennu, and an example orbit shows how heliotropic orbits persist in the presence of other gravity perturbations as well.

[View Full Paper]

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AAS 15-466

ASTEROID FLYBY GRAVIMETRY VIA TARGET TRACKING

Justin A. Atchison[*] and Ryan H. Mitch[†]

We propose a technology for discerning the gravity fields and mass distribution of a solar system small body, without requiring dedicated orbiters or landers. Instead of a lander, a spacecraft releases a collection of small, simple probes during a flyby past an asteroid or comet. By tracking those probes from the host spacecraft, one can estimate the asteroid's gravity field and infer its underlying composition and structure. This approach offers a diverse measurement set, equivalent to planning and executing many independent and unique flyby encounters of a single spacecraft. This paper derives the underlying models and assesses the feasibility of this concept via simulation.

[View Full Paper]

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RELATIVE MOTION

SESSION 17

Chair: Martin Ozimek
Johns Hopkins University
Applied Physics Laboratory

REGULARIZED FORMULATIONS IN RELATIVE MOTION

Javier Roa* and Jesús Peláez†

Variational methods based on orbital elements depend strongly on the eccentricity of the reference orbit. The resulting Jacobian matrix typically becomes singular when the reference orbit is parabolic or hyperbolic. This singularity can be avoided if the problem is formulated using sets of variables that do not depend on the eccentricity of the reference orbit. The solution to the linear equations of relative motion is derived in this paper from the Sperling-Burdet regularization and the Kustaanheimo-Stiefel transformation. A unified description for circular, elliptic, parabolic, and hyperbolic reference orbits is provided by means of the Stumpff functions. The independent variable is the fictitious time introduced by the Sundman transformation. An asynchronous solution is derived and corrected a posteriori. The first order correction recovers the synchronism, while a second order correction introduces nonlinear effects and improves the accuracy of the algorithm.

[View Full Paper]

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AAS 15-272

ERROR PROPAGATION IN RELATIVE MOTION

Javier Roa,* José Ignacio Gómez-Mora† and Jesús Peláez‡

This paper explores the connection between the concept of synchronism and the accuracy of the solutions to relative motion. If the problem is formulated using an independent variable different from time it is possible to escape from the standard time-synchronism, obtaining an asynchronous solution. The synchronism may be recovered through a first order correction. This correction is based on the dynamics of the problem, and higher-order terms are easily retained. A second order correction introduces nonlinear effects in the solution through simple mechanisms, and improves its accuracy. The proposed correction is a generic concept not restricted to any particular formulation. To illustrate this assertion the second order correction is applied to the Clohessy-Wiltshire solution and to the Yamanaka-Ankersen state transition matrix. The fundamentals of synchronism are introduced by deriving the variational solution to relative motion using the equinoctial orbital elements. Numerical results show that the corrected solutions may reduce the error by several orders of magnitude, both in position and velocity. The corrected solution may be more accurate than the exact solution to the second and third-order equations of motion in long-term propagations.

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AAS 15-315

ANALYTIC SOLUTION FOR THE RELATIVE MOTION OF SATELLITES IN NEAR-CIRCULAR LOW-EARTH ORBITS

Vladimir Martinusi,[*] Lamberto Dell'Elce[†] and Gaëtan Kerschen[‡]

The paper presents the solution to the problem of the relative motion between two satellites orbiting Earth under the influence of the oblateness and atmospheric drag perturbations. Starting from the analytic solution to the problem of the absolute motion, the closed-form equations of motion are obtained. No simplifying assumptions are made on the relative dynamics.

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DECALIBRATION OF LINEARIZED SOLUTIONS FOR SATELLITE RELATIVE MOTION

Andrew J. Sinclair,* Brett Newman† and T. Alan Lovell‡

The motion of a deputy satellite relative to a chief satellite can be described with either a Cartesian state or orbital-element differences. The linearized equations of motion for both share an equivalence through the linearized coordinate transformations. Higher-fidelity, analytic, nonlinear approximations for the Cartesian state can be extracted by introducing the nonlinear coordinate transformations. This results in a calibrated solution, which involves linearized propagation of a calibrated initial condition, and a decalibrated solution, where the inverse calibration process is applied to the calibrated solution. Both solutions are shown to have higher accuracy than the linearized solution for the Cartesian state.

[View Full Paper]

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RELATIVE MOTION STATE TRANSITION MATRIX INCLUDING GRAVITATIONAL PERTURBATIONS

Hui Yan,* Srinivas R. Vadali† and Kyle T. Alfriend‡

The paper extends the fidelity of the Gim-Alfriend State Transition Matrix (GA STM) by incorporating the effects of the higher-order gravitational perturbations. The state transition matrix for the relative mean elements and the Jacobian of the mean to osculating transformation are developed from the Kaula theory. The geometric transformation matrix from the nonsingular elements to the relative state vector is extended to include the zonal harmonics using a recursive formulation. The accuracy of the extended GA STM is ascertained by comparison with numerically integrated solutions produced by the GMAT software. The error in the relative position, for a 20x20 field, after a 10 day period is approximately 5 meters for a formation size of 1 km in a low Earth orbit of eccentricity 0.01.

[View Full Paper]

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INITIAL RELATIVE-ORBIT DETERMINATION USING SECOND-ORDER DYNAMICS AND LINE-OF-SIGHT MEASUREMENTS

Shubham K. Garg[*] and Andrew J. Sinclair[†]

This paper addresses the problem of determining the initial state of relative orbit between a chief and a deputy satellite using line-of-sight unit vectors. The relative motion is captured using second-order nonlinear relative equations of motion, and the measurements are represented as a linear matrix equation. Compared to previous such methods, the proposed formulation solves directly for the unknown ranges, and requires fewer measurements. Additionally, discussion on the failure of a new method to remove the scalar ambiguity is presented.

[View Full Paper]

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RELATIVE SATELLITE MOTION SOLUTIONS USING CURVILINEAR COORDINATE FRAMES

Alex Perez,[*] T. Alan Lovell,[†] David K. Geller[‡] and Brett Newman[§]

A novel set of solutions for satellite relative motion is developed. Using nonlinear transformations from a cylindrical and spherical coordinate frame to a Cartesian coordinate frame, nonlinear satellite relative motion equations can be derived. These nonlinear representations better capture the curvature and relative dynamics of an orbit due to the nature of curvilinear coordinate frames. Approximate solutions are also derived using a 2nd order Taylor series expansion of the nonlinear equations. These 2nd order approximate solutions are compared analytically to the Quadratic Volterra solution. Example trajectories are generated and compared using the novel set of solutions and the Quadratic Volterra solution. These novel solutions can be used for many different satellite relative motion applications such as initial relative orbit determination algorithms and maneuver/targeting applications.

[View Full Paper]

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AAS 15-444

CONTROL OF SPACECRAFT RELATIVE MOTION USING ANGLES-ONLY NAVIGATION

Ashish Jagat[*] and Andrew J. Sinclair[†]

Continuous-thrust feedback control of spacecraft relative motion when full state knowledge is not available is explored. A typical approach to such problems is to separate control and estimation – estimate the state using noisy measurements and implement the control law using the estimate. For systems involving nonlinearities, control and estimation may not be separable. In such systems, control input in addition to affecting the system state also affects the quality of the state estimate. This paper addresses the dual effect of control when angles-only measurements are used to estimate relative state of a spacecraft by using an in-formation-weighted LQG approach.

[View Full Paper]

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AAS 15-446

HYBRID LINEAR-NONLINEAR INITIAL ORBIT DETERMINATION WITH SINGLE ITERATION REFINEMENT FOR RELATIVE MOTION

Brett Newman,[*] T. Alan Lovell,[†] Ethan Pratt[‡] and Eric Duncan[#]

Application of Volterra theory to the Keplerian circular relative motion initial orbit determination problem has been considered recently. A series of azimuth-elevation angular measurements are coupled through the observation geometry with an analytic second-order three-dimensional solution for relative motion. One recently explored solution strategy to the resulting nonlinear measurement equations reformulates the problem as an equivalent set of linear equations with constraints solved by matrix decomposition and computation of an unknown scale factor. Two strengths of this technique include 1) improved observability (compared to zero observability when using a linear dynamics solution) and 2) sound computational numerics (eigen computations). One deficiency of this technique is the requirement for additional measurements. In the three-dimensional case, only six measurements are needed to directly solve the nonlinear formulation, while twenty-five measurements are necessary in the reformulated equivalent linear problem. Similarly, in the two-dimensional case, requirements are four vs. fourteen. In this paper, a hybrid solution technique is considered where a linear motion solution and only six measurements are used to obtain an initial estimate of the relative (unscaled) state vector. This state vector is then inserted into the unknown scale factor computation process that uses a nonlinear motion solution. Although this hybrid technique tends to improve the state estimation result beyond the purely linear approach, accuracy is still lacking. A single Newton-Raphson iteration refinement step using the nonlinear measurement equations, inserted between the linear and nonlinear state computations, has been found to restore much of the missing accuracy. The purpose of this investigation is to examine a simple modification to the existing strategy to retain initial state estimation accuracy with fewer measurements.

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SPACECRAFT GUIDANCE AND CONTROL

SESSION 18

Chair: Maruthi Akella
University of Texas at Austin

The following papers were not available for publication:

AAS 15-222
(Paper Withdrawn)

AAS 15-458
(Paper Withdrawn)

AAS 15-269

OBSERVABILITY BASED ANGLES-ONLY RELATIVE NAVIGATION & CLOSED-LOOP GUIDANCE

Baichun Gong,[*] Jianjun Luo,[†] Jianping Yuan[‡] and Weihua Ma[§]

Aimed at the problem of space rendezvous using angles-only observations, relative navigation & closed-loop guidance is developed based on observability analysis. Firstly, the systemic filtering model is established, based on which the observability is investigated from a novel prospect and the observable condition is obtained. Then, integrated with multi-pulse sliding safe guidance strategy, the coupling relationship between angles-only relative navigation and guidance is analyzed, and the mathematical expressions are attained. After that, the integrated scheme of relative navigation & closed-loop guidance is designed by using the coupling expressions. Finally, Monte Carlo simulations are done to validate the approach and the performance of navigation and guidance under different accuracy levels of sensor and initial relative states is analyzed.

[View Full Paper]

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AAS 15-292

A NOVEL DIFFERENTIAL GEOMETRIC NONLINEAR CONTROL APPROACH FOR SPACECRAFT ATTITUDE CONTROL

Hao Sun,[*] Jianjun Luo,[†] Jianping Yuan[‡] and Zeyang Yin[§]

In this paper, a novel methodology is proposed to solve the spacecraft attitude tracking control problem. A new nonlinear control approach based on differential geometry theory and observer-based linear quadratic regulator (LQR) algorithm is presented for a class of complicated nonlinear systems. The spacecraft attitude tracking error equations are built using the modified Rodrigues parameters (MRPs), and the nonlinear model is linearized through the exact feed-back linearization of differential geometry theory. Therefore the LQR algorithm only for the linear system can be used to design the attitude tracking controller. Then the observer-based LQR controller designed for the linearized model is mapped back to the original system to obtain the spacecraft attitude tracking nonlinear LQR control law on basis of differential geometry theory. Finally the proposed approach is tested and validated by numerical simulation of a spacecraft attitude tracking mission.

[View Full Paper]

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AAS 15-307

STATION-KEEPING AND MOMENTUM-MANAGEMENT ON HALO ORBITS AROUND L2: LINEAR-QUADRATIC FEEDBACK AND MODEL PREDICTIVE CONTROL APPROACHES

Uroš Kalabić,[*] Avishai Weiss,[†] Ilya Kolmanovsky[‡] and Stefano Di Cairano[§]

The control of station-keeping and momentum-management is considered while tracking a halo orbit centered at the second Earth-Moon Lagrangian point. Multiple schemes based on linear-quadratic feedback control and model predictive control (MPC) are considered and it is shown that the method based on periodic MPC performs best for position tracking. The scheme is then extended to incorporate attitude control requirements and numerical simulations are presented demonstrating that the scheme is able to achieve simultaneous tracking of a halo orbit and dumping of momentum while enforcing tight constraints on pointing error.

[View Full Paper]

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AAS 15-317

SPACECRAFT SAFE TRAJECTORY INTEGRATED GUIDANCE AND CONTROL USING ARTIFICIAL POTENTIAL FIELD AND SLIDING MODE CONTROL BASED ON HAMILTON-JACOBI INEQUALITY

Dengwei Gao,[*] Jianjun Luo,[†] Weihua Ma,[†] Hao Sun[*] and Jianping Yuan[†]

A new algorithm is proposed on the basis of Hamilton-Jacobi Inequality (HJI) theory and the artificial potential field (APF) in the sliding mode control (SMC). Having taken into consideration the effect of bounded output errors on controller performance and unknown dynamic influence, this algorithm has been developed for the safe trajectory constraints between two spacecraft. The gradient of APF provides the three dimensional sliding manifold and the robust sliding mode control laws is designed based on HJI theory. Because of the disturbances, the control laws can restrain the spacecraft around the safe trajectory which is designed by APF.

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AAS 15-356

PERFORMANCE EVALUATION OF ARTIFICIAL NEURAL NETWORK-BASED SHAPING ALGORITHM FOR PLANETARY PINPOINT GUIDANCE

Jules Simo,* Roberto Furfaro† and Joel Mueting‡

Computational intelligence techniques have been used in a wide range of application areas. This paper proposes a new learning algorithm that dynamically shapes the landing trajectories, based on potential function methods, in order to provide computationally efficient on-board guidance and control. Extreme Learning Machine (ELM) devises a Single Layer Forward Network (SLFN) to learn the relationship between the current spacecraft position and the optimal velocity field. The SLFN design is tested and validated on a set of data comprising data points belonging to the training set on which the network has not been trained. Furthermore, the proposed efficient algorithm is tested in typical simulation scenarios which include a set of Monte Carlo simulation to evaluate the guidance performances.

[View Full Paper]

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AAS 15-358

NEW WAYPOINTS GENERATION METHOD FOR FUEL-EFFICIENT PLANETARY LANDING GUIDANCE

Yanning Guo,[*] Hutao Cui,[†] Guangfu Ma[‡] and Chuanjiang Li[§]

In order to satisfy real-time and low-fuel consumption requirements, a simple yet effective guidance strategy for planetary precise landing is proposed based on fuel optimal solutions. By analyzing the characteristics of open-loop fuel optimal solutions, a new waypoint generation method is introduced, in which all waypoints correspond to significant changes in the magnitude of thrust force. By segmenting the motion trajectory using obtained waypoints, a multi-phase linear guidance strategy is adopted to approach the fuel optimal solution. Several key problems, including the acquirement of global fuel optimal solutions, waypoints selection, waypoints interpolation, and derivation of linear guidance algorithm are presented in details. The feasibility and superiority of the proposed strategy have been evaluated through a variety of simulations for a typical Mars landing scenario.

[View Full Paper]

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AAS 15-447

ADAPTIVE REACTIONLESS CONTROL OF A SPACE SNAKE-ARM ROBOT FOR PRE/POSTCAPTURE OF AN UNCOOPERATIVE TARGET

Wenlong Li,[*] Yushan Zhao,[†] Peng Shi[‡] and Leizheng Shu[§]

This paper pays attention to the dynamics and control of the space snake-arm robot before, during and after the capture of an unknown uncooperative target. Changes in the dynamics parameters of the systems result the poor performance of controller for pre-capture robot. An adaptive reactionless controller is proposed by using the redundant degree of freedom of the robot without any knowledge of the inertia properties and motion of the target. Firstly, the impact dynamics is modeled assuming that the dynamics properties of the target are known to simulate the measured velocities of the base and joints after the capture. Then the adaptive reactionless control algorithm considering the avoidance of joint limits is designed. Simultaneously, the momentum-based parameter identification method is proposed for estimating the unknown properties of the last link after the robot grasps an unknown target with unknown linear momentum and angular momentum. Finally, to verify the validity and feasibility of the method, a numerical simulation example for planar base-manipulator-target model is shown. Results show that the post-capture momentum calculated through the impact model is nearly the same. Space snake-arm robot is able to perform reactionless motion while the inertia parameters converge to their real values.

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A SURVEY OF SPACEFLIGHT DYNAMICS AND CONTROL ARCHITECTURES BASED ON ELECTROMAGNETIC EFFECTS

Benjamin Reinhardt,[*] Ryan Caracciolo[†] and Mason Peck[‡]

This paper provides a broad survey of electromagnetic (EM) actuator technology. There are several different technologies that fall under the EM actuator umbrella, each with its own strengths, weaknesses, and applications. The four major technologies are Coulomb control, electromagnetic formation flight, superconductive flux pinning, and induction couplers. Each section of the paper outlines the state of the art of one of these technologies, presents its underlying principles and discusses its engineering advantages, disadvantages, and applications.

[View Full Paper]

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SATELLITE CONSTELLATIONS

SESSION 19

Chair: David Dunham
KinetX Inc.

The following papers were not available for publication:

AAS 15-308
(Paper Withdrawn)

AAS 15-338
(Paper Withdrawn)

AAS 15-208

ATTITUDE MANEUVER STRATEGY OF AGILE EARTH OBSERVING SATELLITE CONSTELLATION

Xinwei Wang,* Zhongxing Tang,† Leizheng Shu‡ and Chao Han§

Obtaining the attitude maneuver strategy of agile earth observing satellites (AEOS) constellation is a complicated combinatorial optimization problem. A decomposition optimization algorithm for the problem is proposed, which could be divided into two parts: satellites & targets matching method, and the directed acyclic graph theory. The former is to dispatch observing targets to satellites, and the latter is to obtain every single satellite attitude maneuver strategy. Furthermore, three typical observing modes are defined to describe the medium Earth orbit AEOS constellation operating conditions. Numerical results indicate the attitude maneuver strategy could be derived in every typical observing mode, through the decomposition optimization algorithm.

[View Full Paper]

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AAS 15-238

STATION-KEEPING FOR LATTICE-PRESERVING FLOWER CONSTELLATIONS

Daniel Casanova[*] and Eva Tresaco[†]

2D-Lattice Flower Constellations present interesting dynamical features that allow us to explore a wide range of potential applications. Their particular initial distribution (lattice) and their symmetries disappear when some perturbations are considered, such as the J_2 effect. The new lattice-preserving Flower Constellations maintain over long periods of time the initial distribution and its symmetries under the J_2 perturbation, which is known as relative station-keeping. This paper deals with the study of the required velocity change that must be applied to the satellites of the constellation to have an absolute station-keeping.

[View Full Paper]

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DESIGN OF CONSTELLATIONS FOR EARTH OBSERVATION WITH INTER-SATELLITE LINKS

Sanghyun Lee* and Daniele Mortari†

This paper addresses the problem of designing optimal satellite constellations for observing applications, with particular emphasis to the communications between different orbital planes (inter-communications). The communication between satellites of the same orbital plane (intra-communications) is assumed continuous. The 2-D Lattice Flower Constellations theory is here applied to design a 44 satellite constellation using circular orbits. Optimization is performed using Genetic Algorithms to estimate the constellation subject to inter-satellite links connectivity for continuous global communications. Analysis is performed to validate the capability to guarantee continuous communication between one (or two) ground station(s) and any satellite. Graph theory is used to measure connectivity in the constellation. The resulting constellation has been explored from observational performance perspective as well as inter-satellite links performance.

[View Full Paper]

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AAS 15-357

METHOD OF SATELLITE ORBIT AND CONSTELLATION DESIGN FOR EARTH DISCONTINUOUS COVERAGE WITH MINIMAL SATELLITE SWATH UNDER THE GIVEN CONSTRAINT ON THE MAXIMUM REVISIT TIME

Yury N. Razoumny*

The general method for minimization of the satellite swath width required under given constraint on the maximum revisit time (MRT), the main quality characteristic of the satellite constellation discontinuous coverage, is presented. The interrelation between MRT and multiplicity of the periodic coverage – the minimum number of the observation sessions realized for the points of observation region during the satellite tracks' repetition period – is revealed and described. In particular, it is shown that a change of MRT can occur only at points of coverage multiplicity changing. Basic elements of multifold Earth coverage theory are presented and used for obtaining analytical relations for the minimum swath width providing given multifold coverage. The satellite swath width calculation procedure for the multifold coverage of rotating Earth using the iterations on the sphere of stationary coverage is developed. The numerical results for discontinuous coverage with minimal satellite swath, including some known particular cases and implementations of the method, are presented.

[View Full Paper]

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ASTRODYNAMICS TECHNIQUES

SESSION 20

Chair: Roby Wilson
Jet Propulsion Laboratory

The following paper was not available for publication:

AAS 15-217
(Paper Withdrawn)

AAS 15-249

ROBUST HIGH-FIDELITY GRAVITY-ASSIST TRAJECTORY GENERATION USING FORWARD/BACKWARD MULTIPLE SHOOTING

Justin A. Atchison,* Martin T. Ozimek,* Christopher J. Scott* and Fazle E. Siddique*

A common need among trajectory designs is the conversion of a trajectory from low-fidelity models (e.g. patched conic or zero sphere-of-influence methods) to high-fidelity (i.e. higher order acceleration) models. One favorable solution is to approach the problem in terms of control variables, which iteratively satisfy a set of feasibility constraints at match points. The control variables are associated with key events in the trajectory topology, such as gravitational assists. The match points are associated with points in deep space between events. This procedure, involving forward/backward numerical integration and multiple shooting, enables robust convergence by maintaining the trajectory topology during the differential correction process. This paper assesses this benefit in comparison to single shooting approaches and presents a generalizable implementation using the commercial package Systems Tool Kit.

[View Full Paper]

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AAS 15-271

A MODIFIED UPE METHOD TO DESIGN TWO-IMPULSE EARTH-MOON TRANSFERS IN A FOUR-BODY MODEL

Hongli Zhang,[*] Francesco Topputo,[†] Ran Zhang,[‡] Chen Zhang[§] and Chao Han[**]

A hybrid unscented parameter estimation algorithm is proposed for the efficient design of two-impulse Earth-Moon transfers in the planar bicircular restricted four-body model. This scheme is an extension of unscented Kalman filter parameter estimation that accommodates Newton's method. The original transfer problem is firstly converted to a new state-space representation and unscented parameter estimation is utilized in the initial iterations to take advantage of its wide-range convergence ability. Once close the final solution, the algorithm switches to the Newton method, which boosts convergence and accuracy. Numerical experiments show that the proposed method presents a good balance between convergence domain and convergence rate.

[View Full Paper]

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AAS 15-274

NUMERICAL COMPUTATION OF A CONTINUOUS-THRUST STATE TRANSITION MATRIX INCORPORATING ACCURATE HARDWARE AND EPHEMERIS MODELS

Donald H. Ellison,[*] Bruce A. Conway[†] and Jacob A. Englander[‡]

A significant body of work exists showing that providing a nonlinear programming (NLP) solver with analytical expressions for the problem constraint gradients substantially increases the speed of program execution and can also improve the robustness of convergence, especially for local optimizers. Calculation of these derivatives is often accomplished through the computation of the spacecraft's state transition matrix (STM). If the two-body gravitational model is employed, as is often done in the context of preliminary design, closed-form expressions for these derivatives may be provided. If a high-fidelity dynamics model, that might include perturbing forces such as the gravitational effects from multiple third bodies and solar radiation pressure, is used then these STM's must be computed numerically. We present a method for the numerical computation of the state transition matrix including analytical expressions for a state propagation matrix that incorporate an accurate spacecraft solar electric power hardware model and a full ephemeris model. An adaptive-step embedded eighth order Dormand-Prince numerical integrator is discussed and a method for the computation of the time of flight derivatives in this framework is presented. The use of these numerically calculated derivatives offer a substantial improvement over finite differencing in the context of a global optimizer. Specifically, the inclusion of these STM's into the low-thrust mission design tool chain in use at NASA Goddard Spaceflight Center allows for an increased preliminary mission design cadence.

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AAS 15-309

NOVEL METHOD BASED ON DISPLACED ORBIT FOR SOLVING NON-PLANAR ORBIT MANEUVER PROBLEM

Wei Yao,[*] Jianjun Luo,[†] Jianping Yuan[‡] and Chong Sun[§]

The ability to change the orbital plane rapidly is a decisive factor in the constellation design and non-planar rapid rendezvous mission. To conquer this, this paper presents a new more flexible non-planar orbit maneuver method, which uses the displaced orbit as a transfer orbit and the displaced orbit is located on a suppositional sphere which has the same radius with the initial orbit. The displaced orbit is tangent with the initial and target orbits and they all have the same orbital velocity, which results in a reduced consumption. Focusing on the problem, the geometrical models of orbit maneuver by displaced orbit are established, and the characteristic of the displaced orbit for the arbitrary missions is analyzed. Then the general equations for motor thrust requirement, maneuver duration and total velocity impulse for arbitrary missions are derived and analyzed and the correlative consumptions are compared with the traditional method. Finally, the stability of this family of displaced orbit is investigated. Some numerical simulations verify the feasibility and effectiveness of the present method.

[View Full Paper]

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AAS 15-373

METHOD OF PARTICULAR SOLUTIONS AND KUSTAANHEIMO-STIEFEL REGULARIZED PICARD ITERATION FOR SOLVING TWO-POINT BOUNDARY VALUE PROBLEMS

Robyn M. Woollands,[*] Julie L. Read,[*] Brent Macomber,[*] Austin Probe,[*] Ahmad Bani Younes[†] and John L. Junkins[‡]

We simulate transfer trajectories to retrieve two spent rocket boosters in low Earth orbit. We implement the *method of particular solutions* which is a shooting-type method for solving non-linear two-point boundary value problems. For each simulated trajectory, the perturbed orbit equations of motion are integrated using the path approximation numerical integrator, Modified Chebyshev Picard Iteration. We fuse the regularized equations with some recent research on long-arc path approximation (based on Picard iteration) and show significantly improved efficiency for accurate convergence. Determining the globally optimal sequence of maneuvers for retrieving orbital debris can require simulating thousands of feasible transfer trajectories. The Δv cost for each transfer is computed and the results are displayed on an extremal field map. Extremal field maps are used for distinguishing globally optimal from infeasible and sub-optimal orbit maneuver regions. The computations for a two-piece orbit debris simulation were done in a serial mode. However to solve a more realistic problem with hundreds of pieces of debris, it would be highly beneficial to compute using a parallel architecture. Both the orbit propagation method and the method for solving the perturbed boundary value problems are parallelizable algorithms. More generally, the methodology is applicable to generating extremal field maps for impulse maneuvers.

[View Full Paper]

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AAS 15-406

MODIFIED ENCKE CORRECTOR STEP METHOD FOR SEMI-COUPLED ORBIT-ATTITUDE PROPAGATION

Carolin Frueh*

Corrector step methods have been explored initially to save computational time on orbit propagations. In the age of modern computing, this seems almost superfluous. On the other hand, the computational burden is still tremendous, in the coupled and perturbed orbit-attitude propagation, as it is the case, for example with high area-to-mass ratio space debris objects. This stiff orbital problem together with high fidelity modeling makes accurate long term propagations almost impossible. This paper investigates a modification of the classical Encke corrector step method based on information theoretic divergence for the efficient semi-coupled six degree of freedom propagation.

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AAS 15-417

AUTOMATED TUNING PARAMETER SELECTION FOR ORBIT PROPAGATION WITH MODIFIED CHEBYSHEV PICARD ITERATION

Brent Macomber,* Austin Probe,*
Robyn Woollands* and John L. Junkins†

Modified Chebyshev Picard Iteration is a numerical method for integrating Ordinary Differential Equations. MCPI in a serial computation setting has been shown to improve the speed of orbit propagation computations by orders of magnitude over current state-of-the-practice methods, but requires tuning to achieve such performance improvements. This paper presents an MCPI tuning approach for perturbed orbit propagation. An MCPI parameterization scheme is introduced that provides a baseline set of tuning parameters and interpolation to give sub-optimal parameter values for specified initial conditions is generated using an empirical brute-force method. A more optimal scheme is generated using a genetic algorithm, and promises the same final accuracy as the baseline set, but with improved computational efficiency.

[View Full Paper]

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RADIALLY ADAPTIVE EVALUATION OF THE SPHERICAL HARMONIC GRAVITY SERIES FOR NUMERICAL ORBITAL PROPAGATION

Austin Probe,* Brent Macomber,* Julie L. Read,* Robyn M. Woollands,* and John L. Junkins†

Evaluation of the Spherical Harmonic Series for gravity is one of the most computationally intensive requirements for high-accuracy orbital propagation. The Earth's gravity is non-uniform and these perturbative effects must be incorporated into orbital propagation models to ensure an accurate numerical approximation is computed. However, considering the radial nonlinearity of the force-field allows for the judicious selection of the harmonic series degree and order as a method of reducing computational cost, without sacrificing accuracy. This paper details a method of *radial adaptation* for the spherical harmonic series, supporting analysis demonstrating its accuracy, and some characteristic results.

[View Full Paper]

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CUBESAT AND NANOSAT MISSIONS

SESSION 21

Chair: Fu-Yuen Hsiao
Tamkang University

AAS 15-275

LIFETIME SIMULATION OF ATTITUDE CHANGING CUBESAT

Guanyang Luo,* Victoria L. Coverstone,† Alexander R. M. Ghosh‡ and David Trakhtenberg§

The time history of a satellite's attitude has direct impact on the orbital lifetime and the amount of scientific data that can be collected. This problem arises for the Lower Atmosphere Ionosphere Coupling Experiment (LAICE) mission. A simulation is developed accounting for various orbit perturbations. The concept of changing attitude to generate additional science data has been analyzed and shown to not benefit the LAICE mission.

[View Full Paper]

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DYNAMICS OF DEORBITING OF LOW EARTH ORBIT NANO-SATELLITES BY SOLAR SAIL

Yanyan Li,[*] Quan Hu[†] and Jingrui Zhang[‡]

This paper studies the dynamics of deorbiting a nano-satellite by solar sail. Multiple space environment perturbations including atmospheric drag, solar radiation pressure are considered in the dynamic modeling. Approximated analytical solutions and numerical simulations of the perturbation torques are obtained to demonstrate the deorbit ability of the solar sail for the nano-satellite system. The advantage of such approach in the wider context of solar sail development and implementation is discussed.

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AAS 15-300

THE DESIGN OF NPU-PHONESAT: A FOLDABLE PICOSATELLITE USING SMART PHONE TECHNOLOGY

Jianping Yuan,[*] Qiao Qiao,[†] Jing Yuan,[‡] Yong Shi,[§] Jianwen Hou,[**] Shuguang Li,[††] Shengbo Shi,[‡‡] Lixin Li,[§§] Ruonan Zhang,[***] Wu Gao,[†††] Yong Liu[‡‡‡] and Hao Sun[§§§]

This paper presents a novel PhoneSat design which is from a young pioneer satellite project at Northwestern Polytechnical University called “NPU-PhoneSat project”. The ultimate goal of this project is to validate the feasibility of rapid deploying a small-scale satellite network for environmental surveillance at a low Earth orbit (LEO) using a swarm of low cost PhoneSats. In contrast to NASA’s PhoneSat design, the NPU-PhoneSat does not use the CubeSat platform, and instead we specially develop a foldable platform with multi-functional modules for a better incorporation of COTS smart phone components. This paper shows the design of NPU-PhoneSat in detail, including the functions and features of five subsystems, as well as the development of prototypes.

[View Full Paper]

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AAS 15-353

LUNAR CUBE TRANSFER TRAJECTORY OPTIONS

David Folta,[*] Donald Dichmann,[†] Pamela Clark,[‡] Amanda Haapala[§] and Kathleen Howell[**]

Numerous Earth-Moon trajectory and lunar orbit options are available for Cubesat missions. Given the limited Cubesat injection infrastructure, transfer trajectories are contingent upon the modification of an initial condition of the injected or deployed orbit. Additionally, these transfers can be restricted by the selection or designs of Cubesat subsystems such as propulsion or communication. Nonetheless, many trajectory options can be considered which have a wide range of transfer durations, fuel requirements, and final destinations. Our investigation of potential trajectories highlights several options including deployment from low Earth orbit (LEO), geostationary transfer orbits (GTO), and higher energy direct lunar transfers and the use of longer duration Earth-Moon dynamical systems. For missions with an intended lunar orbit, much of the design process is spent optimizing a ballistic capture while other science locations such as Sun-Earth libration or heliocentric orbits may simply require a reduced Delta-V imparted at a convenient location along the trajectory.

[View Full Paper]

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AAS 15-382

AN INTERPLANETARY MICROSATELLITE MISSION CONCEPT TO TEST THE SOLAR INFLUENCE ON NUCLEAR DECAY RATES (SINDR)

Blake A. Rogers,[*] Sarag J. Saikia,[†] James M. Longuski[‡] and Ephraim Fischbach[§]

Experiments showing a variation of the nuclear decay rates of a number of different nuclei have suggested that the distance between the sample and the Sun influences the nuclear decay processes. In order to further test this apparent correlation, the feasibility and efficacy of an experiment onboard a microsatellite that would produce data through large variations in sample-Sun radial distance are studied. Two types of launches are considered where the microsatellite is a secondary payload: on an interplanetary spacecraft and on a geostationary spacecraft. As a secondary payload on the interplanetary spacecraft, the experiment takes less time to obtain useful data, but the opportunities are fewer, while the opposite is true as a secondary payload on satellite going to geostationary orbit. In either case, the scientific measurements required are at least an order of magnitude better than could be obtained from the same experiment performed on Earth. The samples can be retrieved from the spacecraft after entry, descent, and landing at Earth using a deployable decelerator for certain Earth-resonant trajectories with V_∞ less than 7.5 km/s.

[View Full Paper]

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HARDWARE SELECTION AND MODELING FOR SIGMA CUBESAT ATTITUDE CONTROL SYSTEM

Thomas Wright,* Patrick Irvin,† Arthur K. L. Lin,‡ Regina Lee§ and Ho Jin**

SIGMA (Scientific cubesat with Instruments for Global Magnetic field and rAdiation) is a Scientific CubeSat with instruments for global magnetic field and radiation develop by multiple universities. This paper focus on the hardware selection of the SIGMA Attitude Determination and Control Systems (ADCS) developed by the YuSEND group. In this paper, we illustrated the micro-controller, sensors and actuators chosen for the attitude determination and control for SIGMA. In addition, an attitude determination algorithm is shown to provide an accurate attitude of the CubeSat. Rate sensors, and magnetometers are used to determine the attitude of this satellite. A torque rod and 2 torque coils will be used to provide actuation for SIGMA attitude control. Due to the compacted size of the satellite, the three magnetorquer onboard will interfere the magnetometer reading carried on the Attitude Control System (ACS) board. Therefore, the magnetorquers is controlled with a specific algorithm to minimize this effect. Moreover, a degaussing method is applied to the magnetorquers to control the possible magnetic field that affecting the sensors. The result of the Hardware In the Loop Testing (HILT) demonstrate the effectiveness of the proposed algorithm.

[View Full Paper]

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SPACECRAFT DYNAMICS AND AUTONOMY

SESSION 22

Chair: Kyle DeMars
Missouri University
of Science and Technology

The following paper was not available for publication:

AAS 15-321
(Paper Withdrawn)

AAS 15-220

ENERGY CONSERVED PLANAR SPACECRAFT MOTION WITH CONSTANT THRUST ACCELERATION

Sonia Hernandez* and Maruthi R. Akella†

Spacecraft motion with constant thrust acceleration in the direction perpendicular to the velocity is studied. A spacecraft in an initial circular orbit obtains a minimum (perigee) radius along an inbound trajectory or a maximum (apogee) radius along an outbound trajectory, after which the vehicle returns to the initial circular orbit. The energy of the system is the only integral of motion. A full analytical solution does not exist; however, a solution to the flight direction angle, that is, the angle between the position and velocity vectors, is found in terms of the position magnitude. This solution leads to the range of acceleration magnitudes for prograde motion, proving periodicity of the position magnitude, and finding periodic orbits.

[View Full Paper]

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AAS 15-248

POSE ESTIMATION ASSESSMENT USING GEOSYNCHRONOUS SATELLITE IDENTIFICATION

Stoian Borissov,* Daniele Mortari† and Thomas Pollock‡

Autonomous optical navigation is desired as a backup during cislunar missions in the case of loss of communications with Earth. Due to difficulties of position estimation from imaging the Moon or Earth, such as centroid estimation while compensating for surface topography and atmospheric effects, we propose an alternate approach of imaging and identifying geostationary satellites (geosats) using star trackers. In this paper, we first investigate methods of observer position estimation assuming that geosats have been observed and identified. Secondly, we discuss geosat identification methods (GEO-ID) which discriminate between stars and geosats and provide the correspondence for identifying observed geosats. Thirdly, we develop a reflective model for geosats and an observer camera model in order to estimate the limits of observability. Initial sensitivity analysis is also provided giving the variance in position estimation accuracy as functions of measurement noise, observer position, and the number of observed geosats.

[View Full Paper]

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AAS 15-259

POSITION ESTIMATION USING IMAGE DERIVATIVE

Daniele Mortari,[*] Francesco de Dilectis[†] and Renato Zanetti[‡]

This paper describes an image processing algorithm to process Moon and/or Earth images. The theory presented is based on the fact that Moon hard edge points are characterized by the highest values of the image derivative. Outliers are eliminated by two sequential filters. Moon center and radius are then estimated by nonlinear least-squares using circular sigmoid functions. The proposed image processing has been applied and validated using real and synthetic Moon images.

[View Full Paper]

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AAS 15-301

AUTONOMOUS OPERATION OF MULTIPLE FREE-FLYING ROBOTS ON THE INTERNATIONAL SPACE STATION

B. J. Morrell,* G. E. Chamitoff,† P. W. Gibbens‡ and A. Saenz-Otero§

An approach is proposed to address the challenge of real time trajectory optimization for space-based robots in restrictive and obstacle rich environments. The algorithm uses a unique transformation that enables a quick solution to complex, non-linear trajectory optimization problems with capabilities to solve non-convex problems. The algorithm was implemented on the SPHERES (Synchronized Position Hold, Engage, Reorient Experimental Satellites) test facility on the International Space Station. Tests demonstrated the basic capability of the algorithm, and identified areas for improvement. An updated algorithm is tested in numerical simulations that demonstrate the ability to quickly solve problems with geometric constraints, performance constraints, dynamic obstacles and multiple robots.

[View Full Paper]

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AAS 15-347

RIGID BODY ATTITUDE UNCERTAINTY PROPAGATION USING THE GAUSS-BINGHAM DISTRIBUTION

Jacob E. Darling* and Kyle J. DeMars†

A new probability density function, called the Gauss-Bingham distribution, is proposed. The Gauss-Bingham distribution quantifies the correlation between a quaternion attitude representation and angular velocity in a more statistically rigorous manner than conventional methods because it is defined on the cylindrical manifold on which the quaternion and angular velocity naturally exist. The Gauss-Bingham distribution is derived, and a transformation to its canonical form is presented. A sigma point approach coupled with maximum likelihood parameter estimation is used to efficiently propagate the attitude quaternion and angular velocity uncertainty forward in time. A simulation is presented to show the uncertainty propagation of the attitude quaternion and angular velocity of a rigid-body using the Gauss-Bingham distribution.

[View Full Paper]

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ANGLES-ONLY INITIAL RELATIVE-ORBIT DETERMINATION VIA MANEUVER

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

For satellite relative motion modeled with linear, Cartesian dynamics, angles-only measurements are not sufficient for initial relative orbit determination, unless one of the satellites is maneuvering. A known, impulsive maneuver by either chief or deputy satellite, along with six total angle measurements, is sufficient to solve for the initial position and velocity of the deputy satellite. This paper presents an initial relative-orbit determination solution using this type of observability maneuver. The accuracy of the solution is evaluated against the maneuver design, measurement errors, and dynamic modeling errors.

[View Full Paper]

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AAS 15-383

TOUCHLESS ELECTROSTATIC DETUMBLING WHILE TUGGING LARGE AXI-SYMMETRIC GEO DEBRIS

Trevor Bennett* and Hanspeter Schaub†

Touchless detumbling of the three-dimensional spin of axi-symmetric space debris is investigated to enable orbital servicing or active debris removal in the Geosynchronous belt. Using active charge transfer between a servicing spacecraft and debris object, control torques are created to reduce the debris spin rate prior to making any physical contact. First considered is the addition of nominal tugging and pushing of deep space 3-dimensional detumble. The proposed control provides momentum reduction and clear equilibrium surfaces. This work also extends the projection angle theory for three-dimensional tumbling motion to on-orbit relative motion. Prior work has identified the limitations of electrostatic detumble for three degree rotational freedom without relative positioning maneuvers. Using the Multi-Sphere Modeling method for electrostatic torques, servicer formation flying demonstrates improved detumble capability. The numerically simulated orbiting along-track formation provides a natural relative inertial motion that helps remove all debris angular velocity except for the spin about the symmetry axis.

[View Full Paper]

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OPERATIONAL CHALLENGES IN TDRS POST-MANEUVER ORBIT DETERMINATION

Jason Laing,[*] Jessica Myers,[†] Douglas Ward[‡] and Rivers Lamb[§]

The GSFC Flight Dynamics Facility (FDF) is responsible for daily and post-maneuver orbit determination for the Tracking and Data Relay Satellite System (TDRSS). The most stringent requirement for this orbit determination is 75 meters total position accuracy (3-sigma) predicted over one day for Terra's onboard navigation system[1]. To maintain an accurate solution onboard Terra, a solution is generated and provided by the FDF four hours after a TDRS maneuver. A number of factors present challenges to this support, such as maneuver prediction uncertainty and potentially unreliable tracking from User satellites. Reliable support is provided by comparing an Extended Kalman Filter (estimated using ODTK) against a Batch Least Squares system (estimated using GTDS).

[View Full Paper]

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ORBIT DETERMINATION II

SESSION 23

Chair: Renato Zanetti
NASA Johnson Space Center

The following paper was not available for publication:

AAS 15-318
(Paper Withdrawn)

USING ONBOARD TELEMETRY FOR MAVEN ORBIT DETERMINATION

Drew Jones,[*] Try Lam,[†] Nikolas Trawny[‡] and Clifford Lee[§]

Determining the state of Mars orbiting spacecraft has traditionally been achieved using radiometric tracking data, often with data before and after an atmospheric drag pass. This paper describes our approach and results for supplementing radiometric observables with on-board telemetry measurements to improve the reconstructed trajectory estimate for the Mars Atmosphere and Volatile Evolution Mission (MAVEN). Uncertainties in Mars atmospheric models, combined with non-continuous tracking degrade navigation accuracy, making MAVEN a key candidate for using on-board telemetry data to help complement its orbit determination process. The successful demonstration of using telemetry data to improve the accuracy of ground based orbit determination could reduce cost (DSN tracking time) and enhance the performance of future NASA missions. In addition, it presents an important stepping stone to autonomous on-board aerobraking and aerocapture.

[View Full Paper]

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AAS 15-228

CAUCHY DRAG ESTIMATION FOR LOW EARTH ORBITERS

J. Russell Carpenter[*] and Alinda K. Mashiku[*]

Recent work on minimum variance estimators based on Cauchy distributions appears relevant to orbital drag estimation. Samples from Cauchy distributions, which are part of a class of heavy-tailed distributions, are characterized by long stretches of fairly small variation, punctuated by large variations that are many times larger than could be expected from a Gaussian. Such behavior can occur when solar storms perturb the atmosphere. In this context, the present work describes an embedding of the scalar Idan-Speyer Cauchy Estimator to estimate density corrections, within an Extended Kalman Filter that estimates the state of a low Earth orbiter. In contrast to the baseline Kalman approach, the larger formal errors of the present approach fully and conservatively bound the predictive error distribution, even in the face of unanticipated density disturbances of hundreds of percent.

[View Full Paper]

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AAS 15-276

PRECISION ORBIT DERIVED ATMOSPHERIC DENSITY: AN UPDATE

Craig A. McLaughlin,[*] Travis F. Lechtenberg,[†] Samuel Shelton[‡] and Alex Sizemore[‡]

Recent developments in precision orbit ephemerides (POE) derived neutral atmospheric density are examined. POE derived densities for CHAMP and GRACE are compared to HASDM, NRLMSISE-00, and Jacchia 71 densities. In addition, Satellite Laser Ranging (SLR) data for the Atmospheric Neutral Density Experiment (ANDE) satellites are used to derive densities. SLR data from the recently launched Special Purpose Inexpensive Satellite (SPINSat) were also used to derive densities. Finally, precision orbit derived densities from the University of Kansas are compared to those from the Jet Propulsion Laboratory.

[View Full Paper]

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CENTROID DYNAMICS FOR GROUP OBJECT TRACKING

Christopher R. Binz* and Liam M. Healy*

Immediately following a scenario like a CubeSat deployment, the presence of multiple objects in close proximity makes the observation assignment problem—and thus individual object tracking—difficult. One proposed method for mitigating this is to combine the observations in measurement space, and use this to update the "centroid state" of the collection of objects. A consequence of this process is that there is no physical reason that the centroid should itself behave as an orbiting object. This paper presents the first steps towards this type of tracking, describing the motion of the centroid as projected in measurement space.

[View Full Paper]

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AAS 15-376

MULTI-OBJECT FILTERING FOR SPACE SITUATIONAL AWARENESS

E. D. Delande,[*] C. Frueh,[†] J. Houssineau[‡] and D. E. Clark[§]

The sources of information for Earth orbiting space objects are passive or active observations by ground based or space based sensors. The majority of tracking and detection of new objects for contemporary applications is performed by ground based sensors, which are mainly optical or radar based. Challenges lie in the long times spans between very short observation arcs, large number of objects, brightness variations during observations, occlusions, crossing targets and clutter. Traditionally, tracking problems for space situational awareness have been approached through heuristics-based techniques such as Multiple Hypothesis Tracking (MHT). More recently, solutions derived from Finite Set Statistics (FISST) have been used, such as the Probability Hypothesis Density (PHD) filter, that describe the targets at the population rather than individual level. The recent mathematical framework for the estimation of stochastic populations combines the advantages of previous approaches by propagating specific information on targets (i.e. tracks) whenever appropriate, and by avoiding heuristics through its fully probabilistic nature. This paper presents the first application to space situational awareness problems of the novel filter for Distinguishable and Independent Stochastic Populations (DISP), a tracking algorithm derived from this framework, through a multi-object surveillance scenario involving a ground based Doppler radar and five crossing objects in all orbital regions. The preliminary results show that, despite the sensor's limited observability and constrained field of view, the DISP filter is able to detect the orbiting objects entering the field of view and maintain individual information on them, with associated uncertainty, even once they have left the field of view.

[View Full Paper]

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ONE-WAY RADIOMETRIC NAVIGATION WITH THE DEEP SPACE ATOMIC CLOCK

Todd A. Ely[*] and Jill Seubert[†]

The Deep Space Atomic Clock (DSAC) mission is developing a small mercury ion atomic clock with Allan deviation of less than 1e-14 at one day (current estimates ~3e-15) for a yearlong space demonstration in 2016. DSAC's stability yields one-way radiometric tracking data with better accuracy than current two-way tracking data and enables transitioning to more efficient and flexible one-way deep space navigation. This study discusses the potential for one-way radiometric navigation using DSAC, including those navigation uses that are immediately enabled, and those that require additional infrastructure and flight system development for full realization.

[View Full Paper]

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AAS 15-451

NONLINEAR OBSERVABILITY MEASURE FOR RELATIVE ORBIT DETERMINATION WITH ANGLES-ONLY MEASUREMENTS

Evan Kaufman,[*] T. Alan Lovell[†] and Taeyoung Lee[‡§]

A new nonlinear observability measure is proposed for relative orbit determination when lines-of-sight between satellites are measured only. It corresponds to a generalization of the observability Gramian in linear dynamic systems to the nonlinear relative orbit dynamics represented by the two-body problems. An extended Kalman filter (EKF) is adapted to this problem and is evaluated with various gravitational harmonics and initial orbital determination (IOD) predictions. Extensive results illustrate correspondence between the proposed observability measure with filtering errors. An extensive numerical analysis in realistic scenarios includes satellite propagation of the two-body problem the J_2 perturbation effects.

[View Full Paper]

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FLIGHT MECHANICS ASPECTS OF THE LADEE MISSION

SESSION 24

Chair:	Lisa Policastri SkySentry Stratospace Technologies

LADEE FLIGHT DYNAMICS: OVERVIEW OF MISSION DESIGN AND OPERATIONS

Arlen Kam,[*] Laura Plice,[†] Ken Galal,[‡] Alisa Hawkins,[§] Lisa Policastri,[**] Michel Loucks,[††] John Carrico Jr.,[‡‡] Craig Nickel,[§§] Ryan Lebois[***] and Ryan Sherman[†††]

The Lunar Atmosphere and Dust Environment Explorer (LADEE) mission set out on September 7, 2013 to observe the lunar exosphere at low altitudes. This mission overview from a flight dynamics perspective addresses solid rocket dispersions in the first use of the Minotaur V, science orbit maintenance for over 5 months, high precision past and predicted orbit estimation, the automated approach to calculating over 40,000 attitude waypoints, and strong teamwork at an intense operational pace. The unique flight dynamics solutions for the near-circular, near-equatorial orbit in non-uniform lunar gravity resulted in a successful mission from both engineering and scientific standpoints.

[View Full Paper]

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AAS 15-230

PRE-LAUNCH ORBIT DETERMINATION DESIGN AND ANALYSIS FOR THE LADEE MISSION

Lisa Policastri,[*] John P. Carrico Jr.[†] and Craig Nickel[‡]

The Lunar Atmospheric Dust Environment Explorer (LADEE) successfully launched on September 7, 2013. The LADEE mission requirements relevant to orbit determination are listed. The orbit determination plan for each mission phase is described. Ground station assumptions, tracking schedule assumptions, timelines, goals, methods, and analysis results including gravity modeling approaches are discussed. The authors also present how testing with other operational spacecraft was used to verify the tracking plans and configurations prior to launch. Details are given on the analysis for the launch and early orbit phase as well as the nominal operations.

[View Full Paper]

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ORBIT DETERMINATION AND ACQUISITION FOR LADEE AND LLCD MISSION OPERATIONS

Lisa Policastri,[*] John P. Carrico Jr.,[†] Craig Nickel,[‡] Arlen Kam,[§] Ryan Lebois[**] and Ryan Sherman[††]

This paper describes the orbit determination results for the Lunar Atmospheric Dust Environment Explorer (LADEE) from launch through the science operations. This paper also describes how the orbit determination and acquisition team supported the Lunar Laser Communications Demonstration (LLCD). Precise orbit determination was essential to all components in successful maneuver execution, properly correlated science collections, spacecraft situational awareness, and throughout the LLCD acquisition operations. We discuss the concurrent use of overlap analysis with the filter-smoother consistency test as quality-control methods.

[View Full Paper]

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ATTITUDE DESIGN FOR THE LADEE MISSION

Ken Galal,* Craig Nickel† and Ryan Sherman†

This paper summarizes attitude design and operations support provided to satisfy the numerous pointing requirements and constraints of the successfully completed LADEE mission. STK scripts used to automate the modeling of more than a dozen LADEE pointing profiles and a graphical tool used to design custom maneuver attitudes that satisfied communication and star tracker occlusions constraints are described. Also, provided is an overview of how a set of rules and conventions and long-term constraint violation predictions were used to establish keep-out time-frames for particular attitude profiles in order to manage the complexity of this design challenge.

[View Full Paper]

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AAS 15-381

GENERATION OF SIMULATED TRACKING DATA FOR LADEE OPERATIONAL READINESS TESTING

James Woodburn,[*] Lisa Policastri[†] and Brandon Owens[‡]

Operational Readiness Tests were an important part of the pre-launch preparation for the LADEE mission. The generation of simulated tracking data to stress the Flight Dynamics System and the Flight Dynamics Team was important for satisfying the testing goal of demonstrating that the software and the team were ready to fly the operational mission. The simulated tracking was generated in a manner to incorporate the effects of errors in the baseline dynamical model, errors in maneuver execution and phenomenology associated with various tracking system based components. The ability of the mission team to overcome these challenges in a realistic flight dynamics scenario indicated that the team and Flight Dynamics System were ready to fly the LADEE mission.

[View Full Paper]

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AAS 15-396

TRADE STUDIES IN LADEE TRAJECTORY DESIGN

Michel Loucks,* Laura Plice,†
Daniel Cheke,‡ Cary Maunder‡ and Brian Reich‡

The Lunar Atmosphere and Dust Environment Explorer (LADEE) mission design challenge was a "design to capabilities" approach in a tightly constrained trade space. Several trade studies defined feasible trajectory designs and launch opportunities. One trade study selected the insertion orbit and identified usable combinations of transfer orbit plane and arrival nodes per launch block. The next trade study assessed each monthly launch period by day with three-sigma launch energy dispersions against several parameters including delta-v budget, lunar orbit beta angle, and maximum shadow duration. In the final trade study, detailed technical and operational considerations dictated the daily launch windows.

[View Full Paper]

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AAS 15-400

THE LADEE TRAJECTORY AS FLOWN

Michel Loucks,[*] Laura Plice,[†]
Daniel Cheke,[‡] Cary Maunder[‡] and Brian Reich[‡]

The LADEE spacecraft launched on a Minotaur-V launch vehicle from Wallops Flight Facility on 7 September 2013 at 3:27 UTC as planned into a 6.4 day orbit. After three cis-lunar phasing maneuvers, LADEE achieved lunar orbit on 6 October 2013, and entered a 232 x 247 km commissioning orbit on 13 October 2013. LADEE performed many successful maneuvers to execute the baseline science mission plus an extended mission through April of 2014. Final maneuvers executed in early April led to a planned lunar impact on 18 April 2014.

[View Full Paper]

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AAS 15-419

LADEE FLIGHT DYNAMICS SYSTEM OVERVIEW

Craig Nickel,[*] John P. Carrico Jr.,[†] Ryan Lebois,[‡] Lisa Policastri[§] and Ryan Sherman[**]

This paper describes the design and implementation of the Flight Dynamics System (FDS) for the Lunar Atmospheric Dust Environment Explorer (LADEE). This paper also describes how the FDS was utilized by the mission operations team throughout all phases of LADEE mission operations. Automation of many flight dynamics operations processes was essential to reliably generate and deliver all necessary products to keep up with LADEE's mission operations pace. The FDS was utilized for all flight dynamics functions, including Orbit Determination, Maneuver Reconstruction, Trajectory Design, Maneuver Planning, Attitude Planning, and Products & Acquisition Data Generation.

[View Full Paper]

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AAS 15-453

LADEE MANEUVER PLANNING AND PERFORMANCE

Alisa Hawkins,* Arlen Kam† and John Carrico‡

The Lunar Atmosphere and Dust Environment Explorer (LADEE) was launched on September 7, 2013 UTC to investigate the tenuous lunar atmosphere and dust environment. Thirty-one maneuvers were planned, executed, and recovered during the 7-month mission in order to transfer the LADEE spacecraft from the Earth to the Moon and maintain the lunar science orbit. Each maneuver required careful coordination across the LADEE Operations team. Maneuver planning and recovery workflows are discussed, as well as maneuver timelines and execution segments. Also included is a history of maneuver performance.

[View Full Paper]

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ORBITAL DYNAMICS

SESSION 25

Chair: Francesco Topputo
Politecnico di Milano, Italy

The following paper was not available for publication:

AAS 15-214
(Paper Withdrawn)

AAS 15-206

ON SOLVING A GENERALIZATION OF THE KEPLER EQUATION

Juan F. San-Juan,[*] Rosario López[†] and Denis Hautesserres[‡]

In the context of general perturbation theories, the motion of an artificial satellite or space debris object around an Earth-like planet perturbed by the J_2 effect is analyzed. By means of two Lie transforms and the Krylov-Bogoliubov-Mitropolsky method, a first order theory in closed form of the eccentricity is produced. During the integration process it is necessary to solve a perturbed Kepler equation. In this work, the application of the numerical techniques and initial guesses used to solve the classical Kepler equation, or even the solution of Kepler equation itself, to the generalized equation is discussed.

[View Full Paper]

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HYBRID PERTURBATION METHODS: MODELLING THE J2 EFFECT THROUGH THE KEPLER PROBLEM

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

A hybrid orbit propagator based on the analytical integration of the Kepler problem is designed to determine the future position and velocity of any orbiter, usually an artificial satellite or space debris fragment, in 2 steps: an initial approximation generated by means of an integration method, followed by a forecast of its error produced by a prediction technique that models and reproduces the missing dynamics. In this study we analyze the effect of slightly changing the initial conditions for which a hybrid propagator was developed. We explore the possibility of generating a new hybrid propagator from others previously developed for nearby initial conditions. We find that the interpolation of the parameters of the prediction technique, which in this case is an additive Holt-Winters method, yields similarly accurate results to a non-interpolated hybrid propagator when modeling the J_2 effect in the *main problem* propagation.

[View Full Paper]

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ORBIT PROPAGATION IN MINKOWSKIAN GEOMETRY

Javier Roa[*] and Jesús Peláez[†]

A more adequate description of perturbed hyperbolic orbits is found in the geometry underlying Minkowski space-time. Hypercomplex numbers appear naturally when describing vectors, rotations, and metrics in this geometry. The solution to the unperturbed hyperbolic motion is well known in terms of hyperbolic functions and the hyperbolic anomaly. From this, a general solution is derived through the Variation of Parameters technique. Hyperbolic geometry leads to a more coherent formulation. The evolution of the eccentricity vector is described by means of its components on the Minkowski plane. The orbital plane is defined in the inertial reference using quaternions, treated as particular instances of hypercomplex numbers. The performance of the proposed formulation is evaluated for integrating flyby trajectories of NEAR, Cassini, and Rosetta spacecraft. Improvements in accuracy have been observed in these cases, with no penalties on the computational time.

[View Full Paper]

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FROZEN ORBIT COMPUTATION FOR A MERCURY SOLAR SAIL

Eva Tresaco,[*] Jean-Paulo S. Carvalho[†] and Antonio Elipe[‡]

Solar sail is a new concept of spacecraft propulsion that uses solar radiation pressure to generate acceleration. This technology offers new challenging space-science missions such as long term missions in the solar system and deep space exploration, alert of geomagnetic storms and space debris removal strategies. The aim of this work is the computation of frozen orbits for a solar sail orbiting Mercury. Frozen orbits are orbits whose orbital elements remain constant on average, actually frozen orbits are very interesting for scientific missions. The orbital dynamics of the solar sail is governed by the oblateness of the central body (Mercury) and the gravity field of the third body (Sun). Besides the J_2 and J_3 gravity terms of the central body and the third body perturbation, our average model also includes the eccentricity and inclination of the orbit of the third body, finally we must also take into account the solar acceleration pressure. In order to reduce degrees of freedom of the dynamical system and remove short-period terms, a double averaging technique is applied. The double-averaged algorithm includes first averaging over the period of the satellite and second another averaging with respect to the period of the third body. This simplified Hamiltonian model is introduced into the Lagrange Planetary equations, thus frozen orbits are characterized by a surface depending on three variables, the orbital semi-major axis, eccentricity and inclination. Finally, we also analyze the temporal evolution of the eccentricity of these orbits for different values of the sail area-to-mass ratio, which is a parameter related to the efficiency of the solar sail.

[View Full Paper]

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AAS 15-326

ADVANCES IN BALLISTIC CAPTURE ORBITS COMPUTATION WITH APPLICATIONS

F. Topputo*

In this paper, recent developments on the computation of ballistic capture orbits are discussed, together with a presentation on their applications to practical cases. The paper focuses on the method used to derive the stable sets. These are sets of initial conditions that generate orbits satisfying a simple definition of stability, whose manipulation produces ballistic capture orbits. The way this method has evolved over the years will be illustrated, from the simple planar circular restricted three-body model to a three-dimensional high-fidelity context. Applications involve interplanetary trajectory design, lunar missions, and asteroid retrieval scenarios.

[View Full Paper]

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AAS 15-351

TEST PROBLEMS FOR EVALUATING THE PERFORMANCE OF NUMERICAL ORBIT PROPAGATORS

Hodei Urrutxua[*] and Jesús Peláez[*]

A collection of test cases is proposed for the validation and testing of numerical orbit propagators. These test problems are designed to characterize the performance of the propagators and intended to highlight their possible deficiencies and expose their limitations. Every problem in the collection is accompanied by an accurate solution, and the performance of several orbit propagators is shown as examples to these problems.

[View Full Paper]

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AAS 15-395

LONG-TERM EVOLUTION OF HIGHLY-ELLIPTICAL ORBITS: LUNI-SOLAR PERTURBATION EFFECTS FOR STABILITY AND RE-ENTRY

Camilla Colombo[*]

This paper investigates the long-term evolution of spacecraft in Highly Elliptical Orbits (HEOs). The single averaged disturbing potential due to luni-solar perturbations and zonal harmonics of the Earth gravity field is written. The double averaged potential is also derived in the Earth-centered equatorial system. Maps of long-term evolution are constructed to identify conditions for quasi-frozen, or long-lived libration orbits. In addition to allow meeting specific mission constraints, quasi-frozen orbits can be selected as graveyard orbits for the end-of-life of HEO missions. On the opposite side, unstable conditions can be exploited to target an Earth re-entry at the end-of-mission.

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AAS 15-435

DYNAMICAL INSTABILITIES IN MEDIUM EARTH ORBITS: CHAOS INDUCED BY OVERLAPPING LUNAR RESONANCES

Aaron J. Rosengren,[*] Elisa Maria Alessi,[*] Giovanni B. Valsecchi,[†] Alessandro Rossi,[*] Florent Deleflie[‡] and Jérôme Daquin[‡]

Recent numerical integrations have shown that the inclined, nearly circular orbits of the navigation satellites are unstable, resulting in large and unpredictable excursions in eccentricity. The motion of these medium-Earth orbits, governed mainly by the inhomogeneous, non-spherical gravitational field of the Earth, is usually only weakly disturbed by lunar and solar gravitational perturbations. For certain initial conditions, however, appreciable effects can build up through accumulation over long periods of time; such resonances, which can drastically alter the satellite's orbital lifetime, generally occur when the second harmonic of the Earth's gravitational potential (the oblateness perturbation) causes nodal and apsidal motions which preserve a favorable relative orientation between the orbit and the direction of the disturbing force. A clear picture of the physical significance of these resonances is of considerable practical interest for the design of disposal strategies for the four constellations. Here we identify the source of the noted orbital instability, tied chiefly to the Moon's perturbed motion, and the nature of its consequences. We discuss the implications of the complex dynamical structure of MEO orbits for the management of the navigation satellites.

[View Full Paper]

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ATTITUDE DYNAMICS AND CONTROL

SESSION 26

Chair: Maruthi Akella
University of Texas at Austin

The following paper was not available for publication:

AAS 15-279
(Paper Withdrawn)

AAS 15-215

SPACECRAFT ATTITUDE CONTROL USING NEURO-FUZZY CONTROLLER TRAINED BY STATE-DEPENDENT RICCATI EQUATION CONTROLLER

Sung-Woo Kim,* Sang-Young Park† and Chandeok Park‡

In this study, a neuro-fuzzy controller is developed for spacecraft attitude control in order to mitigate the large computation load of the State-Dependent Riccati Equation (SDRE) controller. The neuro-fuzzy controller is developed by training a neuro-fuzzy network to approximate the SDRE controller. Further, the stability of the controller is numerically verified using a Lyapunov-based method and its performance is analyzed in terms of approximation accuracy, cost, and execution time for the developed neuro-fuzzy control system. The results of simulations and tests conducted indicate that the neuro-fuzzy controller developed efficiently approximates the SDRE controller with asymptotical stability in a bounded region of angular velocity containing the operational range of rapid attitude maneuvers.

[View Full Paper]

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AAS 15-242

CHARACTERIZATION OF SELF-EXCITED, ASYMMETRIC, SPINNING RIGID-BODY MOTION AS AN OBLATE EPICYCLOID

S. Lauren McNair* and Steven Tragesser†

Despite the numerous analytic studies of Euler's equations of motion for a spinning rigid-body with a body-fixed torque, the solution for an asymmetric object subject to a constant transverse torque has not been treated using the assumption that the deviation of the spin axis is small. The solution is found herein to give accurate results while avoiding the complexity of more general formulations. The simplicity of the formulation lends itself to a better understanding of the system behavior. Specifically, the motion of the spin axis for this asymmetric case is described by an oblate epicycloid, an extension of the classic epicycloid solution for axisymmetric objects.

[View Full Paper]

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AAS 15-250

AN INSTANTANEOUS QUADRATIC POWER OPTIMAL ATTITUDE-TRACKING CONTROL POLICY FOR N-CMG SYSTEMS

Daniel P. Lubey* **and Hanspeter Schaub†**

This paper develops an attitude reference tracking control policy that is optimized with respect to the instantaneous power usage for a spacecraft with N Control Moment Gyroscopes (CMGs). Along with the derivation of this control policy, this paper develops the equations of motion for such a system and the control policy is proven to be globally asymptotically stable in both attitude and attitude rate tracking. A numerical simulation is provided to show the power-optimal tracking law performance compared to other control laws such as the minimum norm law for attitude tracking applications.

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AAS 15-288

EXPERIMENTAL IMPLEMENTATION OF RIEMANN-STIELTJES OPTIMAL CONTROL FOR AGILE CMG MANEUVERING

Mark Karpenko[*] and Ronald J. Proulx[†]

Standard optimal control solutions provide open-loop controls based on a nominal model of the plant. When implemented in the closed-loop, unpredictable interactions between the nominal open-loop controls and the feedback law can cause the system to fail to perform as expected. Riemann-Stieltjes optimal control is a new concept that allows the effects of such uncertainties to be addressed in an optimal control framework. This paper details the application of Riemann-Stieltjes optimal control for agile maneuvering of a CMG imaging satellite. Experimental implementation on Honeywell's momentum control system testbed demonstrates the efficacy of the approach.

[View Full Paper]

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AAS 15-327

HYBRID SWITCHING ATTITUDE CONTROL OF UNDERACTUATED SPACECRAFT SUBJECT TO SOLAR RADIATION PRESSURE

Chris Petersen,* Frederick Leve† and Ilya Kolmanovsky‡

In this paper, attitude control of an underactuated spacecraft with two control moments is considered. Both the case of two external moments, that can, for instance, be applied by thrusters or two internal moments, that can, for instance, be applied by reaction wheels, are treated. Both problems are known to be challenging, e.g., there exists no smooth or even continuous time-invariant stabilizing feedback law in either of these cases. Our controller is based on a hybrid switching feedback law that exploits an inner-loop controller and an outer-loop controller. The fast inner-loop controller tracks periodic reference trajectories while parameters which determine the amplitude of these reference trajectories are adjusted by an outer-loop controller. We demonstrate through simulations on a nonlinear spacecraft attitude dynamics model that this switching feedback law successfully accomplishes rest-to-rest reorientation maneuvers, even in the presence of solar radiation pressure disturbance moments or in the case of nonzero total angular momentum.

[View Full Paper]

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SPHERICAL MAGNETIC DIPOLE ACTUATOR FOR SPACECRAFT ATTITUDE CONTROL

Joshua Chabot* and Hanspeter Schaub†

This paper develops an analytical force and torque model for a spherical magnetic dipole attitude control device, along with a control scheme that includes singularity avoidance. The device proposed consists of a non-contact spherical dipole rotor enclosed in an array of coils that is fixed to the spacecraft body. Excitation of the coils as prescribed by the control law rotates the dipole rotor in such a manner as to produce a desired reaction torque for orienting the spacecraft. The coils also control the rotor's position inside the spacecraft body via a separate control law because of the non-contact nature of the device. Due to the axisymmetric field of the dipole rotor, underactuation is possible with one device and therefore two spherical actuators are needed for full attitude control.

[View Full Paper]

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A NON-SINGULAR DROMO-BASED REGULARIZED METHOD FOR THE PROPAGATION OF ROTO-TRANSLATIONALLY COUPLED ASTEROIDS

Hodei Urrutxua* **and Jesús Peláez***

There are many asteroids for which the attitude coupling imposes harsh demands to the numerical propagation of their dynamics. Special regularization methods are appropriate to overcome such difficulties, where perturbations techniques make their best. The perturbation techniques used to derive the DROMO regularization method for orbital dynamics, have now been extended to the attitude dynamics problem with equally remarkable results both in terms of speed and accuracy. The combination of these DROMO-based techniques is thus appropriate for the propagation of strongly coupled bodies.

[View Full Paper]

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AAS 15-411

SURVEY OF OPTIMAL RIGID-BODY ATTITUDE MANEUVERS

Kaushik Basu* **and Robert G. Melton†**

This paper surveys the literature on optimal rigid-body attitude maneuvers, covering a span of approximately 45 years, with an emphasis on the newer work. The papers comprise a range of problems and methods, including time- and fuel-optimal formulations, systems with and without path constraints, and analytic and numerical approaches.

[View Full Paper]

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AAS 15-429

ROBUSTIFICATION OF ITERATIVE LEARNING CONTROL PRODUCED BY MULTIPLE ZERO ORDER HOLDS AND INITIAL SKIPPED STEPS

Te Li* and Richard W. Longman†

Iterative Learning Control (ILC) iterates with a real world control system that repeatedly executes the same command, aiming to converge to zero tracking error, in the real world, not in one's model of the world. It has use in spacecraft for maneuvers of fine pointing sensors that repeatedly perform scanning maneuvers. ILC is an inverse problem, asking for that input that produces zero error, and mathematically this is very often an unstable problem. Two approaches eliminate this difficulty, appending one or more time steps to the start of the desired tracking problem, and inserting extra time steps for control updates between addressed time steps. It is shown here that it is best to combine these approaches, which results in substantially better error levels between addressed time steps. Robustness for three classes of ILC laws is evaluated for these different approaches. Quadratic cost ILC is seen to have substantially better robustness to parameter uncertainty than the other laws.

[View Full Paper]

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ORBIT DETERMINATION III

SESSION 27

Chair: Brandon Jones
University of Colorado at Boulder

The following paper was not available for publication:

AAS 15-313
(Paper Withdrawn)

AAS 15-251

ROBUST TRACKING AND DYNAMICS ESTIMATION WITH THE ADAPTIVE OPTIMAL CONTROL BASED ESTIMATOR

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

All tracked objects in orbit do not have accurate dynamical models associated with them, thus we need techniques that maintain tracking even with inaccurate dynamical models. Given the volume of objects in orbit it is important to automate this estimation algorithm so that it may feasibly be applied to orbit tracking problems. This paper develops the Adaptive Optimal Control Based Estimator, which automatically detects the level of dynamic uncertainty, and then jointly estimates the system's state and its mismodeled dynamics. Along with the derivation, sample tracking scenarios are provided to demonstrate the abilities of this algorithm.

[View Full Paper]

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AAS 15-252

ESTIMATING OBJECT-DEPENDENT NATURAL ORBITAL DYNAMICS WITH OPTIMAL CONTROL POLICIES: A VALIDATION STUDY

Daniel P. Lubey,* Alireza Doostan† and Daniel J. Scheeres‡

Object-dependent dynamics for Earth orbiting objects are often poorly modeled, so they require estimation. A method proposed by the authors estimates dynamics parameters using information from optimal control policies that connect state estimates across an observation gap. In this paper we both test the validity of linear assumptions made in the original algorithm and relax Gaussian assumptions within it. To validate the linear assumptions, we demonstrate two methods of uncertainty quantification: a Monte Carlo analysis, and Stochastic Collocation using Gauss-Hermite abscissas on a Smolyak sparse grid. A discussion of the results and the appropriateness of each method are included.

[View Full Paper]

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AAS 15-253

PARTICLE AND MATCHED FILTERING USING ADMISSIBLE REGIONS

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

The main result to be presented in this paper is a novel matched filter based on orbital mechanics. The matched filter is an image processing technique which allows low signal-to-noise ratio objects to be detected. By using previous orbital knowledge, the matched filter utility can be increased. First, the particle filter implementation will be discussed followed by the implementation of the matched filter. Then a pair of simulation results will be presented, showing the results from the particle filter and matched filter.

[View Full Paper]

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AAS 15-398

QUADRATIC HEXA-DIMENSIONAL SOLUTION FOR RELATIVE ORBIT DETERMINATION – REVISITED

Brett Newman,[*] T. Alan Lovell,[†] Ethan Pratt[‡] and Eric Duncan[§]

The Keplerian circular relative motion initial orbit determination problem is investigated using an approximate second-order nonlinear closed-form solution for three-dimensional relative motion, based on quadratic Volterra series. Nonlinear line-of-sight measurement equations, which have a special multivariate polynomial structure, are solved by elimination theory and Macaulay resultants. This solution strategy to the orbit determination problem is interpreted as finding the intersection of quadratic surfaces representing the measurement equations in a hexa-dimensional space for the relative initial state variables. The equation set is reformulated as a single resultant polynomial equation, which is then solved with eigen decomposition concepts. Although, previous work presented the problem formulation in three-dimensions, specific details concerning construction of the Macaulay resultant and numerical test cases were only addressed for two-dimensional cases. The subject of this paper is to review the problem and solution framework, and then expand on details for the three-dimensional case. An algorithm to construct the numerator and denominator Macaulay matrices in symbolic form is offered. Numeric three-dimensional examples are presented to assess the performance of the new solution strategy. The requirement for quad-precision math is also addressed. The intent of the study is to expose and discuss any advantages and/or deficiencies of the new solution technique.

[View Full Paper]

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AAS 15-405

NEW ALGORITHM FOR ATTITUDE AND ORBIT DETERMINATION USING MAGNETIC FIELD MEASUREMENTS

Mohammad Abdelrahman[*]

A generalized algorithm for a Combined Nonlinear Control and Estimation CNCE process for spacecraft attitude and orbit determination and control is presented. The approach tends to eliminate the delays due to the separation between the estimation and control processes. Also, it minimizes the possibility of control degradation due to estimator divergence and instabilities. In addition, it enhances the convergence and accuracy of the estimation and control as a result of the coupling and synchronization of the both processes in the combined approach. The approach is implemented using a Modified State–Dependent Riccati Equation MSDRE scheme in optimal nonlinear estimation and control. The algorithm is applied to a spacecraft in low Earth orbit utilizing magnetic measurements and actuation only. The algorithm successfully satisfied the mission requirements in attitude and rate estimation and in pointing accuracy. Also, it has been applied to orbit determination and has shown fast convergence with enhanced accuracy.

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AAS 15-415

THE ESTIMATION OF ANGULAR POSITION FOR A SPACECRAFT USING TRACKING STATION

Tsutomu Ichikawa*

The problem of estimating the angular position of a spacecraft moving at a constant velocity using two rotating tracking stations is considered. This reports on an initial phase of analytical studies on the optimal attainable estimation performance and associated receiver design. Perametric dependence of the optimum attainable estimation is also studied.

[View Full Paper]

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MINIMUM UNCERTAINTY JPDA FILTER AND COALESCENCE AVOIDANCE PERFORMANCE EVALUATIONS

Evan Kaufman,* T. Alan Lovell† and Taeyoung Lee‡§

Two variations of the joint probabilistic data association filter (JPDAF) are derived and simulated extensively in this paper. First, an analytic solution for an optimal gain that minimizes posterior estimate uncertainty is derived, referred to as the minimum uncertainty JPDAF (MUJPDAF). Second, the coalescence-avoiding optimal JPDAF (C-JPDAF) is derived, which removes coalescence by minimizing a weighted sum of the posterior uncertainty and a measure of similarity between estimated probability densities. Both novel algorithms are tested in much further depth than any prior work to show how the algorithms perform in various scenarios. In particular, the MUJPDAF more accurately tracks objects than the conventional JPDAF in all simulated cases. When coalescence degrades the estimates at too great of a level, and the C-JPDAF is often superior at removing coalescence when its parameters are properly tuned.

[View Full Paper]

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AAS 15-433

DISTRIBUTED IMU NETWORK NAVIGATION USING MULTI-SENSOR DATA FUSION

Samuel J. Haberberger,* Jacob E. Darling† and Kyle J. DeMars‡

Precision dead-reckoning based navigation typically relies upon a single high-cost, high-performance inertial measurement unit (IMU). Low-cost navigation solutions can be obtained by dead-reckoning several inexpensive IMUs and subsequently fusing the output data. This multi-sensor topology provides inherent robustness to failure while providing improvements to navigation accuracy. Different fusion methods are analyzed for a multi-sensor network using cost effective IMUs, including direct averaging and covariance intersection. Simulations of a spacecraft in low Earth orbit are used to baseline a typical expensive IMU and compare the navigation solution obtained from a network of several low-cost IMUs from fused data.

[View Full Paper]

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SPACECRAFT UNCERTAINTY PROPAGATION USING GAUSSIAN MIXTURE MODELS AND POLYNOMIAL CHAOS EXPANSIONS

Vivek Vittaldev,* Richard Linares† and Ryan P. Russell‡

Polynomial Chaos Expansion (PCE) and Gaussian Mixture Models (GMM) are combined in a hybrid fashion to quantify state uncertainty for spacecraft. The PCE approach models the uncertainty by performing an expansion using orthogonal polynomials (OPs). The accuracy of PCE for a given problem can be improved by increasing the order of the OP expansion. Due to the "*curse of dimensionality*" the number of terms in the OP expansion increases exponentially with dimensionality of the problem, thereby reducing the effectiveness of the PCE approach for problems of moderately high dimensionality. Including a GMM with the PCE (GMM-PC) is shown to reduce the overall order required to achieve a desired accuracy. The initial distribution is converted into a GMM, and PCE is used to propagate each of the elements. Splitting the initial distribution into a GMM reduces the size of the covariance associated with each element and therefore, lower order polynomials can be used. The GMM-PC effectively reduces the function evaluations required for accurately describing a non-Gaussian distribution that results from the propagation of a state with an initial Gaussian distribution through a nonlinear function. Several examples of state uncertainty are propagated using GMM-PC. The resulting distributions are shown to efficiently capture shape and skewness.

[View Full Paper]

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DYNAMICS AND CONTROL OF LARGE SPACE STRUCTURES AND TETHERS

SESSION 28

Chair: Ryan Russell
University of Texas at Austin

The following paper was not available for publication:

AAS 15-312
(Paper Withdrawn)

AAS 15-304

NONLINEAR SUBOPTIMAL CONTROL OF FLEXIBLE SPACECRAFT TRACKING A NON-COOPERATE TARGET

Dayu Zhang,[*] Jianjun Luo,[†] Dengwei Gao[‡] and Jianping Yuan[§]

A modified $\theta - D$ control algorithm is presented in this paper to solve for flexible spacecraft approaching a non-cooperative target. First, "Orbit-Attitude-Flexibility" coupled equation based on state-dependent coefficient form is established to describe the coupling effect of translational, rotational motion and its structure flexibleness. Second, with respect to the situation of target exists both orbit and attitude motion, we provide an modified $\theta - D$ controller, designed by combining standard $\theta - D$ algorithm and Lyapunov min-max approach, to solve this problem. Simulation results show standard $\theta - D$ controller and modified $\theta - D$ controller have fine performance to respectively solve the situation that targets exists orbital maneuvering and situation that exists both orbital and attitude motion, meanwhile vibration of flexible structures is suppressed effectively during the tracking process.

[View Full Paper]

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AAS 15-371

DYNAMICS AND CONTROL OF ELECTRODYNAMIC TETHER FOR SPACE DEBRIS REMOVAL

Zheng H. Zhu[*] and Rui Zhong[†]

This paper studied the dynamics and control of electrodynamic tether for space debris deorbit. A short electrodynamic tether is used for passive deorbiting. The optimal control theory is adopted and a piecewise two-phased optimal control strategy is proposed. In the first phase, the orbital dynamics is simplified and a cost function minimization problem is established, resulting in an open-loop optimal control for fast deorbit. In the second phase, a close-loop feedback control is used to follow the derived optimized trajectory, where the receding horizontal control is used to calculate the control gain. The resulting piecewise nonlinear programing problems in the sequential intervals reduces the problem size and improve the computational efficiency thus enable an on-orbit control application. Numerical results prove the efficiency of the proposed control method.

[View Full Paper]

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TETHERED SATELLITE DEPLOYMENT AND RETRIEVAL BY FRACTIONAL ORDER TENSION CONTROL

Zheng H. Zhu* and Guanghui Sun†

This paper develops a fractional order tension control law for deployment and retrieval of tether satellite system. The effectiveness and advantage of the fractional order control law is validated by simulations. Compared with the classic integer order tension control law, the newly proposed fractional order tension control law can deploy and retrieve the tethered system fast and stably while (i) reduce the overshoot of system response in deployment and (ii) reduce the in-plane libration for the tether deployment and prevent the subsatellite from hitting or winding the main satellite in the tether retrieval.

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AAS 15-378

ARCHITECTURES FOR VIBRATING MASS ATTITUDE CONTROL ACTUATORS

Burak Akbulut*[*] and Ozan Tekinalp[†]

Reaction wheels, magnetic torque rods, momentum wheels and control moment gyroscopes (CMGs) are the most common actuators used in attitude control. However, they use rotor and/or gimbal mechanisms susceptible to failure. An alternative solution may be vibrating mass actuators. Previous research by Reiter *et al.* and Chang *et al.* showed the possibility of obtaining a net output torque from vibrating actuators. To build upon this, current research aims to expand the vibratory actuators to different and more complex architectures such as double axis CMGs. Additionally simulation models will be built to investigate their functioning in satellite attitude pointing scenarios.

[View Full Paper]

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[‡] A section on mathematical notation is provided in the sequel.

AAS 15-388

ATTITUDE CONTROL OF AN EARTH ORBITING SOLAR SAIL SATELLITE TO PROGRESSIVELY CHANGE THE SELECTED ORBITAL ELEMENT

Omer Atas[*] and Ozan Tekinalp[†]

Solar sailing where the radiation pressure from Sun is utilized to propel the spacecraft is examined in the context of orbital maneuvers. In this vein a locally optimal steering law to progressively change the selected orbital elements, without considering others, of an Earth centered Keplerian orbit of a cubesat satellite with solar sail is addressed. The proper attitude maneuver mechanization is proposed to harvest highest solar radiation force in the desired direction for such Earth orbiting satellites. The satellite attitude control is realized using quaternion error feedback control. The effectiveness of the approach to progressively changing the orbital parameters is demonstrated.

[View Full Paper]

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NUMERICAL INDEX

Volume 155 I, II & III

ADVANCES IN THE ASTRONAUTICAL SCIENCES
SPACEFLIGHT MECHANICS 2015 (2015)

(AAS/AIAA Space Flight Mechanics Meeting, January 11–15, 2015, Williamsburg, Virginia, U.S.A.)

AAS 15-216 (Paper Withdrawn)

AAS 15-217 (Paper Withdrawn)

AAS 15-218 SFDT-1 Camera Pointing and Sun-Exposure Analysis and Flight Performance, Joseph White, Soumyo Dutta and Scott Striepe (Part I)

AAS 15-219 Supersonic Flight Dynamics Test 1 - Post-Flight Assessment of Simulation Performance, Soumyo Dutta, Angela L. Bowes, Scott A. Striepe, Jody L. Davis, Eric M. Queen, Eric M. Blood and Mark C. Ivanov (Part I)

AAS 15-220 Energy Conserved Planar Spacecraft Motion With Constant Thrust Acceleration, Sonia Hernandez and Maruthi R. Akella (Part III)

AAS 15-221 The Reboot of the International Sun/Earth Explorer 3: The Orbit Determination and Trajectory Design Option Analysis, Timothy Craychee, Craig Nickel, Lisa Policastri and Michel Loucks (Part I)

AAS 15-222 (Paper Withdrawn)

AAS 15-223 High Altitude Venus Operations Concept Trajectory Design, Modeling, and Simulation, Rafael A. Lugo, Thomas A. Ozoroski, John W. Van Norman, Dale C. Arney, John A. Dec, Christopher A. Jones and Carlie H. Zumwalt (Part I)

AAS 15-224 Supersonic Flight Dynamics Test: Trajectory, Atmosphere, and Aerodynamics Reconstruction, Prasad Kutty, Christopher D. Karlgaard, Eric M. Blood, Clara O'Farrell, Jason M. Ginn, Mark Schoenenberger and Soumyo Dutta (Part I)

AAS 15-225 (Paper Withdrawn)

AAS 15-226 (Not Assigned)

AAS 15-227 Multi-Objective Hybrid Optimal Control for Multiple-Flyby Low-Thrust Mission Design, Jacob A. Englander, Matthew A. Vavrina and Alexander R. Ghosh (Part II)

AAS 15-228 Cauchy Drag Estimation for Low Earth Orbiters, J. Russell Carpenter and Alinda K. Mashiku (Part III)

AAS 15-229 (Not Assigned)

AAS 15-230 Pre-Launch Orbit Determination Design and Analysis for the LADEE Mission, Lisa Policastri, John P. Carrico Jr. and Craig Nickel (Part III)

AAS 15-231 Improved Models for Attitude Estimation of Agile Space Objects, Ryan D. Coder, Richard Linares and Marcus J. Holzinger (Part I)

AAS 15-232 LDSD POST2 Simulation and SFDT-1 Pre-Flight Launch Operations Analyses, Angela L. Bowes, Jody L. Davis, Soumyo Dutta, Scott A. Striepe, Mark C. Ivanov, Richard W. Powell and Joseph White (Part I)

AAS 15-233 Formulation of Collision Probability With Time-Dependent Probability Density Functions, Ken Chan (Part I)

AAS 15-234 Hovering Collision Probability, Ken Chan (Part I)

AAS 15-235 (Not Assigned)

AAS 15-236 Analysis of the Evolution of Space Debris Through a Synthetic Population, Daniel Casanova, Anne Lemaitre and Alexis Petit (Part II)

AAS 15-237 Optimization of Many-Revolution, Electric-Propulsion Trajectories With Engine Shutoff Constraints, Jason A. Reiter, Austin K. Nicholas and David B. Spencer (Part II)

AAS 15-238 Station-Keeping for Lattice-Preserving Flower Constellations, Daniel Casanova and Eva Tresaco (Part II)

AAS 15-239 Frozen Orbit Computation for a Mercury Solar Sail, Eva Tresaco, Jean-Paulo S. Carvalho and Antonio Elipe (Part III)

AAS 15-240 A General Perturbations Method for Spacecraft Lifetime Analysis, Emma Kerr and Malcolm Macdonald (Part I)

AAS 15-241 Helium Discrepancy In Nrlmsise-2000 Density Model Detected Via Champ/Grace Data And Decaying Spheres, Chia-Chun Chao, James R. Wilson, John P. McVey and Richard L. Walterscheid (Part I)

AAS 15-242 Characterization of Self-Excited, Asymmetric, Spinning Rigid-Body Motion as an Oblate Epicycloid, S. Lauren McNair and Steven Tragesser (Part III)

AAS 15-243 (Paper Withdrawn)

AAS 15-244 Utilization of the Deep Space Atomic Clock for Europa Gravitational Tide Recovery, Jill Seubert and Todd Ely (Part I)

AAS 15-245 (Paper Withdrawn)

AAS 15-246 A Study on the Trajectory Optimization of a Korean Lunar Orbiter Using Pattern Search Method, Su-Jin Choi, Sang-Cher Lee and Hae-Dong Kim (Part II)

AAS 15-247 Similar Analysis for Ground-Based Astrodynamical Experiment of Space Relative Maneuver, Yu Qi, Peng Shi and Yushan Zhao (Part I)

AAS 15-248 Pose Estimation Assessment Using Geosynchronous Satellite Identification, Stoian Borissov, Daniele Mortari and Thomas Pollock (Part III)

AAS 15-249 Robust High-Fidelity Gravity-Assist Trajectory Generation Using Forward/Backward Multiple Shooting, Justin A. Atchison, Martin T. Ozimek, Christopher J. Scott and Fazle E. Siddique (Part II)

AAS 15-250 An Instantaneous Quadratic Power Optimal Attitude-Tracking Control Policy for N-CMG Systems, Daniel P. Lubey and Hanspeter Schaub (Part III)

AAS 15-251 Robust Tracking and Dynamics Estimation With the Adaptive Optimal Control Based Estimator, Daniel P. Lubey and Daniel J. Scheeres (Part III)

AAS 15-252 Estimating Object-Dependent Natural Orbital Dynamics With Optimal Control Policies: A Validation Study, Daniel P. Lubey, Alireza Doostan and Daniel J. Scheeres (Part III)

AAS 15-253 Particle and Matched Filtering Using Admissible Regions, Timothy S. Murphy, Brien Flewelling and Marcus J. Holzinger (Part III)

AAS 15-254 Discrete and Continuous Time Adaptive Angular Velocity Estimators, Daniele Mortari and Maruthi R. Akella (Part I)

AAS 15-255 Designing Transfers to Geostationary Orbit Using Combined Chemical-Electric Propulsion, Craig A. Kluever (Part I)

AAS 15-256 (Not Assigned)

AAS 15-295 Efficient Computation of Short-Period Analytical Corrections Due to Third-Body Effects, M. Lara, R. Vilhena de Moraes, D. M. Sanchez and A. F. B. de A. Prado (Part I)

AAS 15-296 Philae Landing Site Selection and Descent Trajectory Design, Eric Jurado, Alejandro Blazquez, Thierry Martin, Elisabet Canalias, Julien Laurent-Varin, Romain Garmier, Thierry Ceolin, Jens Biele, Laurent Jorda, Jean-Baptiste Vincent, Vladimir Zakharov, Jean-François Crifo and Alexander Rodionov (Part II)

AAS 15-297 Weak Stability Boundary and Trajectory Design, James K. Miller and Gerald R. Hintz (Part I)

AAS 15-298 High-Speed, High-Fidelity Low-Thrust Trajectory Optimization Through Parallel Computing and Collocation Methods, Jonathan F. C. Herman, Jeffrey S. Parker, Brandon A. Jones and George H. Born (Part II)

AAS 15-299 Optimized Low-Trust Mission to the Atira Asteroids, Marilena Di Carlo, Natalia Ortiz Gómez, Juan Manuel Romero Martín, Chiara Tardioli, Fabien Gachet, Kartik Kumar and Massimilano Vasile (Part I)

AAS 15-300 The Design of NPU-Phonesat: A Foldable Picosatellite Using Smart Phone Technology, Jianping Yuan, Qiao Qiao, Jing Yuan, Yong Shi, Jianwen Hou, Shuguang Li, Shengbo Shi, Lixin Li, Ruonan Zhang, Wu Gao, Yong Liu and Hao Sun (Part III)

AAS 15-301 Autonomous Operation of Multiple Free-Flying Robots on the International Space Station, B. J. Morrell, G. E. Chamitoff, P. W. Gibbens and A. Saenz-Otero (Part III)

AAS 15-302 Ballistic Capture Into Distant Retrograde Orbits From Interplanetary Space, Collin Bezrouk and Jeffrey Parker (Part I)

AAS 15-303 Design of Constellations for Earth Observation With Inter-Satellite Links, Sanghyun Lee and Daniele Mortari (Part II)

AAS 15-304 Nonlinear Suboptimal Control of Flexible Spacecraft Tracking a Non-Cooperate Target, Dayu Zhang, Jianjun Luo, Dengwei Gao and Jianping Yuan (Part III)

AAS 15-305 (Not Assigned)

AAS 15-306 (Paper Withdrawn)

AAS 15-307 Station-Keeping and Momentum-Management on Halo Orbits Around L2: Linear-Quadratic Feedback and Model Predictive Control Approaches, Uroš Kalabić, Avishai Weiss, Ilya Kolmanovsky and Stefano Di Cairano (Part II)

AAS 15-308 (Paper Withdrawn)

AAS 15-309 Novel Method Based on Displaced Orbit for Solving Non-Planar Orbit Maneuver Problem, Wei Yao, Jianjun Luo, Jianping Yuan and Chong Sun (Part II)

AAS 15-310 (Paper Withdrawn)

AAS 15-311 Low-Energy Transfers to Distant Retrograde Orbits, Jeffrey S. Parker, Collin J. Bezrouk and Kathryn E. Davis (Part I)

AAS 15-312 (Paper Withdrawn)

AAS 15-313 (Paper Withdrawn)

AAS 15-314 (Not Assigned)

AAS 15-315 Analytic Solution for the Relative Motion of Satellites in Near-Circular Low-Earth Orbits, Vladimir Martinusi, Lamberto Dell'Elce and Gaëtan Kerschen (Part II)

AAS 15-316 (Not Assigned)

AAS 15-317 Spacecraft Safe Trajectory Integrated Guidance and Control Using Artificial Potential Field and Sliding Mode Control Based on Hamilton-Jacobi Inequality, Dengwei Gao, Jianjun Luo, Weihua Ma, Hao Sun and Jianping Yuan (Part II)

AAS 15-318 (Paper Withdrawn)

AAS 15-319 Coarse Sun Acquisition Only With Sun Sensors for Micro Satellites, Fu-Yuen Hsiao, Wei-Ting Chou, Trendon Cato and Carla Rebelo (Part I)

AAS 15-320 Automated Trajectory Refinement of Three-Body Orbits in the Real Solar System Model, Diogene A. Dei-Tos and Francesco Topputo (Part I)

AAS 15-321 (Paper Withdrawn)

AAS 15-322 Approximation of Invariant Manifolds by Cubic Convolution Interpolation, F. Topputo and R. Y. Zhang (Part I)

AAS 15-323 (Paper Withdrawn)

AAS 15-324 Precise Relative Navigation for SJ-9 Mission Using Reduced-Dynamic Technique, Shu Leizheng, Chen Pei and Han Chao (Part I)

AAS 15-325 (Not Assigned)

AAS 15-326 Advances in Ballistic Capture Orbits Computation With Applications, F. Topputo (Part III)

AAS 15-327 Hybrid Switching Attitude Control of Underactuated Spacecraft Subject to Solar Radiation Pressure, Chris Petersen, Frederick Leve and Ilya Kolmanovsky (Part III)

AAS 15-328 (Not Assigned)

AAS 15-329 Control Metric Maneuver Detection With Gaussian Mixtures and Real Data, Andris D. Jaunzemis, Midhun Mathew and Marcus J. Holzinger (Part I)

AAS 15-330 Orbital Perturbation Analysis Near Binary Asteroid Systems, Loic Chappaz, Stephen B. Broschart, Gregory Lantoine and Kathleen Howell (Part II)

AAS 15-331 Decalibration of Linearized Solutions for Satellite Relative Motion, Andrew J. Sinclair, Brett Newman and T. Alan Lovell (Part II)

AAS 15-332 Propagation of Uncertainty in Support of SSA Missions, Jeffrey M. Aristoff, Joshua T. Horwood and Aubrey B. Poore (Part II)

AAS 15-333 Rapid Prototyping of Asteroid Deflection Campaigns With Spatially and Temporally Distributed Phases, Sung Wook Paek, Patricia Egger and Olivier de Weck (Part I)

AAS 15-334 Survey of Spacecraft Rendezvous and Proximity Guidance Algorithms for On-Board Implementation, Costantinos Zagaris, Morgan Baldwin, Christopher Jewison and Christopher Petersen (Part I)

AAS 15-413	A Labeled Multi-Bernoulli Filter for Space Object Tracking, Brandon A. Jones and Ba-Ngu Vo (Part I)
AAS 15-414	(Not Assigned)
AAS 15-415	The Estimation of Angular Position for a Spacecraft Using Tracking Station, Tsutomu Ichikawa (Part III)
AAS 15-416	Low Thrust Orbit-Raising Using Non-Singular Orbital Elements and Proximity Quotient Approach, Sainath Vijayan and Atri Dutta (Part I)
AAS 15-417	Automated Tuning Parameter Selection for Orbit Propagation With Modified Chebyshev Picard Iteration, Brent Macomber, Austin Probe, Robyn Woollands and John L. Junkins (Part II)
AAS 15-418	Collaborative Multi-Sensor Tracking and Data Fusion, Kyle J. DeMars, James S. McCabe and Jacob E. Darling (Part I)
AAS 15-419	LADEE Flight Dynamics System Overview, Craig Nickel, John P. Carrico Jr., Ryan Lebois, Lisa Policastri and Ryan Sherman (Part III)
AAS 15-420	Tracking of the Landsat 2 Rocket Body Primary Breakup, Kyle J. DeMars and James S. McCabe (Part II)
AAS 15-421	(Not Assigned)
AAS 15-422	Propagation of Chip-Scale Spacecraft Swarms With Uncertainties Using the Kustaanheimo-Stiefel Transformation, Lorraine Weis and Mason Peck (Part I)
AAS 15-423	Generalized Gaussian Cubature for Nonlinear Filtering, Richard Linares and John L. Crassidis (Part I)
AAS 15-424	Accurate Deployment of Landers to Dynamically Challenging Asteroids, Simon Tardivel and Daniel J. Scheeres (Part II)
AAS 15-425	Assessing GOES-R Magnetometer Accuracy, Craig Babiarz, Delano Carter, Douglas Freesland, Monica Todirita, Jeff Kronenwetter, Kevin Kim, Kumar Tadikonda and Donald Chu (Part I)
AAS 15-426	(Not Assigned)
AAS 15-427	Divergence Characteristic of the Exterior Spherical Harmonic Gravity Potential, Kiichiro J. DeLuca and Daniel J. Scheeres (Part II)
AAS 15-428	Aero-Gravity Assist Mission Design, Jeremy M. Knittel, Mark J. Lewis and Ken Yu (Part I)
AAS 15-429	Robustification of Iterative Learning Control Produced by Multiple Zero Order Holds and Initial Skipped Steps, Te Li and Richard W. Longman (Part III)
AAS 15-430	Asteroid Landing Guidance Design in the Framework of Coupled Orbit-Attitude Spacecraft Dynamics, Gaurav Misra, Amit Sanyal and Ehsan Samiei (Part II)
AAS 15-431	Low-Thrust Orbit-Raising Trajectories Considering Eclipse Constraints, Suwat Sreesawet and Atri Dutta (Part II)
AAS 15-432	Minimum Uncertainty JPDA Filter and Coalescence Avoidance Performance Evaluations, Evan Kaufman, T. Alan Lovell and Taeyoung Lee (Part III)

AAS 15-451 Nonlinear Observability Measure for Relative Orbit Determination With Angles-Only Measurements, Evan Kaufman, T. Alan Lovell and Taeyoung Lee (Part III)

AAS 15-452 Collision Avoidance for Electromagnetic Spacecraft Formation Flying With Consensus Algorithms, Xu Zengwen, Shu Leizheng, Shi Peng and Zhao Yushan (Part I)

AAS 15-453 LADEE Maneuver Planning and Performance, Alisa Hawkins, Arlen Kam and John Carrico (Part III)

AAS 15-454 (Not Assigned)

AAS 15-455 Sensor Resource Management for Sub-Orbital Multi-Target Tracking and Discrimination, Ajay Verma, Maruthi Akella, John Freeze and Kalyan Vadakkeveedu (Part II)

AAS 15-456 Trajectory Design From GTO to Near-Equatorial Lunar Orbit for the Dark Ages Radio Explorer (DARE) Spacecraft, Anthony L. Genova, Fan Yang Yang, Andres Dono Perez, Ken F. Galal, Nicolas T. Faber, Scott Mitchell, Brett Landin, Abhirup Datta and Jack O. Burns (Part I)

AAS 15-457 (Not Assigned)

AAS 15-458 (Paper Withdrawn)

AAS 15-459 (Not Assigned)

AAS 15-460 A Greedy Random Adaptive Search Procedure for Multi-Rendezvous Mission Planning, Atri Dutta (Part I)

AAS 15-461 (Not Assigned)

AAS 15-462 Redirection Of Asteroids Onto Earth-Mars Cyclers, Nathan Strange, Damon Landau and James Longuski (Part I)

AAS 15-463 Hardware Selection and Modeling for Sigma CubeSat Attitude Control System, Thomas Wright, Patrick Irvin, Arthur K. L. Lin, Regina Lee and Ho Jin (Part III)

AAS 15-464 The Phasing Problem for Sun-Earth Halo Orbit to Lunar Encounter Transfers, Hongru Chen, Yasuhiro Kawakatsu and Toshiya Hanada (Part I)

AAS 15-465 Technical Research Area Identification Working Group Process, Michele Gaudreault, Timothy K. Roberts and Moriba Jah (Part II)

AAS 15-466 Asteroid Flyby Gravimetry Via Target Tracking, Justin A. Atchison and Ryan H. Mitch (Part II)

AAS 15-467 to -470 (Not Assigned)

AUTHOR INDEX*

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* For each author the paper number is given. The page numbers refer to Volume 155, Parts I, II and III, *Advances In the Astronautical Sciences* .