SPACEFLIGHT MECHANICS 2017

EDITORS
Dr. Jay W. McMahon — University of Colorado
Dr. Yanping Guo — The Johns Hopkins University Applied Physics Laboratory
Dr. Frederick A. Leve — U.S. Air Force Research Laboratory
Dr. Jon A. Sims — NASA Jet Propulsion Laboratory

SERIES EDITOR
Robert H. Jacobs — Univelt, Incorporated

Front Cover Illustration:

This artist concept shows NASA's Dawn spacecraft above dwarf planet Ceres.
Credit: NASA/JPL-Caltech/UCLA/MPS/DLR/IDA.

SPACEFLIGHT MECHANICS 2017

Volume 160

ADVANCES IN THE ASTRONAUTICAL SCIENCES

Edited by
Jay W. McMahon
Yanping Guo
Frederick A. Leve
Jon A. Sims

Proceedings of the 27th AAS/AIAA Space Flight Mechanics Meeting held February 5–9, 2017, San Antonio, Texas, U.S.A.

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

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

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

First Printing 2017

Library of Congress Card No. 57-43769

ISSN 1081-6003

ISBN 978-0-87703-637-1 (Hard Cover Plus CD ROM)
ISBN 978-0-87703-638-8 (Digital Version)

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

Printed and Bound in the U.S.A.

FOREWORD

This volume is the twenty-seventh 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, digital, or in microfiche form. The appendix of the volume lists proceedings available through the American Astronautical Society.

Spaceflight Mechanics 2017, Volume 160, Advances in the Astronautical Sciences, consists of four parts totaling about 4,300 pages, plus a CD ROM/digital format version which also contains all the available papers. Papers which were not available for publication are listed on the divider pages of each section in the hard copy volume. A chronological index and an author index appear at the end of the main linking file, and are appended to the fourth part of the volume.

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

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

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

AAS/AIAA SPACEFLIGHT MECHANICS VOLUMES

Spaceflight Mechanics 2017 appears as Volume 160, *Advances in the Astronautical Sciences*. This publication presents the complete proceedings of the 27th AAS/AIAA Space Flight Mechanics Meeting 2017.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

AAS/AIAA ASTRODYNAMICS VOLUMES

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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 27th Space Flight Mechanics Meeting was held in San Antonio, Texas, February 5-9, 2017. The meeting was sponsored by the American Astronautical Society (AAS) Space Flight Mechanics Committee and co-sponsored by the American Institute of Aeronautics and Astronautics (AIAA) Astrodynamics Technical Committee. Approximately 280 people registered for the meeting; attendees included engineers, scientists, and mathematicians representing government agencies, the military services, industry, and academia from the United States and abroad.

There were 249 technical papers presented in 29 sessions on topics related to space flight mechanics and astrodynamics. The special session on Interdisciplinary Challenges in Space Situational Awareness was well received and strongly attended.

Dr. Felix R. Hoots was the recipient of the 2016 AAS Dirk Brouwer award. As part of the awards ceremony on Monday evening, Dr. Hoots gave a lecture titled "Analytic Exploration in Astrodynamics."

The editors extend their gratitude to the Session Chairs who made this meeting successful: Maruthi Akella, Rodney Anderson, Brent Barbee, Angela Bowes, Kyle DeMars, Atri Dutta, Roberto Furfaro, Marcus Holzinger, Kathleen Howell, Moriba Jah, Brandon Jones, Daniel Lubey, Manoranjan Majji, Cameron Meek, Zubin Olikara, Martin Ozimek, Ryan Park, Jeff Parker, Ryan Russell, John Seago, Andrew Sinclair, Puneet Singla, David Spencer, Thomas Starchville, Nathan Strange, Sean Wagner, Matthew Wilkins, Roby Wilson, and Renato Zanetti.

Dr. Jay W. McMahon
University of Colorado
AAS Technical Chair

Dr. Frederick A. Leve
U.S. Air Force Research Laboratory
AAS General Chair

Dr. Yanping Guo
Applied Physics Laboratory
AIAA Technical Chair

Dr. Jon A. Sims
Jet Propulision Laboratory
AIAA General Chair

CONTENTS

Part II

Part III

ASTEROID MISSIONS

Session Chairs:

Session 1: Ryan Park

Session 13: Nathan Strange

Session 21: Brent Barbee

NASA DOUBLE ASTEROID REDIRECTION TEST (DART) TRAJECTORY VALIDATION AND ROBUSTNESS

**Bruno V. Sarli,* Martin T. Ozimek,† Justin A. Atchison,†
Jacob A. Englander‡ and Brent W. Barbee‡**

The Double Asteroid Redirection Test (DART) mission will be the first to test the concept of a kinetic impactor. Several studies have been made on asteroid redirection and impact mitigation, however, to this date no mission tested the proposed concepts. An impact study on a representative body allows the measurement of the effects on the target's orbit and physical structure. With this goal, DART's objective is to verify the effectiveness of the kinetic impact concept for planetary defense. The spacecraft uses solar electric propulsion to escape Earth, fly by (138971) 2001 CB_{21} for impact rehearsal, and impact Didymos-B, the secondary body of the binary (65803) Didymos system. This work focuses on the heliocentric transfer design part of the mission with the validation of the baseline trajectory, performance comparison to other mission objectives, and assessment of the baseline robustness to missed thrust events. Results show a good performance of the selected trajectory for different mission objectives: latest possible escape date, maximum kinetic energy on impact, shortest possible time of flight, and use of an Earth swing-by. The baseline trajectory was shown to be robust to a missed thrust with 1% of fuel margin being enough to recover the mission for failures of more than 14 days.

[View Full Paper]

* Research Fellow, Catholic University of America at NASA Goddard Space Flight Center, Member AAS.
† Senior Professional Staff, Astrodynamics and Control Systems Group, The Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel, Maryland 20723, U.S.A. Member AAS.
‡ Aerospace Engineer, Navigation and Mission Design Branch, NASA Goddard Space Flight Center, Greenbelt, Maryland 20771, U.S.A. Member AAS.

AAS 17-210

THE DYNAMICAL CHARACTERISTICS OF HETEROGENEOUS ASTEROID 25143 ITOKAWA

Lei Lan,[*] Hexi Baoyin[†] and Junfeng Li[‡]

In this paper, we develop a methodology to study the periodic dynamics of irregular heterogeneous celestial bodies. It has been found that 25143 Itokawa may have varied internal structure reflected in the density variety of different areas, which may originate from the collision formation from multiple objects. We compare dynamical characteristics with that of homogeneous case. It is found that Jacobi-map, positions of equilibrium points and the types of bifurcations in the continuation of orbital family near the heterogeneous body are different from those of homogeneous one. More detailed location and stability of equilibrium points outside may guide a better choice of orbits in mission near the heterogeneous body. Besides, investigation of equilibrium points inside may reflect the internal structure and pressure of the body different from homogeneous case.

[View Full Paper]

[*] Ph.D. Candidate, School of Aerospace Engineering, Tsinghua University, Room N-904, Meng Minwei Science and Technology Building, Beijing 100084, China. E-mail: lanl14@mails.tsinghua.edu.cn.
[†] Professor, School of Aerospace Engineering, Tsinghua University, Room N-904, Meng Minwei Science and Technology Building, Beijing 100084, China. E-mail: baoyin@tsinghua.edu.cn.
[‡] Professor, School of Aerospace Engineering, Tsinghua University, Room N-904, Meng Minwei Science and Technology Building, Beijing 100084, China. E-mail: lijunf@tsinghua.edu.cn.

AAS 17-214

MULTI-OBJECTIVE OPTIMIZATION OF SPACECRAFT TRAJECTORIES FOR SMALL-BODY COVERAGE MISSIONS

David W. Hinckley, Jr.,[*] Jacob A. Englander[†] and Darren L. Hitt[‡]

Visual coverage of surface elements of a small-body object requires multiple images to be taken that meet many requirements on their viewing angles, illumination angles, times of day, and combinations thereof. Designing trajectories capable of maximizing total possible coverage may not be useful since the image target sequence and the feasibility of said sequence given the rotation-rate limitations of the spacecraft are not taken into account. This work presents a means of optimizing, in a multi-objective manner, surface target sequences that account for such limitations. [View Full Paper]

[*] Mechanical Engineering Graduate Student, University of Vermont, Burlington, Vermont 05405, U.S.A.
[†] Aerospace Engineer, Navigation and Mission Design Branch, NASA Goddard Space Flight Center, Greenbelt, Maryland 20771, U.S.A.
[‡] Professor of Mechanical Engineering, University of Vermont, Burlington, Vermont 05405, U.S.A.

ECONOMICAL SPACECRAFT TO INVESTIGATE TEMPORARILY CAPTURED OBJECTS NEAR EARTH

Andrew E. Turner*

Temporarily Captured Objects (TCOs) are small asteroids captured by lunar gravity assists (LGAs). A TCO resides in Earth orbit, possibly for several years, until destroyed by a lunar or an Earth impact, or re-ejected by an LGA into deep space. TCOs could contain valuable minerals, thus permitting asteroid mining to commence without the investment of launching to deep space and the long light-time delays associated with operations there. This paper discusses a proposed spacecraft orbiting the Sun-Earth L1 point to search for TCOs optically using reflected Sunlight, also to undertake close passes by selected TCOs following the L1 Observatory phase. [View Full Paper]

* Senior Engr. Specialist, Advanced Program & Systems, Space Systems Loral (SSL), 3825 Fabian Way, MS G-54, Palo Alto, California 94303-4604. Senior Member AIAA.

AAS 17-221

NASA DOUBLE ASTEROID REDIRECTION TEST (DART) LOW-THRUST TRAJECTORY CONCEPT

Martin T. Ozimek* and Justin A. Atchison*

The Double Asteroid Redirection Test (DART) mission is the first flight test of a kinetic impactor at an asteroid. DART targets the binary system Didymos, where it will measurably change the orbit period of the secondary member. Following a formal trade study, the mission will use the NASA Evolutionary Xenon Thruster (NEXT) ion propulsion system, representing the first in-space operation of the thruster. This paper presents the new low-thrust trajectory, including mission objectives and constraints, the trajectory design approach, the concept-of-operations, and results of key trade studies. [View Full Paper]

* Senior Professional Staff, The Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel, Maryland 20723, U.S.A.

AAS 17-231

AN IMPROVED METHOD FOR CHARACTERIZING SMALL BODY DENSITY DISTRIBUTION

Siamak G. Hesar,[*] Andrew French,[†] Daniel J. Scheeres,[‡]
Yu Takahashi[§] and Jay W. McMahon[**]

An improved method for characterizing the density distribution of small bodies is presented in this paper. It utilizes a set of interior gravity field spherical harmonics expansions to place constraints on the likely distribution of the density inhomogeneities inside a body of mass. An interior spherical harmonics expansion is defined within the interior Brillouin sphere that extends down to the surface of a body of mass allowing it to be closer and more sensitive to the regional density dispersions. Furthermore, due to the way the interior expansion is constructed, using multiple expansion fields provides added geometry advantage to the problem. [View Full Paper]

[*] Research Associate, Colorado Center for Astrodynamics Research, University of Colorado, Boulder, Colorado 80309, U.S.A.
[†] Graduate Research Assistant, Colorado Center for Astrodynamics Research, University of Colorado, Boulder, Colorado 80309, U.S.A.
[‡] A. Richard Seebass Chair Professor, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado 80309, U.S.A.
[§] Navigation Engineer, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, U.S.A.
[**] Assistant Research Professor, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado 80309, U.S.A.

AAS 17-240

A PRECISE MODEL FOR SMALL BODY THERMAL RADIATION PRESSURE ACTING ON SPACECRAFT: APPLICATIONS TO OSIRIS-REX SPACECRAFT*

Siamak G. Hesar,† Daniel J. Scheeres,‡
Jay W. McMahon§ and Benjamin Rozitis**

A precise representation of small body surface thermal radiation pressure effects acting on orbiting spacecraft is discussed. This paper is an extension to an earlier paper by the same authors that looks at the implementation of a precise framework for representing solar radiation pressure effects on spacecraft orbiting small bodies. The discussed model utilizes a general Fourier series expansion to compute small body surface thermal radiation pressure. Taking into account the shape and surface properties of spacecraft, this method allows for the precise representation of thermal radiation perturbation effects that may easily be used in the generation of precise orbit determination solutions. After presenting the general model, we provide an example application of the model for the OSIRIS-REx spacecraft in orbit about Asteroid (101955) Bennu. Via simulation studies, we evaluate the effect of mis-modeling the thermal radiation pressure on the spacecraft and study the utilization of the proposed method for generating precise orbit determination solutions. [View Full Paper]

---

* This paper is submitted to the *Journal of Guidance, Control, and Dynamics* (AIAA) and is currently under review.
† Research Associate, Colorado Center for Astrodynamics Research, University of Colorado, Boulder, Colorado 80309, U.S.A.
‡ A. Richard Seebass Chair Professor, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado 80309, U.S.A.
§ Assistant Research Professor, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado 80309, U.S.A.
** RAS Research Fellow, Planetary and Space Sciences, School of Physical Sciences, The Open University, Milton Keynes, MK7 6AA, United Kingdom.

AAS 17-252

INFLATABLE SAIL FOR ASTEROID CAPTURE

Samuel W. Ximenes,[*] Barney Gorin,[†] Roy Hartfield,[‡] David Cicci,[§] Bruce Tatarchuk[**] and Marek Teichmann[††]

Addressed is a unique and innovative approach for robotically capturing an irregularly shaped asteroid, spinning in its lowest energy state. The concept permits capture of higher-aspect ratio asteroids outside of a mean 4-10m diameter. The concept employs an innovative, large "Sail" capture mechanism. The Sail is deployed beyond the spacecraft envelope and can adapt to an asteroid with a long dimension significantly larger than 10 meters. [View Full Paper]

[*] Managing Partner/Space Architect, XArc Exploration Architecture Corporation, San Antonio, Texas 78232, U.S.A.
[†] Vice President, GoVentures, Inc., Gaithersburg, Maryland 20878, U.S.A.
[‡] Ph.D., Walt and Virginia Woltosz Professor, Aerospace Engineering, Auburn University, Auburn, Alabama 36849, U.S.A.
[§] Ph.D., Professor, Aerospace Engineering Department, Auburn University, Auburn, Alabama 36849 U.S.A.
[**] Ph.D., Charles E. Gavin III Professor of Chemical Engineering/Director, Center for Microfibrous Materials Manufacturing, Auburn University, Auburn, Alabama 36849, U.S.A.
[††] Ph.D., Chief Technology Officer, CM Labs Simulations Inc., Montreal, Quebec H3C 1T2, Canada.

AAS 17-257

SENSITIVITY OF THE ASTEROID REDIRECT ROBOTIC MISSION (ARRM) TO LAUNCH DATE AND ASTEROID STAY TIME

Melissa L. McGuire,[*] Laura M. Burke,[†] Steven L. McCarty,[‡]
Nathan J. Strange,[§] Min Qu,[**] Haijun Shen[††] and Matthew A. Vavrina[‡‡]

National Aeronautics and Space Administration's (NASA's) proposed Asteroid Redirect Mission (ARM) is being designed to robotically capture and then redirect an asteroidal boulder into a stable orbit in the vicinity of the moon, where astronauts would be able to visit and study it.[1] The current reference trajectory for the robotic portion, ARRM, assumes a launch on a Delta IV H in the end of the calendar year 2021, with a return for astronaut operations in cislunar space in 2026. The current baseline design allocates 245 days of stay time at the asteroid for operations and boulder collection. This paper outlines analysis completed by the ARRM mission design team to understand the sensitivity of the reference trajectory to launch date and asteroid stay time. [View Full Paper]

[*] Lead Mission Design Engineer, ARRM Mission Design Deputy, Mission Architecture and Analysis Branch, NASA Glenn Research Center, 21000 Brookpark Road, Cleveland, Ohio 44135, U.S.A. E-mail: melissa.l.mcguire@nasa.gov.
[†] Aerospace Engineer, Mission Architecture and Analysis Branch, NASA Glenn Research Center, 21000 Brookpark Road, Cleveland, Ohio 44135, U.S.A. E-mail: Laura.M.Burke@nasa.gov.
[‡] Aerospace Engineer, Mission Architecture and Analysis Branch, NASA Glenn Research Center, 21000 Brookpark Road, Cleveland, Ohio 44135, U.S.A. E-mail: Steven.McCarty@nasa.gov.
[§] ARRM Mission Design Manager, Mission Design and Navigation Section, Jet Propulsion Laboratory, 4800 Oak Grove Dr. Pasadena, California 91109, U.S.A. E-mail: Nathan.J.Strange@jpl.nasa.gov.
[**] Staff Scientist, Analytical Mechanics Associates, Inc., 21 Enterprise Parkway, Suite 300, Hampton, Virginia 23666, U.S.A. E-mail: min.qu-1@nasa.gov.
[††] Supervising Engineer, Analytical Mechanics Associates, Inc., 21 Enterprise Parkway, Suite 300, Hampton, Virginia 23666, U.S.A. E-mail: Haijun.shen@nasa.gov.
[‡‡] Senior Systems Engineer, a.i. solutions, 4500 Forbes Boulevard Suite 300, Lanham, Maryland 20706, U.S.A. E-mail: matthew.a.vavrina@nasa.gov.

AAS 17-258

DYNAMICAL STRUCTURES FOR THE STUDY OF IRREGULAR GRAVITY FIELDS

Simon Tardivel[*] and Daniel J. Scheeres[†]

This paper introduces dynamical structures relevant for the study of the effective gravity field of small bodies. The variety of shapes that small bodies display hinders the analytical study of their gravity fields. Yet, they all exhibit the same fundamental dynamical structure. Introducing the z^* plane, the ridge line and its equilibrium points, and the potential barrier, this work allows to generalize previous analytical studies on simpler fields (e.g. CR3BP). These dynamical structures are defined, described, and computed for different bodies. They are useful for the description of the dynamical environment of the small body, e.g. equilibrium points and entrapment. [View Full Paper]

[*] Department of Aerospace Engineering Sciences, The University of Colorado Boulder, M/S-431, UCB, Boulder, Colorado 80309-0431, U.S.A. E-mail: simon.tardivel@colorado.edu.

[†] Department of Aerospace Engineering Sciences, The University of Colorado Boulder, M/S-429, UCB, Boulder, Colorado 80309-0431, U.S.A. E-mail: scheeres@colorado.edu.

AAS 17-260

HYDRAZINE CONSERVATION FOR THE DAWN SPACECRAFT OPERATIONS AT THE DWARF PLANET CERES*

Ryan S. Lim,† Brett A. Smith,‡ Antonette W. Feldman§ and Mana Salami**

Dawn is a low-thrust interplanetary spacecraft currently orbiting the dwarf planet Ceres. After successfully completing its Vesta and Ceres prime missions, Dawn is now in its extended mission, continuously exploring Ceres. After losing the second reaction wheel assembly at the end of the Vesta mission, the feasibility of the Ceres mission was at risk due to the potentially significant increase in hydrazine consumption from using only the reaction control system thrusters. This paper summarizes the intense, collaborative efforts undertaken by the project to conserve hydrazine prior to Vesta departure, during cruise to Ceres, and throughout the Ceres mission. The project's efforts in minimizing the number of turns are discussed. A special emphasis is given to describing various efforts taken by the Attitude Control Subsystem team in an attempt to reduce hydrazine consumption. These efforts include: changing default slew rates, control gain tuning, changing nadir pointing strategy with Ahead Cross Nadir pointing, hybrid control implementation using hydrazine based thrusters and two remaining reaction wheels, optimal science turn location analysis, and reaction wheel angular momentum management strategies for reducing the number of momentum unloadings. In addition to the Attitude Control Subsystem team's efforts, the Mission Design and Navigation team's efforts taken in designing hydrazine friendly orbit transfers are discussed. The trade study performed collaboratively by the Attitude Control Subsystem team and the Science Operations Support Team in choosing hydrazine friendly off-nadir targets is also discussed. Various simulation results are presented and compared against actual flight data obtained. Lastly, remaining hydrazine status at the end of the prime Ceres mission and the hydrazine management planning for the extended mission are discussed. [View Full Paper]

† Technical Staff, Planning and Execution Systems Section. M/S 264-853, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109-8099, U.S.A.
E-mail: Ryan.S.Lim@jpl.nasa.gov.
‡ Technical Staff, Guidance and Control Section. M/S 321-550G, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109-8099, U.S.A. E-mail: Brett.A.Smith@jpl.nasa.gov.
§ Technical Staff, Flight Systems Engineering, Integration and Test Section. M/S 264-847, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109-8099, U.S.A.
E-mail: Antonette.W.Feldman@jpl.nasa.gov.
** Technical Staff, Flight Systems Engineering, Integration and Test Section. M/S 321-550J, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109-8099, U.S.A.
E-mail: Mana.Salami@jpl.nasa.gov.

AAS 17-270

HYBRID GUIDANCE CONTROL FOR A HYPERVELOCITY SMALL SIZE ASTEROID INTERCEPTOR VEHICLE

Melak M. Zebenay,[*] Joshua R. Lyzhoft[†] and Brent W. Barbee[‡]

Near-Earth Objects (NEOs) are comets and/or asteroids that have orbits in proximity with Earth's own orbit. NEOs have collided with the Earth in the past, which can be seen at such places as Chicxulub crater, Barringer crater, and Manson crater, and will continue in the future with potentially significant and devastating results. Fortunately, such NEO collisions with Earth are infrequent, but can happen at any time. Therefore, it is necessary to develop and validate techniques as well as technologies necessary to prevent them. One approach to mitigate future NEO impacts is the concept of high-speed interceptor. This concept is to alter the NEO's trajectory via momentum exchange by using kinetic impactors as well as nuclear penetration devices. The interceptor has to hit a target NEO at relative velocity which imparts a sufficient change in NEO velocity. NASA's Deep Impact mission has demonstrated this scenario by intercepting Comet Temple 1, 5 km in diameter, with an impact relative speed of approximately 10 km/s. This paper focuses on the development of hybrid guidance navigation and control (GNC) algorithms for precision hypervelocity intercept of small sized NEOs. The spacecraft's hypervelocity and the NEO's small size are critical challenges for a successful mission as the NEO will not fill the field of view until a few seconds before intercept. The investigation needs to consider the error sources modeled in the navigation simulation such as spacecraft initial state uncertainties in position and velocity. Furthermore, the paper presents three selected spacecraft guidance algorithms for asteroid intercept and rendezvous missions. The selected algorithms are classical Proportional Navigation (PN) based guidance that use a first order difference to compute the derivatives, Three Plane Proportional Navigation (TPPN), and the Kinematic Impulse (KI). A manipulated Bennu orbit that has been changed to impact Earth will be used as a demonstrative example to compare the three methods. In addition, a hybrid approach that is a combination between proportional navigation and kinematic impulse will be investigated to find an effective, error tolerant, and power saving approach. A 3-dimension mission scenario for both the asteroid and the interceptor spacecraft software simulator is developed for testing of the controllers. The current result demonstrates that a miss distance magnitude of less than 10m is found using the PN and TPPN guidance laws for small asteroid in the presence of error in the spacecraft states. Moreover, the paper presents these results and also the hybrid control approach simulation results. [View Full Paper]

[*] NASA Postdoctoral Researcher, Solar System Exploration Division, OAK Ridge Institute for Science and Education, Oak Ridge, Tennessee 37831, U.S.A. E-mail: Melak.m.zebenay@nasa.gov. AIAA Member.
[†] Student Trainee, Navigation and Mission Design Branch, NASA, Iowa State University, Ames, Iowa 50011, U.S.A.
[‡] Ast, Aerospace Veh Design & MSN Analyst, Navigation and Mission Design Branch, NASA, NASA Goddard Space Flight Center, Greenbelt, Maryland 20770, U.S.A.

AAS 17-284

DYNAMICS AND MODELING OF A BINARY ASTEROID SYSTEM WITH APPLICATIONS TO 65803 DIDYMOS

Alex B. Davis[*] and Daniel J. Scheeres[†]

We apply a new methodology for computing the dynamics of the Full Two-Body Problem to investigate the dynamics and equilibria of a binary asteroid system. The goal of this study is to understand the comparative effects of higher order shape model expansion levels and parameters on the behavior of a binary asteroid system and to apply these higher order shape models to equilibria computations of binary systems. For our model we use the detailed 1998 KW4b secondary asteroid model scaled to the 65803 Didymos system, in order to help predict expected behaviors for the AIDA mission which will explore this system in 2020. We find that a fourth order expansion is sufficient for simulations to reach centimeter level accuracy and also identify system behaviors linked to primary and secondary asteroid shape model parameters. [View Full Paper]

[*] Ph.D. Pre-Candidate, Colorado Center for Astrodynamics Research, University of Colorado, Boulder, Colorado 80309, U.S.A.

[†] A. Richard Seabass Chair Professor, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado 80309, U.S.A.

AAS 17-305

SEARCH FOR STABLE REGIONS IN THE IRREGULAR HAUMEA-NAMAKA BINARY SYSTEM

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

This work aims to describe the dynamics of small spacecraft around a binary system comprised by the irregular bodies Haumea and Namaka. The dynamics of Haumea and Namaka is assumed as a full two body problem, considering the inclination of Namaka. The equations of motion of the spacecraft are written incorporating the information coming from this model and also considering the eccentricity of Namaka's orbit, resulting in the "Elliptic Restricted Full Three Body Problem". We found regions of interest in the system, formed by periodic and quasi-periodic orbits. The integral of the acceleration technique is used to compare the classical "Elliptic Restricted Three Body Problem" with the Full problem, to find regions where the two models have minimum differences.

[View Full Paper]

[*] Postdoctoral fellow, DMC, National Institute for Space Research - INPE, São José dos Campos, Brazil. E-mail: diogo.sanchez@inpe.br.

[†] Hsu Lo Distinguished Professor of Aeronautics and Astronautics, School of Aeronautics and Astronautics, Purdue University, 701 West Stadium Avenue, West Lafayette, Indiana 47907-2045, U.S.A. E-mail: howell@purdue.edu.

[‡] President of the Board of the Graduate School at INPE in Brazil, National Institute for Space Research - INPE, São José dos Campos, Brazil. E-mail: antonio.prado@inpe.br.

AAS 17-306

APPLICATIONS OF REFINED LAGRANGIAN COHERENT STRUCTURES TO CAPTURE NEAR-EARTH ASTEROIDS IN NONAUTONOMOUS MULTI-BODY PROBLEM

Xiaoyu Wu,[*] Haibin Shang[†] and Xiao Qin[‡]

This paper discusses the applications of refined Lagrangian coherent structures to capture Near-Earth Asteroids (NEA) in nonautonomous multi-body system. Two types of nonautonomous multi-body model, incorporating the influence of the Jupiter and the Moon are constructed. We address the feasibility of capturing an NEA asteroid to the vicinity of the Moon. The capture trajectory is constructed by two segments, that the target transfers to Sun-Earth L_2 substitution and then it transfers to Earth-Moon L_2 substitution. For the first segment, a method is developed utilizing FTLE field and attracting LCS to evaluate the required velocity increment for the asteroid to the destination. The second segment, that the asteroid transfers to the vicinity of the Moon, is connected by several transport barriers identified using the refined Lagrange coherent structures. The results reveal the capture mechanism for asteroids to the Moon in nonautonomous multi-body systems. A capture example, a 10-m object asteroid 2009BD, is presented to perform the capture process. The required transfer velocity and time are calculated in contrast to these of the classical methods. [View Full Paper]

[*] Ph.D. Candidate, Key Laboratory of Dynamics and Control of Flight Vehicle, Beijing Institute of Technology, 5 South Zhongguancun Street, Haidian District, Beijing 100081, China. AIAA Student Member.
[†] Associate Professor, Key Laboratory of Dynamics and Control of Flight Vehicle, Beijing Institute of Technology, 5 South Zhongguancun Street, Haidian District, Beijing 100081, China.
[‡] Ph.D. Candidate, Key Laboratory of Dynamics and Control of Flight Vehicle, Beijing Institute of Technology, 5 South Zhongguancun Street, Haidian District, Beijing 100081, China.

AAS 17-315

SENSITIVITY ANALYSIS OF SURFACE FEATURE NAVIGATION USING STEREOPHOTOCLINOMETRY

Andrew J. Liounis,[*] Coralie Jackman,[†]
Kenneth Getzandanner[*] and Leilah McCarthy[‡]

Missions that plan to orbit and navigate about small bodies frequently need to rely on optical navigation (OpNav) in order to generate relative state information between the spacecraft and the target. The current state of the art for OpNav in close proximity to a small body is the process of Stereophotoclinometry (SPC), which uses images to generate a three-dimensional model of the body, and then uses the produced model to navigate about the body. This paper performs sensitivity analysis on the navigation portion of SPC through the use of synthetic images of the asteroid Bennu. Results are presented in the form of measurement residuals and point solutions for camera position and pointing.

[View Full Paper]

[*] Aerospace Engineer, Navigation and Mission Design Branch (Code 595), NASA Goddard Spaceflight Center, Greenbelt, Maryland 20771, U.S.A.
[†] Lead Optical Navigation Engineer, Space Navigation and Flight Dynamics Practice, KinetX, Inc., 21 W. Easy Street, Ste. 108, Simi Valley, California 93065, U.S.A.
[‡] Optical Navigation Engineer, Space Navigation and Flight Dynamics Practice, KinetX, Inc., 21 W. Easy Street, Ste. 108, Simi Valley, California 93065, U.S.A.

AAS 17-326

THE DYNAMICS OF COMET SHOEMAKER-LEVY 9: INITIAL CAPTURE PHASE

Travis Swenson,[*] Robyn Woollands[†] and Martin Lo[‡]

The impact of Comet Shoemaker-Levy 9 (SL9) with Jupiter in 1994 was the ultimate confirmation of Eugene Shoemaker's theory that impacts are a common, fundamental process in the Solar System. On Earth, asteroid impacts have produced several near extinction level events. We tend to visualize these collisions as billiard balls hitting one another. But how, exactly, do they occur? The actual dynamics is much more complex and subtle because it is highly nonlinear and involves chaos in the Three-Body Problem. In this paper we investigate the effects of Lyapunov orbits, halo orbits, and their associated invariant manifolds, on the orbital motion of SL9. We demonstrate that periodic orbits act as gateways to Jupiter, and their invariant manifolds control the dynamics of SL9 during the Initial Capture Phase. [View Full Paper]

[*] Ph.D. Candidate, Department of Aeronautics and Astronautics, Stanford University, Stanford, California 94305-4035, U.S.A. E-mail: swens558@gmail.com.
[†] Graduate Research Assistant, Department of Aerospace Engineering, Texas A&M University, College Station, Texas 77843-3141, U.S.A. E-mail: robyn.woollands@gmail.com.
[‡] Technologist, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, U.S.A. E-mail: martin.w.lo@jpl.nasa.gov.

AAS 17-346

AN ANALYSIS OF LOW-THRUST ORBITAL MANEUVERS AROUND SMALL BODIES

**Donald H. Kuettel III,[*] Jay W. McMahon,[†]
Alessandro Vanzella[*] and Michael Van den Broeck[*]**

This paper examines the maneuverability of a spacecraft using low-thrust propulsion around small bodies such as asteroids and comets. Due to the low gravity of these bodies, spacecraft in orbit are able to perform complicated orbital maneuvers with little thrust. Current small body missions (e.g., OSIRIS-Rex and Rosetta) use chemical thrusters which are inefficient for maneuvering in this low gravity environment. It is hypothesized that low-thrust propulsion may be used to more efficiently maneuver spacecraft in this environment. This paper studies the orbital characteristics and maneuver costs of small bodies using asteroid 101955 Bennu as a test environment. [View Full Paper]

[*] Graduate Research Assistant, Colorado Center for Astrodynamics Research, University of Colorado - Boulder, 431 UCB, Boulder, Colorado 80309, U.S.A.

[†] Assistant Professor, Colorado Center for Astrodynamics Research, University of Colorado - Boulder, 431 UCB, Boulder, Colorado 80309, U.S.A.

AAS 17-357

TIME-DELAYED FEEDBACK CONTROL OF HOVERING AND ORBITING ABOUT ASTEROIDS

Haiyang Li[*] and Hexi Baoyin[†]

In asteroid exploration, hovering and orbiting the asteroid are necessary before further operation. Dynamic characteristics about asteroids are mainly equilibrium points and periodic orbits. Hovering on the natural equilibrium points and orbiting on the natural periodic orbits about asteroids are efficient and economical. However, due to the presence of orbit-determination and model-uncertainly error, the motion will be extremely difference. Time-delayed feedback control is used to solve this problem. Orbit-determination and model-uncertainly errors are formulated. Adaptive gain matrix algorithm and delay time determination method are proposed. Simulations prove that control method presented in this paper is effective. [View Full Paper]

[*] Ph.D. Candidate, School of Aerospace Engineering, Tsinghua University, Beijing, 100084, China.
E-mail: lihy15@mails.tsinghua.edu.cn.
[†] Professor, School of Aerospace Engineering, Tsinghua University, Beijing, 100084, China. Senior Member AIAA.
E-mail: baoyin@tsinghua.edu.cn.

AAS 17-371

FROM SIMPLIFIED TO COMPLEX SMALL-BODY MODELS: SENSITIVITY ANALYSIS OF PERIODIC ORBIT SETS[*]

Alex J. Pini,[†] Benjamin F. Villac[‡] and Rodney L. Anderson[§]

A previous study introduced the use of clustering as a tool to support mission designers in organizing sets of ballistic orbits for small-body missions. In that study, periodic orbits generated in simplified dynamical models were examined, leading to the identification of attractive characterization orbits. This paper furthers that study by analyzing the sensitivity of these periodic orbits when exposed to various perturbations. In particular, the issue of transferring the initial conditions to higher fidelity models and the characterization of the resulting behavior is explored in light of the underlying dynamics. The asteroid 2008 EV5 is selected as a test case. [View Full Paper]

[†] Systems Engineer, a.i. solutions, Inc., NASA GSFC, B11 S222, Greenbelt, Maryland 20771, U.S.A.
[‡] Consulting Systems Engineer, a.i. solutions, Inc., 4500 Forbes Blvd., Suite 300, Lanham, Maryland 20706, U.S.A.
[§] Technologist, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, M/S 301-121, Pasadena, California 91109, U.S.A.

SOLAR SAIL ORBITAL MOTION ABOUT ASTERIODS AND BINARY ASTEROID SYSTEMS

Jeannette Heiligers[*] and Daniel J. Scheeres[†]

While SRP is often considered an undesirable effect, especially for missions to small bodies like asteroids and binary asteroid systems, this paper utilizes the SRP on a solar sail to generate artificial equilibrium points (AEPs) and displaced periodic orbits in these systems. While the solar sail dynamics for the single asteroid case are described using the Hill + SRP problem, those for the binary system are either described in the Hill four-body + SRP problem or the full bi-circular + SRP problem. The results for the single asteroid case include solar sail acceleration contours to remain stationary with respect to the asteroid on either the Sun-lit or dark side of the asteroid and either in or above its orbital plane. Using a combination of analytical and numerical methods, i.e., the Lindstedt-Poincaré method and a differential corrector, orbits around these AEPs can be found. By switching to the Hill four-body problem and employing a direct multiple shooting method, these orbits can be extended to a binary system where the effect of the smaller asteroid is an oscillatory motion around the orbits found for the single asteroid case. Finally, by switching to the bi-circular + SRP problem, AEPs can once again be obtained, though their location becomes time-dependent due to the changing direction of the Sun-vector. However, high above the binary system's orbital plane, the AEPs trace out a circular orbit that suggests the existence of so-called pole-sitter-like orbits. Using an analytical inverse method and a numerical differential corrector, the results indeed show families of solar sail periodic orbits above the binary system's orbital plane. Though all orbits, both in the single asteroid case and the binary system, are linearly unstable, they exist for near-term solar sail technology and for a simple steering law where the sail remains at a fixed attitude with respect to the Sun. These orbits therefore allow unique, geostationary-equivalent vantage points from where to monitor the asteroid(s) over extended periods of time. [View Full Paper]

[*] Marie Curie Research Fellow, Delft University of Technology, Faculty of Aerospace Engineering, Kluyverweg 1, 2629 HS Delft, the Netherlands and University of Colorado, Department of Aerospace Engineering Sciences, Colorado Center for Astrodynamics Research, Boulder, Colorado 80309, U.S.A. E-mail: M.J.Heiligers@tudelft.nl.

[†] A. Richard Seebass Endowed Chair Professor, University of Colorado Boulder, Department of Aerospace Engineering Sciences, Colorado Center for Astrodynamics Research, Boulder, Colorado 80309, U.S.A.
E-mail: Scheeres@colorado.edu.

AAS 17-380

NEAR EARTH ASTEROIDS CAPTURE TO LUNAR ORBITS USING RESONANT GRAVITY ASSISTS

Changchun Bao,[*] Hongwei Yang,[†] Jingyang Li[‡] and Hexi Baoyin[§]

In this paper, a trajectory design approach for capturing NEAs to a lunar orbit is presented. There are no NEAs that can be captured by moon naturally because of the Moon's weak gravitational field. Therefore, leveraging techniques and lunar gravity assists are used in the capturing process to decrease the delta-V of the capturing mission. Leveraging techniques can reduce the relative NEAs velocity to the Moon by applying a smaller impulse at the apogee of the asteroid. First, we plot the leveraging graph using the leveraging techniques and design the NEAs capturing orbit easily through the leveraging graph. Then, efficiency of the leveraging and flight time of capturing process is computed. Finally, a NEAs capture numerical example to lunar orbit using the leveraging graph is provided to demonstrate the resonant gravity-assists method. [View Full Paper]

[*] Ph.D. Candidate, School of Aerospace Engineering, Tsinghua University, Beijing 100084, China.
E-mail: imut007@163.com.
[†] Ph.D. Candidate, School of Aerospace Engineering, Tsinghua University, Beijing 100084, China.
E-mail: yang.hw.thu@gmail.com.
[‡] Assistant Researcher, School of Aerospace Engineering, Tsinghua University, Beijing 100084, China.
E-mail: lijing-yang.thu@hotmail.com.
[§] Professor, School of Aerospace Engineering, Tsinghua University, Beijing 100084, China.
E-mail: baoyin@tsinghua.edu.cn.

AAS 17-397

DYNAMICS OF A SPACECRAFT ORBITING A BINARY ASTEROID

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

This work includes analytical and numerical studies of the motion of spacecrafts orbiting binary asteroid systems. The binary system is modeled using different assumptions, from two point masses to full irregular bodies, showing the impact of the irregular gravity field in the lifetime of the orbits. The initial orbit of the spacecraft is defined by the three classical Keplerian elements: semi-major axis, eccentricity and inclination, while the other elements are assumed to be zero. The equations of motion are derived from the Lagrange Equations. This paper maps the orbits by measuring their lifetime before a collision with an asteroid or before the escape from system. [View Full Paper]

[*] National Institute for Space Research, São Jose dos Campos, Brazil, 12227-010. E-mail: thais.oliveira@inpe.br.
[†] National Institute for Space Research, São Jose dos Campos, Brazil, 12227-010. E-mail: antonio.prado@inpe.br.

AAS 17-404

GRAVITATIONAL POTENTIAL MODELING OF NEAR-EARTH CONTACT BINARIES

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

A significant component of recent space exploration has been unmanned mission to comets and asteroids. The increase in interest for these bodies necessitates an increase in demand for higher fidelity trajectory simulations in order to assure mission success. Most methods that are available for simulating trajectories about asymmetric bodies assume they are of uniform density. Here we propose a hybrid method that merges a mascon model and a spherical harmonic model using the Brillouin sphere as the interface. This joint model will be used for simulating trajectories about variable density bodies. In particular, we will look at contact binaries which are bodies consisting of two different densities. [View Full Paper]

[*] Graduate Student in Mechanical Engineering, Department of Mechanical Engineering, University of Vermont, Burlington, Vermont 05405, U.S.A.

[†] Professor of Mechanical Engineering, Department of Mechanical Engineering, University of Vermont, Burlington, Vermont 05405, U.S.A.

AAS 17-422

SMALL BODY SPIN-STATE DETERMINATION USING LANDED TRANSPONDERS

Andrew S. French[*] and Jay W. McMahon[†]

A new method for small body spin-state estimation is presented here. This paper investigates the effectiveness of using landed radiometric transponders to estimate torque-free rigid body dynamics. Solution accuracy is quantified in terms of measurement quality to determine if landed transponders can be used to improve upon current methods, such as ground based radar and satellite based optical tracking. Accurate spin-state characterization of asteroids and comets is vitally important to both mission navigators and scientists as the rotation rate and pole orientation can be used to place constraints on internal density distributions and provide insights into rotational evolution and history.

[View Full Paper]

[*] Graduate Research Assistant, Colorado Center for Astrodynamics Research, University of Colorado, Boulder, Colorado 80309, U.S.A.

[†] Assistant Professor, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado 80309, U.S.A.

ASTEROID GRAVITATIONAL MODELS USING SURFACE-CONCENTRATIONS

J. M. Pearl* and D. L. Hitt†

A number of recent and future missions to irregularly shaped asteroids have initiated an interest in accurately modeling the irregular gravitational field of these bodies. Close to highly irregular asteroids this is often accomplished using the polyhedral model. This method uses a small number of computational elements because only the surface is discretized; however, the number of computations required per element is large. As such, a simplification of the polyhedral model is proposed that approximates each face of the surface mesh as a surface-concentration. The simplified surface-concentration model and the full polyhedral model are compared using a sphere as a test-case so that the accuracy of both methods can be compared to an analytical solution. Both methods are then applied to surface meshes of Asteroid 24153 Itokawa to assess their abilities to model irregular bodies. For a given level of surface resolution, the surface-concentration model is found to be 30_ faster than the polyhedral model with only a marginal reduction in accuracy at sufficiently large altitudes. Moreover, for meshes requiring equivalent CPU-times the surface-concentration model is found to be over an order of magnitude more accurate.

[View Full Paper]

* Graduate Student in Mechanical Engineering, Department of Mechanical Engineering, University of Vermont, Burlington, Vermont 05405, U.S.A.

† Professor of Mechanical Engineering, Department of Mechanical Engineering, University of Vermont, Burlington, Vermont 05405, U.S.A.

COMPARING THE COMPUTATIONAL EFFICIENCY OF POLYHEDRAL AND MASCON GRAVITY MODELS

J. M. Pearl* and D. L. Hitt†

A number of recent missions by space agencies to irregularly shaped asteroids have spawned an interest in accurately modeling their irregular gravitational fields. Two common methods for approximating these irregular gravity fields are the polyhedral model and the mass-concentration model. The polyhedral model employs Gauss's theorem to calculate gravitational acceleration from a closed surface mesh. The mass-concentration model uses a finite number of point-masses, distributed throughout the interior of the body, to approximate the gravitational field. In the present study, the accuracy and computational efficiency of the mascon model and polyhedral model are directly compared. Finite volume meshes are used to distribution mascons. The unit sphere is used as a test-case allowing the error of both methods to be calculated analytically. Both models are then applied to the more practical case of asteroid 25143 Itokawa. Results indicate that, for the same computational expenditure, the polyhedral model is more accurate directly on the surface, however, off the surface the mascon model is more accurate.

[View Full Paper]

* Graduate Student in Mechanical Engineering, Department of Mechanical Engineering, University of Vermont, Burlington, Vermont 05405, U.S.A.

† Professor of Mechanical Engineering, Department of Mechanical Engineering, University of Vermont, Burlington, Vermont 05405, U.S.A.

NUMERICAL SIMULATION OF N-BODY ASTEROID AGGREGATION WITH GPU-PARALLEL HIERARCHICAL TREECODE ALGORITHM

Emmanuel Blazquez,[*] Fabio Ferrari[†] and Michèle Lavagna[‡]

Over the past years significant evidence has shown that asteroids with dimensions exceeding few hundreds of meters are gravitational aggregates of smaller bodies bound together only by gravitational forces.[1] The study of such complex bodies is motivated by the recent efforts by space agencies, trying to intercept or redirect near-Earth asteroids (DART, ARM missions), as well as the ever-expanding possibilities of reaching further objects such as Jupiter trojans. The development of models for orbital dynamics about gravitational aggregates, complex gravity fields around irregular objects and collisions between orbiters and asteroids is therefore required. This work presents a new modeling and implementation of a N-body numerical solver using a GPU-parallel Barnes-Hut implementation to evaluate the effects of gravitational interactions and the Chrono::Engine multi-physics simulation engine to simulate collisions between bodies and integrate the dynamics of the problem.[2] The code is successfully validated for different cases of study based on previous works by P. Michel and P. Tanga concerning collisional disruption and gravitational re-accumulation leading to formation of asteroid families in different energetic regimes and by comparing relevant results obtained for well-known dynamical scenarios.[3–5] Results of numerical simulations show good agreement with established theories and observations and confirm the ability of the developed code to predict natural aggregation phenomena. [View Full Paper]

[*] Graduate Student, Aerospace Science and Technology Department, Politecnico di Milano, via La Masa 34, 20156, Milano, Italy. E-mail: emmanuel.blazquez@mail.polimi.it.
[†] Ph.D. Candidate, Aerospace Science and Technology Department, Politecnico di Milano, via La Masa 34, 20156, Milano, Italy. E-mail: fabio1.ferrari@polimi.it.
[‡] Associate Professor, Aerospace Science and Technology Department, Politecnico di Milano, via La Masa 34, 20156, Milano, Italy. E-mail: michelle.lavagna@polimi.it.

AAS 17-469

MODELLING IRREGULAR SMALL BODIES GRAVITY FIELD VIA EXTREME LEARNING MACHINES

Roberto Furfaro,[*] Richard Linares,[†] Vishnu Reddy,[‡] Jules Simo[§] and Lucille Le Corre[**]

Close proximity operations around small bodies are extremely challenging due to their uncertain dynamical environment. Autonomous guidance and navigation around small bodies require fast and accurate modeling of the gravitational field for potential on-board computation. In this paper, we investigate a model-based, data-driven approach to compute and predict the gravitational acceleration around irregular small bodies. More specifically, we employ Extreme Learning Machine (ELM) theories to design, train and validate Single-Layer Forward Networks (SLFN) capable of learning the relationship between the spacecraft position and the gravitational acceleration. ELMs-base neural networks are trained without iterative tuning therefore dramatically reducing the training time. Analysis of performance in constant density models for 433 Eros and 25143 Itokawa show that ELM-based SLFN are able learn the desired functional relationship both globally and in localized areas near the surface. The latter results in a robust neural algorithm for on-board, real-time calculation of the gravity field needed for close-proximity operations near the asteroid surface. [View Full Paper]

[*] Assistant Professor, Department of Systems and Industrial Engineering, Department of Aerospace and Mechanical Engineering, University of Arizona, 1127 E. James E. Roger Way, Tucson, Arizona, 85721, U.S.A.

[†] Assistant Professor, Department of Aerospace Engineering and Mechanics, University of Minnesota, Minneapolis, Minnesota 55455-0153, U.S.A.

[‡] Assistant Professor, Department of Planetary Science, Lunar and Planetary Laboratory, University of Arizona, 1629 E University Blvd, Tucson, Arizona 85721, U.S.A.

[§] Lecturer, School of Engineering, University of Central Lancashire, Preston, Lancashire, PR1 2HE, United Kingdom.

[**] Research Scientist, Planetary Science Institute, 1700 East Fort Lowell, Suite 106, Tucson, Arizona 85719, U.S.A.

TRAJECTORY OPTIMIZATION

Session Chairs:

Session 2: Atri Dutta

Session 10: Ryan Russell

IMPROVED PROPULSION MODELING FOR LOW-THRUST TRAJECTORY OPTIMIZATION

Jeremy M. Knittel,[*] Jacob A. Englander,[*] Martin T. Ozimek,[†] Justin A. Atchison[†] and Julian J. Gould[‡]

Low-thrust trajectory design is tightly coupled with spacecraft systems design. In particular, the propulsion and power characteristics of a low-thrust spacecraft are major drivers in the design of the optimal trajectory. Accurate modeling of the power and propulsion behavior is essential for meaningful low-thrust trajectory optimization. In this work, we discuss new techniques to improve the accuracy of propulsion modeling in low-thrust trajectory optimization while maintaining the smooth derivatives that are necessary for a gradient-based optimizer. The resulting model is significantly more realistic than the industry standard and performs well inside an optimizer. A variety of deep-space trajectory examples are presented. [View Full Paper]

[*] Aerospace Engineer, Navigation and Mission Design Branch, NASA Goddard Space Flight Center, Greenbelt, Maryland 20771, U.S.A. Member AAS.
[†] Aerospace Engineer, Astrodynamics and Control Systems Group, The Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel, Maryland 20723, U.S.A. Member AAS.
[‡] Student, John Hopkins University.

AAS 17-243

NEAR OPTIMAL FINITE-TIME FEEDBACK CONTROL SYNTHESIS USING THE SDRE-BASED APPROACH EXTENDED FOR NONLINEAR TERMINAL HYPERSURFACES

Rajnish Sharma[*] and George W. P. York[†]

This paper presents a novel development to synthesize finite-time near optimal feedback control for nonlinear systems with nonlinear terminal constraints such as hypersurfaces. To design such terminal controllers, as a first development, the SDRE-based approach is extended for the fixed final time continuous optimal control problem (OCP) via solving the governing pointwise Hamilton-Jacobi-Bellman equation subject to the converted pseudo-linear dynamical system. Further, to utilize this new extension for a class of OCPs with terminal hypersurfaces, the procedure that successively obtains closely approximated tangent hyperplanes is introduced to establish the complete unified algorithm. To exhibit the performance, numerous nonlinear examples including space applications are illustrated with numerical details. The results are compared with the respective openloop solutions to demonstrate the efficacy of the novel approach which offers the synthesis of near optimal terminal feedback controller to attain the least cost-to-go for accomplishing exceedingly high terminal accuracy with no a priori knowledge of the optimal state at terminal hypersurface. [View Full Paper]

[*] Assistant Professor in the Department of Engineering and Aviation Sciences at University of Maryland Eastern Shore, Princess Anne, Maryland 21853, U.S.A. Visiting Professor at the United States Air Force Academy. E-mail: rsharma3@umes.edu.

[†] Associate Professor in the Department of Electrical and Electrical and Computer Engineering, United States Air Force Academy, Colorado Springs, Colorado 80920, U.S.A. E-mail: george.york@usafa.edu.

AAS 17-253

LOW-THRUST MANY-REVOLUTION TRAJECTORY OPTIMIZATION VIA DIFFERENTIAL DYNAMIC PROGRAMMING AND A SUNDMAN TRANSFORMATION

Jonathan D. Aziz,* Jeffrey S. Parker,† Daniel J. Scheeres‡ and Jacob A. Englander§

Low-thrust trajectories about planetary bodies characteristically span a high count of orbital revolutions. Directing the thrust vector over many revolutions presents a challenging optimization problem for any conventional strategy. This paper demonstrates the tractability of low-thrust trajectory optimization about planetary bodies by applying a Sundman transformation to change the independent variable of the spacecraft equations of motion to the eccentric anomaly and performing the optimization with differential dynamic programming. Fuel-optimal geocentric transfers are shown in excess of 1000 revolutions while subject to Earth's J_2 perturbation and lunar gravity. [View Full Paper]

* Ph.D. Candidate, Colorado Center for Astrodynamics Research, University of Colorado, Boulder, Colorado 80309, U.S.A.

† Adjunct Professor, Colorado Center for Astrodynamics Research, University of Colorado, Boulder, Colorado 80309, U.S.A.

‡ Distinguished Professor, A. Richard Seebass Endowed Chair, Colorado Center for Astrodynamics Research, University of Colorado, Boulder, Colorado 80309, U.S.A.

§ Aerospace Engineer, NASA/GSFC, Code 595, 8800 Greenbelt Road, Greenbelt, Maryland 20771, U.S.A.

AAS 17-273

ATMOSPHERIC MODELING USING ACCELEROMETER DATA DURING MARS ATMOSPHERE AND VOLATILE EVOLUTION (MAVEN) FLIGHT OPERATIONS

Robert H. Tolson,[*] Rafael A. Lugo,[†] Darren T. Baird,[‡] Alicia D. Cianciolo,[§] Stephen W. Bougher[**] and Richard M. Zurek[††]

The Mars Atmosphere and Volatile EvolutioN (MAVEN) spacecraft is a NASA orbiter designed to explore the Mars upper atmosphere, typically from 140 to 160 km altitude. MAVEN has performed several Deep Dip campaigns in which the orbit periapsis was lowered to an altitude range of 115 to 135 km. MAVEN accelerometer data were used during mission operations to estimate atmospheric parameters such as density, scale height, along-track gradients, and wave structures. These estimates were used to aid the MAVEN navigation team in planning maneuvers to raise and lower periapsis during Deep Dip operations. This paper describes the processes used to reconstruct atmosphere parameters from accelerometer data and presents comparisons between model and navigation-derived values.

[View Full Paper]

[*] Professor Emeritus, National Institute of Aerospace, 100 Exploration Way, Hampton Virginia 23666, U.S.A.
[†] Aerospace Engineer, Analytical Mechanics Associates, Inc., Hampton, Virginia 23666, U.S.A.
[‡] Aerospace Engineer, NASA Johnson Space Center, Houston, Texas 77058, U.S.A.
[§] Aerospace Engineer, NASA Langley Research Center, Hampton, Virginia 23666, U.S.A.
[**] Professor, Climate and Space Sciences and Engineering Department, University of Michigan, Ann Arbor, Michigan 48109, U.S.A.
[††] Aerospace Engineer, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, U.S.A.

AAS 17-281

ASTEROID DEFLECTION WITH SAFE HARBORS FOUND VIA NUMERICAL OPTIMIZATION

Bruce A. Conway,[*] Siegfried Eggl[†] and Daniel Hestroffer[‡]

If it were feasible, given the warning time of an actual hazardous asteroid approach, to conduct the deflection in such a way as to place the asteroid in a region of phase space that does not yield a significant future impact risk (i.e. a "safe harbor") with the Earth, this should certainly be done. In this work a numerical method is used to optimize all of the relevant mission parameters for a spacecraft to deflect an asteroid via impact. The objective of the numerical optimizer is to maximize the initial deflection obtained while assuring that subsequent close approach distances of the asteroid to the Earth are only increased by the initial deflection. [View Full Paper]

[*] Professor, IMCCE - Observatoire de Paris, Paris, France and Department of Aerospace Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, U.S.A.
[†] Post-Doctoral Associate, IMCCE - Observatoire de Paris, Paris, France.
[‡] Director, IMCCE - Observatoire de Paris, PSL Research University, CNRS, Paris, France.

AAS 17-299

GLOBAL SEARCH FOR LOW-ENERGY TRANSFERS TO THE MOON WITH LONG TRANSFER TIME

Kenta Oshima,* Francesco Topputo† and Tomohiro Yanao‡

The present paper globally searches for two-impulse, low-energy transfers to the Moon in the planar bicircular restricted four-body problem with transfer time up to 200 days. A grid search combined with a direct transcription and multiple shooting technique reveals numerous families of optimal low-energy solutions. We investigate characteristics of solutions in terms of two- and three-body parameters, and discuss a trade-off between time and cost (Δv) by exploring Pareto–optimal solutions, considering the presence or absence of lunar gravity assist. Analyzing orbital characteristics based on multi–body dynamics, we show useful perturbations of the Sun, Earth, and Moon to reduce Δv.

[View Full Paper]

* Ph.D. Candidate, Department of Applied Mechanics and Aerospace Engineering, Waseda University, Tokyo, 169-8555, Japan.

† Assistant Professor, Department of Aerospace Science and Technology, Politecnico di Milano, 20156, Milano, Italy.

‡ Associate Professor, Department of Applied Mechanics and Aerospace Engineering, Waseda University, Tokyo, 169-8555, Japan.

AAS 17-303

COMBINING NON-LINEAR PROGRAMMING AND HYPERHEURISTIC ALGORITHMS FOR LOW-THRUST TRAJECTORY OPTIMIZATION

Lake A. Singh,[*] Jose J. Guzman,[†] Christopher L. Ranieri,[‡] Demyan V. Lantukh[§] and Gregory Fruth[**]

This work reports on an effort to drive a non-linear programming (NLP) optimizer with a hyperheuristic MOEA in order to mitigate workflow challenges associated with traditional iterative, constructive NLP approaches. Calculus of variations and Non-linear programming approaches can efficiently and rapidly produce optimized low-thrust trajectories in complex design spaces. However, for non-globally convex function spaces, these approaches optimize locally. In contrast, hyperheuristic many-objective evolutionary algorithms efficiently identify globally optimal regions of the design space, even in the presence of discontinuities and large regions of infeasibility. Coupling hyperheuristics and NLP helps users avoid time consuming iteration by passing the task of construction to the hyperheuristic. [View Full Paper]

[*] Engineering Manager, The Aerospace Corporation, 14745 Lee Road, CH1-510, Chantilly, Virginia 20151, U.S.A.
[†] Engineering Specialist, The Aerospace Corporation, 14745 Lee Road, CH1-510, Chantilly, Virginia 20151, U.S.A.
[‡] Engineering Manager, The Aerospace Corporation, 2310 E. El Segundo Blvd., M4-942, El Segundo, California 90245, U.S.A.
[§] Member of the Technical Staff, The Aerospace Corporation, 2310 E. El Segundo Blvd., M4-942, El Segundo, California 90245, U.S.A.
[**] Director, The Aerospace Corporation, 2310 E. El Segundo Blvd., M4-942, El Segundo, California 90245, U.S.A.

AAS 17-309

TWO-IMPULSE EVOLUTIONARY OPTIMIZATION OF SATELLITE FORMATION TRAJECTORIES OVER MULTIPLE REVOLUTIONS WITH TOPOLOGICAL CONSTRAINTS

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

In this work we apply the evolutionary technique of Differential Evolution (DE) to topologically constrained trajectory optimization of a satellite formation limited to two-impulsive maneuvers considering a region of interest that spans multiple revolutions. The motivation and constraints for the problem are drawn from NASA's Magnetospheric Multi-Scale Mission (MMS). A single-revolution framework has been demonstrated to be capable of optimizing trajectories adhering to mission constraints. This two-impulse approach extends the amount of time considered during optimization such that trajectory optimization can be done in a manner that reduces the need for corrective maneuvers.

[View Full Paper]

[*] Graduate Student in Mechanical Engineering, University of Vermont, Burlington, Vermont 05405, U.S.A.
[†] Professor of Mechanical Engineering, University of Vermont, Burlington, Vermont 05405, U.S.A.

AAS 17-410

USING PARTICLE SWARM OPTIMIZATION FOR EARTH-RETURN TRAJECTORIES FROM LIBRATION POINT ORBITS

Mollik Nayyar[*] and David B. Spencer[†]

This paper presents a methodology to use particle swarm optimization to design optimal space trajectories from Lagrange point orbits to Earth orbits. We present an approximate, computationally inexpensive method to scan the available search space and obtain the locations and trajectories associated the with lowest ΔV, which can be used as an initial guess that can be later used in advanced methods to obtain ΔV optimal trajectories. The analysis suggests that it is possible to reach almost any inclination from the manifold of a halo Lagrange Point Orbit without incurring huge ΔV costs depends on the target location for insertion. Ways to improve upon the solver and the optimization algorithm are suggested.

[View Full Paper]

[*] Graduate Student, Department of Aerospace Engineering, The Pennsylvania State University, University Park, Pennsylvania 16802, U.S.A.

[†] Professor, Department of Aerospace Engineering, The Pennsylvania State University, University Park, Pennsylvania 16802, U.S.A.

AAS 17-416

MULTI-TIERED APPROACH TO CONSTELLATION MANEUVER OPTIMIZATION FOR LOW-THRUST STATION-KEEPING

Andris D. Jaunzemis,[*] Christopher W. T. Roscoe[†] and Marcus J. Holzinger[‡]

This paper presents a multi-tiered approach to constellation-wide optimization of low-thrust station-keeping maneuvers. Starting from the general problem of constellation maneuver optimization, a tractable solution is presented for station-keeping. The approach utilizes a gradient-descent algorithm to efficiently drive each satellite toward its nominal orbit, encapsulating this trajectory optimization in an outer-loop genetic algorithm to optimize within discrete and non-differentiable constellation-level constraints. The output trajectories are validated and refined in a high-fidelity environment using NASA's General Mission Analysis Tool. A concrete example with operational constraints is presented, and limits of the computation-driven assumptions in the tractable solution are assessed.

[View Full Paper]

[*] Graduate Research Assistant, Aerospace Engineering, Georgia Institute of Technology, Atlanta, Georgia 30332, U.S.A. E-mail: adjaunzemis@gatech.edu.

[†] Aerospace Engineer, Applied Defense Solutions, Inc., Columbia, Maryland 21044, U.S.A.
E-mail: croscoe@applieddefense.com.

[‡] Assistant Professor, Aerospace Engineering, Georgia Institute of Technology, Atlanta, Georgia 30332, U.S.A.
E-mail: holzinger@ae.gatech.edu.

AAS 17-429

A TIME-REGULARIZED, MULTIPLE GRAVITY-ASSIST LOW-THRUST, BOUNDED-IMPULSE MODEL FOR TRAJECTORY OPTIMIZATION

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

The multiple gravity-assist low-thrust (MGALT) trajectory model is a computationally efficient preliminary design algorithm, and provides an accurate estimation of the total mass budget that will be required by the flight-suitable integrated trajectory. However, it suffers from one major drawback, namely its temporal spacing of the control nodes. We introduce a variant of the MGALT transcription that utilizes either the generalized anomaly from the universal formulation of Kepler's equation or the true anomaly as a decision variable in addition to the trajectory phase propagation time. This results in two improvements over the traditional model. The first is that the maneuver locations are now at regular intervals of the chosen anomaly, rather than at locations separated by equal propagation times. The second is that the Kepler propagator now has as its independent variable the generalized anomaly, instead of time and thus becomes an iteration-free propagation method. The new algorithm is outlined, including the impact that this has on the computation of Jacobian entries for numerical optimization, and a motivating application problem is presented that illustrates the improvements that this model has over the original MGALT transcription. [View Full Paper]

* Ph.D. Candidate, Department of Aerospace Engineering, University of Illinois at Urbana-Champaign, Mail Code-236, 104 South Wright Street, Urbana, Illinois 61801, U.S.A. Member AAS, Student Member AIAA.

† Aerospace Engineer, Navigation and Mission Design Branch, NASA Goddard Space Flight Center, 8800 Greenbelt Road, Greenbelt, Maryland 20771, U.S.A. Member AIAA.

‡ Professor Emeritus, Department of Aerospace Engineering, University of Illinois at Urbana-Champaign, Mail Code-236, 104 South Wright Street, Urbana, Illinois 61801, U.S.A. Fellow AAS, Associate Fellow AIAA.

MINIMUM-TIME LOW THRUST ORBIT TRANSFERS USING THE METHOD OF PARTICULAR SOLUTIONS

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

We have developed a method for solving the minimum-time, constant, continuous low thrust, near circular-to-circular transfers using the *method of particular solutions* and collocation. The first step is to compute a sub-optimal solution by iteratively solving for the coefficients of the Chebyshev polynomials that parameterize the steering angle of the control vector. This unique implementation of minimum norm direct optimization is attractive in that it does not require partial derivatives, yet we have shown that we can accommodate a relatively high dimensional parameterization of the control variables. Once the sub-optimal solution has been obtained it is used as an initial guess to "warm start" a collocation algorithm. The collocation algorithm is simply used to generate a low fidelity solution for the costates (about 4 digit accuracy) that is fed as an initial guess to start the *method of particular solutions* shooting method. This low fidelity collocation solution is computed using finite difference derivatives and only a few iterations (and expensive matrix inversions) are required to produce an adequate initial guess. The *method of particular solutions*, which does not require partial derivatives to be computed or propagated, is extremely efficient and is used to solve the state/costate two-point boundary value problem by iterating on the initial costates that converge to a solution that satisfies the final boundary conditions in the minimum time-offlight. One approach for solving a minimum-time problem is to map time onto the fixed domain from 0 to 1, and append a trivial differential equation to the set of state equations that integrates to give an unknown free constant (final time). Since our basis functions are the orthogonal Chebyshev polynomials, we map time onto the domain from –1 to 1 where Chebyshev polynomials exist, and thus our algorithm minimizes time-of-flight while converging to the optimal minimum-time solution. We demonstrate the capability of our algorithm by computing an example orbit transfer from a medium Earth orbit (a = 26; 000 km) to rendezvous with a piece of debris in a geostationary orbit. [View Full Paper]

[*] Postdoctoral Research Associate, Department of Aerospace Engineering, Texas A&M University, TAMU 3141, College Station, Texas 77843-3141, U.S.A.
[†] Ph.D. Graduate, Department of Aerospace Engineering, Texas A&M University, TAMU 3141, College Station, Texas 77843-3141, U.S.A.
[‡] Distinguished Professor, Department of Aerospace Engineering, Texas A&M University, TAMU 3141, College Station, Texas 77843-3141, U.S.A.

AAS 17-439

LOW-THRUST TRAJECTORY OPTIMIZATION FOR MULTI-ASTEROID MISSION: AN INDIRECT APPROACH

Ehsan Taheri,[*] Ilya Kolmanovsky[†] and Anouck Girard[‡]

We investigate the problem of visiting multiple asteroids using low-thrust engines; our solution methodology is based on indirect methods. Our approach is to present a methodology that benefits from two critical components, namely, a smoothing formulation and effective methods for generating initial guesses for the unknown values of the initial costates. Considering transfers between near-circular near-coplanar orbits, two different strategies are considered: 1) to exploit the solution of Lambert's problem, and 2) to simplify the dynamics by ignoring the gravitational parameter of the central body and assuming no fuel consumption. Numerical examples of various low-thrust sequences of asteroids are generated. [View Full Paper]

[*] Postdoctoral Research Fellow, Department of Aerospace Engineering, University of Michigan, Ann Arbor, Michigan 48109, U.S.A. E-mail: etaheri@umich.edu. AIAA Member.
[†] Professor, Department of Aerospace Engineering, University of Michigan, Ann Arbor, Michigan 48109, U.S.A. E-mail: ilya@umich.edu. AIAA Member.
[‡] Associate Professor, Department of Aerospace Engineering, University of Michigan, Ann Arbor, Michigan 48109, U.S.A. E-mail: anouck@umich.edu. AIAA Associate Fellow.

AAS 17-440

SHAPING VELOCITY COORDINATES FOR GENERATING LOW-THRUST TRAJECTORIES

Ehsan Taheri,[*] Ilya Kolmanovsky[†] and Ella Atkins[‡]

This paper investigates application of shape-based methods to spacecraft trajectory optimization. Low-thrust trajectories are represented by the evolution of the velocity coordinates in spherical coordinates and are characterized in terms of an overall required velocity increment ΔV. The defined performance index requires the evaluation of an integral that must be evaluated numerically. This work applies a standard Gauss quadrature scheme shows it is accurate to within 0.1% of the true index value and substantially faster than trapezoidal integration. The proposed improvements are applied to generate ΔV contours similar to porkchop plots conventionally defined for impulsive maneuvers.

[View Full Paper]

[*] Postdoctoral Research Fellow, Department of Aerospace Engineering, University of Michigan, Ann Arbor, Michigan 48109, U.S.A. E-mail: etaheri@umich.edu. AIAA Member.
[†] Professor, Department of Aerospace Engineering, University of Michigan, Ann Arbor, Michigan 48109, U.S.A. E-mail: ilya@umich.edu. AIAA Member.
[‡] Professor, Department of Aerospace Engineering, University of Michigan, Ann Arbor, Michigan 48109, U.S.A. E-mail: ematkins@umich.edu. AIAA Associate Fellow.

AAS 17-443

RELATIONSHIPS BETWEEN UNSCENTED AND SENSITIVITY FUNCTION-BASED OPTIMAL CONTROL FOR SPACE FLIGHT

Richard Shaffer,* Mark Karpenko† and Qi Gong‡

Nearly all practical control problems in space engineering have uncertainty in system parameters creating the need for methods which can manage parametric uncertainty. Recently, open-loop optimal control has been proposed as a tool to manage uncertainties in the absence of feedback. Especially, unscented optimal control, which discretizes an uncertain optimal control problem into a deterministic problem, has been demonstrated as an efficient approach for problems with uncertain parameters/initial conditions. In this paper we study the performance of unscented optimal control methods using the concept of the sensitivity function. We show that the unscented optimal control formulation can capture the first and higher order effects introduced by parameter uncertainty. We also develop conditions under which the unscented discretion introduces no approximation errors in solving the continuous uncertain optimal control problems. The results shed new light on the unscented optimal control concept small-scale; and can be further explored to improve the efficiency in solving uncertain optimal control problems. [View Full Paper]

* R. Shaffer is a Graduate Student at the University of California, Santa Cruz, California 95064, U.S.A. E-mail: rshaffer@soe.ucsc.edu.

† M. Karpenko is a Research Associate Professor of Mechanical and Aerospace Engineering at the Naval Postgraduate School, Monterey, California 93940, U.S.A. E-mail: mkarpenk@nps.edu.

‡ Q. Gong is an Associate Professor of Applied Mathematics and Statistics at the University of California, Santa Cruz, California 95064. E-mail: qigong@soe.ucsc.edu.

AAS 17-445

AUTOMATED GLOBAL OPTIMIZATION OF MULTI-PHASE TRAJECTORIES IN THE THREE-BODY PROBLEM USING A VARIABLE CHROMOSOME TRANSCRIPTION

Vishwa Shah,[*] Ryne Beeson[†] and Victoria Coverstone[‡]

This paper investigates the use of a variable chromosome transcription to enable construction and global optimization of multi-phase trajectory problems by an automated global optimization framework for multi-body problems. We demonstrate how the variable chromosome transcription operates with NSGA-II, a multi-objective genetic algorithm, to select number of phases and phase types for impulsive and low-thrust missions in three-body transfer problems. For both impulsive and low-thrust transfers, we show how our framework with the variable chromosome transcription naturally converges GA populations to phase-specific groups on multi-objective fronts. [View Full Paper]

[*] Masters Student, Aerospace Engineering, University of Illinois Urbana-Champaign, 104 S. Wright Street, Urbana, Illinois 61801, U.S.A.

[†] Ph.D. Candidate, Aerospace Engineering, University of Illinois Urbana-Champaign, 104 S. Wright Street, Urbana, Illinois 61801, U.S.A.

[‡] Adjunct Professor, Aerospace Engineering, University of Illinois Urbana-Champaign, 104 S. Wright Street, Urbana, Illinois 61801, U.S.A.

MULTI-BODY RESONANCE ORBIT GENERATION AND APPLICATION WITHIN A HYBRID OPTIMAL CONTROL FRAMEWORK

Devin Bunce,[*] Ryne Beeson,[†] Vishwa Shah[*] and Victoria Coverstone[‡]

This paper details early work to incorporate resonance orbits, their invariant manifolds, and associated families into an automated global optimization tool for solution of optimal impulsive and low-thrust spacecraft trajectories in multi-body environments. Previous work by the authors have shown the ability to use other key dynamical structure of the circular restricted three-body problem (e.g. libration point orbits and their invariant manifolds) within the same automated global optimization framework to produce low-energy trajectory solutions. We first show how to generate resonance orbits of the *first species*, providing examples of the Earth-Moon and Jupiter-Europa systems, and proceed to show how these structures are used within the optimization framework. Several non-trivial impulsive and low-thrust trajectory problems from low-Earth to resonance orbits, and resonance-resonance transfers are shown with Pareto front solutions. [View Full Paper]

[*] Masters Student, Aerospace Engineering, University of Illinois Urbana-Champaign, 104 S. Wright Street, Urbana, Illinois 61801, U.S.A.
[†] Ph.D. Candidate, Aerospace Engineering, University of Illinois Urbana-Champaign, 104 S. Wright Street, Urbana, Illinois 61801, U.S.A.
[‡] Adjunct Professor, Aerospace Engineering, University of Illinois Urbana-Champaign, 104 S. Wright Street, Urbana, Illinois 61801, U.S.A.

AAS 17-453

A MULTIPLE-SHOOTING DIFFERENTIAL DYNAMIC PROGRAMMING ALGORITHM

Etienne Pellegrini[*] and Ryan P. Russell[†]

Multiple-shooting benefits a wide variety of optimal control algorithms, by alleviating large sensitivities present in highly nonlinear problems, improving robustness to initial guesses, and increasing the potential for a parallel implementation. In this work, the multiple shooting approach is embedded for the first time in the formulation of a differential dynamic programming algorithm. The necessary theoretical developments are presented for a DDP algorithm based on augmented Lagrangian techniques, using an outer loop to update the Lagrange multipliers, and an inner loop to optimize the controls of independent legs and select the multiple-shooting initial conditions. Numerical results are shown for several optimal control problems, including the low-thrust orbit transfer problem. [View Full Paper]

[*] Graduate Student, Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, Austin, Texas 78712, U.S.A.
[†] Associate Professor, Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, Austin, Texas 78712, U.S.A.

AAS 17-476

A NOVEL STATE SPACE REPRESENTATION OF PARTICLE SWARM OPTIMIZATION DYNAMICS

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

Particle Swarm Optimization (PSO) is a heuristic optimization technique that has risen to popularity in recent years. The method was originally conceived by trying to mimic swarms of animals in nature. There has been a bevy of experimental research demonstrating the viability of PSO on both benchmark optimization functions and in real-world applications. While the performance of PSO has shown great promise, this performance depends heavily on the configuration of certain parameters. Since the algorithm was originally developed from empirical observation, there does not currently exist a strong theoretical framework to inform the selection of these PSO parameters. Presented here is a derivation of a state-space dynamics representation of the PSO equations, which allows for the use of existing dynamical system analysis methods to select these PSO parameters, such as Root Locus, Nyquist, Bode Plots, and Phase Plane Analysis. This representation of the equations firmly roots the PSO equations in the foundations of Control Theory and Digital Signal Processing. The results of this analysis show that the subsequent system is fully controllable, fully observable, and has the advantage of decoupled dynamics.

[View Full Paper]

* Graduate Student of Mechanical Engineering, University of New Hampshire, Durham, New Hampshire 03824, U.S.A. AIAA Student Member.

† Associate Professor of Mechanical Engineering, University of New Hampshire, Durham, New Hampshire 03824, U.S.A. AIAA Senior Member.

ACCOMMODATING MEASUREMENT UNCERTAINTY IN THE OPTIMIZATION OF SPACE FLIGHT TRAJECTORIES

Alan Zorn[*] and Matt West[†]

Equality constraints in trajectory optimization are typically handled as exact in space flight optimization. Frequently, however, the constraints are not known exactly, perhaps due to measurement uncertainty. In this paper, it is shown how this inexactness can be accommodated in a natural way by solving the deterministic optimization problem as a maximum a posteriori estimation problem. An example illustrating the approach is given in which an optimal two-impulse Lambert control law is developed which maintains a satellite in a desired Earth orbit. By accommodating uncertainty in this manner, the approach might improve cost performance, facilitate implementation, and reveal new relationships. [View Full Paper]

[*] Ph.D. Student, Department of Aeronautics and Astronautics, Stanford University, 496 Lomita Mall, Stanford, California 94305, U.S.A. E-mail: azorn@stanford.edu.

[†] Associate Professor, Department of Mechanical Science and Engineering, University of Illinois, 1206 West Green Street, Urbana-Champaign, Illinois 61801, U.S.A.

OPTIMAL SLEW-RATE-LIMITED GUIDANCE FOR COMBINED FORMATION ESTABLISHMENT AND RECONFIGURATION OF INSPECTOR SATELLITE WITH EXCLUSION CONE[*]

Eric R. Prince,[†] Richard G. Cobb[‡] and Joshuah A. Hess[§]

This paper utilizes the Radau Pseudospectral Method via GPOPS-II, an optimal control software package for MATLAB, and employs the nonlinear programming problem solver IPOPT to find the optimal control of an inspector satellite conducting proximity operations in a geosynchronous orbit. The mission of the inspector satellite is to optimally inject itself into a zero-drift natural circumnavigation orbit about the target starting from an arbitrary location nearby, then after a specified amount of minimum dwell time, optimally transfer to another orthogonal zero-drift natural circumnavigation, allowing the inspector to obtain spherical coverage of the target. Thus instead of optimizing formation establishment and reconfiguration separately, this work optimizes the combined mission. The trajectories are constrained to avoid an exclusion zone emitting from the target to avoid interfering with its operations. The control type investigated is slew rate limited control introducing two angle states which are controlled by bounded angular rate controls. The thrust is also continuous, able to throttle from zero to the maximum available magnitude as necessary, eliminating the need for separate burn and coast phases. With the minimum time solution presented as the baseline, various fixed final time, minimum fuel solutions are presented to show fuel savings for lengthened total times. Results are sets of optimal constrained trajectory solutions, providing potential mission planners options based on specific time and fuel requirements. [View Full Paper]

---

[*] 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, the Department of Defense, or the U.S. Government. This material is declared a work of the U.S. Government and is not subject to copyright protection in the United States. This document has been cleared for public release.

[†] Captain, USAF, Graduate Student, Department of Aeronautics and Astronautics, AFIT, 2950 Hobson Way, WPAFB, Ohio 45433, U.S.A. E-mail: eric.prince@afit.edu.
[‡] Professor, Department of Aeronautics and Astronautics, AFIT. E-mail: richard.cobb@afit.edu.
[§] Captain, USAF, Assistant Professor, Department of Aeronautics and Astronautics, AFIT. E-mail: joshuah.hess@afit.edu.

RENDEZVOUS AND PROXIMITY OPERATIONS

Session Chairs:

Session 3: Andrew Sinclair

Session 19: Brandon Jones

AAS 17-229

AUTONOMOUS SHAPE DETERMINATION USING FLASH-LIDAR OBSERVATIONS

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

Flash-Lidar sensors provide valuable observations usable to determine the shape model of a target, but the collected data is too dense to be used as state model parameters. Algorithms autonomously constructing an a-priori from the observations are thus needed. To this end, a feature extractor autonomously computing an a-priori facet-vertex shape model from the observations is constructed. A batch estimator is used to determine the model parameters from the a-priori and the observations. This framework has been successfully tested on noise-free observations. Future work will consist in making the algorithm more robust to noisy data and complex topology. [View Full Paper]

[*] Pre-Ph.D. Candidate, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado 80309, U.S.A. AIAA Student Member.
[†] Assistant Research Professor, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado 80309, U.S.A. AIAA Senior Member.

AAS 17-232

ROBUST TRIAD AND QUAD GENERATION ALGORITHMS FOR STAR TRACKERS

David Arnas,[*] Márcio A. A. Fialho[†] and Daniele Mortari[‡]

Star Identification (Star-ID) is a complex problem, mainly because some of the observations are not generated by actual stars, but by reflecting debris, other satellites, visible planets, or by electronic noise. For this reason, the capability to discriminate stars from non-stars is an important aspect of Star-ID robustness. Usually, the Star-ID task is performed by first attempting identification on a small group of observed stars (a kernel) and, in case of failure, replacing that kernel with another until a kernel made only of actual stars is found. This work performs a detailed analysis of kernel generator algorithms, suitable for on-board implementation in terms of speed and robustness, for kernels of three (triad) and four (quad) stars. Three new kernel generator algorithms and, in addition to the existing *expected time to discovery*, three new metrics for robustness evaluation are proposed. The proposed algorithms are fast, robust to find good kernels, and do not require pre-stored data. [View Full Paper]

[*] Centro Universitario de la Defensa, Zaragoza, Spain. GME - IUMA - Universidad de Zaragoza, Spain. E-mail: darnas@unizar.es.

[†] Divisão de Eletrônica Aeroespacial, INPE - Instituto Nacional de Pesquisas Espaciais, São José dos Campos, SP, Brazil. E-mail: marcio.fialho@inpe.br.

[‡] Department of Aerospace Engineering, Texas A&M University, 3141 TAMU, College Station, Texas 77843-3141, U.S.A. E-mail: mortari@tamu.edu. IEEE and AAS Fellow, AIAA Associate Fellow.

DESIGN OF BOUNDED RELATIVE TRAJECTORIES IN THE EARTH ZONAL PROBLEM

Nicola Baresi* and Daniel J. Scheeres†

The generation of a continuous set of bounded relative motions about an arbitrary satellite orbit is developed. This is done using a rigorous computational approach for finding the quasi-periodic orbits about an axis-symmetric Earth gravity field. The method also allows families of bounded trajectories to be found with specified nodal and orbital periods. This enables the precise design of constellations and clusters of orbits that never drift apart from each other under zonal harmonics perturbations. [View Full Paper]

* Graduate Research Assistant, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado 80309, U.S.A. E-mail: nicola.baresi@colorado.edu.
† A. Richard Seebass Endowed Chair Professor, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado 80309, U.S.A. E-mail: scheeres@colorado.edu.

AAS 17-246

ANGLES-ONLY INITIAL RELATIVE ORBIT DETERMINATION FOR SPACE RENDEZVOUS USING HYBRID DYNAMICS AND VIRTUAL DISTRIBUTION METHOD

Baichun Gong,[*] Jianjun Luo,[†] Jianping Yuan[†] and Jinglang Feng[‡]

This research develops a closed-form solution to the angles-only initial relative orbit determination problem for space rendezvous where a method of hybrid dynamics for virtual spacecraft formations produces range observability. Emphasis is placed on developing the solution in the context of Clohessy-Wiltshire orbital relative motion equations, obtaining spacecraft formation geometries that produce position/velocity observability, and deriving the closed-form error covariance equations for the initial relative orbit state solution. A two-body Monte Carlo simulation system is used to verify the feasibility and evaluate the performance of the closed-form relative state estimation algorithms. The sensitivity of the solution accuracy to the formation geometry, observation numbers is presented and discussed. [View Full Paper]

[*] Assistant Professor, College of Astronautics, Nanjing University of Aeronautics and Astronautics, 29 Yudao Street, Nanjing, China 210016.
[†] Professor, College of Astronautics, Northwestern Polytechnical University, 127 Youyi West Road, Xi'an, China 710072.
[‡] Postdoc, School of Astronomy and Space Science, Nanjing University, 22 Hankou Road, Nanjing, China 210023.

AAS 17-263

INITIAL POSE ESTIMATION USING PMD SENSOR DURING THE RENDEZVOUS PHASE IN ON-ORBIT SERVICING MISSIONS

Ksenia Klionovska* and Heike Benninghoff†

This paper describes a designed visual model-based algorithm using the PMD (Photonic Mixer Device) sensor for the initial pose estimation of the target in future On-Orbit Servicing missions. The initial relative pose (position and orientation) in a close range has to be estimated, starting less than 7 meters between target and a camera. The verification of the algorithm is conducted by comparing the estimated pose with a ground truth. The ground truth is derived from the high-accuracy hardware-in-the-loop European Proximity Operations Simulator offered for the simulations of On-Orbit Servicing scenarios on the ground.

The results of the simulations have shown the feasibility of the algorithm to estimate the pose with sufficient accuracy as required for a pose initialization algorithm. Consequently, the designed algorithm is applicable for the initial pose estimation using PMD sensor with definite working parameters and conditions. [View Full Paper]

* DLR/GSOC, Münchener Str. 20, 82234, Germany. Tel. +49 8153 28 3465. E-mail: ksenia.klionovska@dlr.de.
† Dr., DLR/GSOC, Münchener Str. 20, 82234, Germany. Tel. +49 8153 28 1465. E-mail: heike.benninghoff@dlr.de.

AAS 17-272

APPROACHES AND FLY-AROUNDS FOR SPACECRAFT PROXIMITY OPERATIONS

John L. Goodman*

Proximity operations (range < 2 km) includes an approach trajectory leading to chaser spacecraft docking or robotic grappling with a target spacecraft. For current human and robotic spacecraft, low energy approaches along the target spacecraft velocity or radius vectors can be flown due to the availability of redundant sensors, and are preferred over higher energy inertial approaches. A fly-around of the target by the chaser may be performed to reach a final approach axis or to perform visual inspection. Back-out and separation (nominal or contingency) are also a part of proximity operations. A partial fly-around may be flown to reach the location of a separation burn. [View Full Paper]

* Specialist Engineer, Odyssey Space Research, LLC, 1120 NASA Parkway, Suite 505, Houston, Texas 77058, U.S.A.

AAS 17-276

ORBIT DETERMINATION WITH LEAST-SQUARES AND FLASH LIDAR MEASUREMENTS IN PROXIMITY TO SMALL BODIES

Ann Dietrich* and Jay W. McMahon†

Flash lidar measurements were investigated as a means for proximity spacecraft navigation relative to the asteroid, Itokawa, with an overall goal of increasing spacecraft navigation autonomy. A flash lidar measurement can be thought of as a three-dimensional point cloud of its target, and an image array can contain thousands of range measurements. This work estimated the position and pointing of a spacecraft with a single flash lidar image through a least-squares minimization algorithm, and then passed that estimate to an extended Kalman filter to estimate the position, velocity, and pointing of the spacecraft. A Monte Carlo simulation studied the least-squares algorithm's robustness to state errors with one flash lidar image, and an extended Kalman filter was implemented for flash lidar measurements in a terminator orbit about Itokawa. In the filter simulation, this algorithm provided centimeter-level accuracy in position, and below 1 mrad accuracy in pointing. While previous measurement processing methods saw the filter saturate, this algorithm provided state errors within the resulting covariance bounds and improved estimation performance. [View Full Paper]

* Graduate Research Assistant, Aerospace Engineering Sciences, University of Colorado at Boulder, 431 UCB, Boulder, Colorado 80309, U.S.A.

† Assistant Professor, Aerospace Engineering Sciences, University of Colorado at Boulder, 431 UCB, Boulder, Colorado 80309, U.S.A.

AAS 17-330

VELOCITY-FREE CONTROL OF SPACECRAFT BODY-FIXED HOVERING AROUND ASTEROIDS

Haichao Gui[*] and Anton H. J. de Ruiter[†]

This paper addresses the control of spacecraft hovering about uniformly rotating asteroids without translational velocity measurements. An extended state observer is designed to estimate the spacecraft velocity and uncertain perturbations simultaneously. It ensures ultimately bounded estimation errors irrespective of the control law applied. A velocity-free hovering controller is then obtained by driving a full-state feedback controller with estimates from the observer. The observer and controller design accounts for both measurement errors and unknown perturbations, and Lyapunov analysis shows that the resultant control scheme globally stabilizes the spacecraft trajectory to the vicinity of the desired hovering state. Furthermore, body-fixed hovering operations, implemented by either continuous or on-off thrusters are simulated with sensor noise and multiple unknown disturbances to demonstrate the effectiveness of the proposed methods. [View Full Paper]

[*] Postdoctoral Researcher, Department of Aerospace Engineering, Ryerson University, 50 Victoria Street, Toronto, ON, M5B 2K3, Canada.

[†] Associate Professor, address is the same as the first author.

AAS 17-379

GUIDANCE SOLUTIONS FOR SPACECRAFT PLANAR REPHASING AND RENDEZVOUS USING INPUT SHAPING CONTROL

M. Lawn,* G. Di Mauro† and R. Bevilacqua‡

Small satellites formation flying has been attracting growing interest. While economical to design and to launch, they have limited computational capability and propellant capacity. Thrusters must generally have a small form factor and use minimal propellant, often operating only in on/off configurations and with a few set force magnitudes. Therefore, efficient relative orbit control techniques must be developed to satisfy low-thrust constraints without reducing performance ac-curacy or straining the limited computational power of the small on-board systems. This paper presents analytical guidance solutions for orbital planar spacecraft rephasing and rendezvous using in-plane continuous low-thrust profiles de-rived from input shaping theory. [View Full Paper]

* Graduate Student, Department of Mechanical & Aerospace Engineering, ADAMUS Laboratory, University of Florida, 939 Sweetwater Drive, Gainesville, Florida 32611-6250, U.S.A.

† PostDoc Associate, Department of Mechanical & Aerospace Engineering, ADAMUS Laboratory, University of Florida, 939 Sweetwater Drive, Gainesville, Florida 32611-6250, U.S.A.

‡ Associate Professor, Department of Mechanical & Aerospace Engineering, ADAMUS Laboratory, University of Florida, 939 Sweetwater Drive, Gainesville, Florida 32611-6250, U.S.A.

AAS 17-402

ADAPTIVE FILTERING FOR MANEUVER-FREE ANGLES-ONLY NAVIGATION IN ECCENTRIC ORBITS

Joshua Sullivan* and Simone D'Amico†

This paper addresses the design and validation of accurate estimation architectures for autonomous angles-only navigation in orbits of arbitrary eccentricity. The proposed filtering strategies overcome the major deficiencies of existing approaches in the literature, which mainly focus on applications in near-circular orbits and generally suffer from poor dynamical observability due to linearizing the dynamics and measurement models implemented in the filter. Consequently, traditional angles-only navigation solutions require conducting known orbital maneuvers to reconcile the ambiguous relative range. In contrast, the algorithms developed in this work enable accurate maneuver-free reconstruction of the relative orbital motion. This is done through the full exploitation of nonlinearities in the measurement model using the unscented Kalman filter to improve dynamical observability and filter performance. The filter estimates mean relative orbit elements, adopting a state transition matrix subject to secular and long-period J_2 perturbation effects to decouple observable from unobservable parameters. The complete state is then reconciled with the angle measurements in the measurement model through a nonlinear transformation which includes the conversion from mean to osculating orbital elements. The resulting linear dynamics model is supplemented by a covariance-matching approach to online adaptive process noise tuning to increase performance at minimal computational complexity. Finally, the estimation architecture is completed by a novel deterministic algorithm for batch initial relative orbit determination to accurately initialize the sequential filters. [View Full Paper]

* Doctoral Candidate, Stanford University, Department of Aeronautics and Astronautics, Space Rendezvous Laboratory, Durand Building, 496 Lomita Mall, Stanford, California 94305-4035, U.S.A.

† Assistant Professor, Stanford University, Department of Aeronautics and Astronautics, Space Rendezvous Laboratory, Durand Building, 496 Lomita Mall, Stanford, California 94305-4035, U.S.A.

AAS 17-411

SAFE RELATIVE MOTION TRAJECTORY PLANNING FOR SATELLITE INSPECTION

Gregory R. Frey,* Christopher D. Petersen,† Frederick A. Leve,‡ Anouck R. Girard§ and Ilya V. Kolmanovsky**

Safe trajectory planning for satellite inspection involves calculating an inspection path to be traversed by an inspector spacecraft in order to obtain information about a target spacecraft while satisfying constraints. The solution to this problem is complicated by dimensionality and, in the case of certain types of constraints, non-convexity. We report on three methods to calculate safe inspection paths to obtain information with reduced computational effort. Simulation results illustrate each approach and comparisons are made between the methods to highlight relative strengths and weaknesses.

[View Full Paper]

* Ph.D. Candidate, Department of Aerospace Engineering, The University of Michigan, 1320 Beal Avenue, Ann Arbor, Michigan 48109, U.S.A.

† Post-Doctoral Researcher, Department of Aerospace Engineering, The University of Michigan, 1320 Beal Avenue, Ann Arbor, Michigan 48109, U.S.A.

‡ Program Officer, Dynamics and Controls Program, Air Force Office of Scientific Research, Arlington, Virginia 22203, U.S.A.

§ Associate Professor, Department of Aerospace Engineering, The University of Michigan, 1320 Beal Avenue, Ann Arbor, Michigan 48109, U.S.A.

** Professor, Department of Aerospace Engineering, The University of Michigan, 1320 Beal Avenue, Ann Arbor, Michigan 48109, U.S.A.

AAS 17-418

CONVEX OPTIMIZATION FOR PROXIMITY MANEUVERING OF A SPACECRAFT WITH A ROBOTIC MANIPULATOR

Josep Virgili-Llop,[*] Costantinos Zagaris,[†] Richard Zappulla II,[†] Andrew Bradstreet[‡] and Marcello Romano[§]

This paper presents a convex optimization-based guidance algorithm for maneuvering a spacecraft equipped with a robotic manipulator. A local solution to the original optimization problem is found by solving a collection of simpler convex programming problems. Given the deterministic convergence properties of convex programming, the proposed algorithm can be implemented onboard a spacecraft and used for real-time applications. To reduce the complexity of the original optimization problem, we first divide the maneuver into two simultaneously occurring sub-maneuvers: a system-wide translation and an internal re-configuration. These two sub-maneuvers are individually optimized using a sequential convex optimization approach to overcome the presence of non-convex inequality and nonlinear equality constraints. The paradigmatic example of capturing a tumbling object is used throughout the paper to illustrate the use of the proposed optimization approach. Additionally, a new explicitly convex formulation of a line-of-sight constraint is introduced. [View Full Paper]

[*] Research Associate, Spacecraft Robotics Laboratory, Naval Postgraduate School, 1 University Circle, Monterey, California 93940 U.S.A.

[†] Ph.D. Candidate, Spacecraft Robotics Laboratory, Naval Postgraduate School.

[‡] Graduate Student, Spacecraft Robotics Laboratory, Naval Postgraduate School.

[§] Associate Professor, Spacecraft Robotics Laboratory, Naval Postgraduate School.

AAS 17-419

ANALYSIS OF SPACECRAFT PLANAR DOCKING WITH ROTATING BODY IN CLOSE PROXIMITY

Costantinos Zagaris[*] and Marcello Romano[†]

Spacecraft rendezvous and proximity missions have been addressed in several past publications, focusing on many different aspects of the problem. This paper investigates a scenario where the target spacecraft is rotating on a plane, at a constant rate, and the chaser spacecraft is on the same plane within close proximity. The controllability characteristics of the problem are analyzed for both unbounded and bounded control inputs. The goal of this research is to identify a reachable set of initial conditions, from which the chaser can successfully dock with the target. [View Full Paper]

[*] Ph.D. Candidate, Spacecraft Robotics Laboratory, Naval Postgraduate School, 1 University Circle, Monterey, California 93940, U.S.A.
[†] Associate Professor, Spacecraft Robotics Laboratory, Naval Postgraduate School.

AAS 17-454

A MULTI-MODE RENDEZVOUS CONTROL ALGORITHM FOR A SATELLITE UTILIZING STEREO CAMERA BASED PROXIMITY SENSOR

Burak Akbulut,[*] Kagan Ataalp[†] and Mehmet Can Unlu[‡]

Rendezvous missions are key milestones for space technology; however, they require dedicated sensors for realization. Different types of sensors are currently available for this purpose, involving LIDAR and Vision based ones. In the current study a stereo-camera based sensor is utilized. This particular sensor already has a proof-of-concept model implemented. Utilizing a mathematical model of this sensor, a hypothetical rendezvous mission would be developed involving a chaser and a target satellites. Dedicated control algorithm architecture will be built, including multiple control modes.

[View Full Paper]

[*] AODCS Engineer, Satellite Systems Division, Turkish Aerospace Industries Inc., TUSAS Fethiye Mah. Havacilik Blv. No:17, Kahramankazan/Ankara 06980, Turkey. E-mail: bakbulut@tai.com.tr.

[†] AODCS Engineer, Satellite Systems Division, Turkish Aerospace Industries Inc., TUSAS Fethiye Mah. Havacilik Blv. No:17, Kahramankazan/Ankara 06980, Turkey. E-mail: kataalp@tai.com.tr.

[‡] AODCS Engineer, Satellite Systems Division, Turkish Aerospace Industries Inc., TUSAS Fethiye Mah. Havacilik Blv. No:17, Kazan/Ankara 06980, Turkey. E-mail: mehmetcan.unlu@tai.com.tr.

AAS 17-474

A PURSUIT-EVASION GAME IN THE ORBITAL PLANE

Jhanani Selvakumar[*] and Efstathios Bakolas[†]

We consider a pursuit-evasion game in the Hill's frame, in which a deputy spacecraft aims to capture a chief spacecraft as fast as possible while the chief tries to delay or avoid capture. Capture is defined as positional coincidence of the two spacecraft within a user-specified tolerance, and both spacecraft operate under input constraints. This zero-sum game of pursuit and evasion with free final time is treated as a game with a terminal cost and fixed final time. For the case of circular orbits, a semi analytical solution for the time of capture is presented along with a closed form expression for the optimal control inputs. Furthermore, for a circular orbit, we can precisely characterize the sets of initial conditions that ensure capture of the chief by the deputy. [View Full Paper]

[*] Graduate Student, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, 210 E 24th Street, Austin, Texas 78712-1221, U.S.A.

[†] Assistant Professor, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, 210 E 24th Street, Austin, Texas 78712-1221, U.S.A.

ANALYTIC SOLUTION OF PERTURBED RELATIVE MOTION WITH ZONAL AND TESSERAL HARMONICS

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

A state transition matrix for satellite relative motion including the perturbation effects due to zonal and tesseral harmonics is presented. Recently, a new solution for short-period variations of the orbital elements of a satellite due to tesseral and sectorial harmonics was found by the authors without resorting to eccentricity expansions or the method of relegation. This novel approach makes use of non-conservative canonical transformations to normalize the disturbing potential and produce generalized analytic formulae, closed-form in eccentricity, for second-order tesseral short-period effects. Using these analytic formulae, a state transition matrix solution for the perturbed relative motion that includes the effects of zonals and tesserals up to second order is presented in this work. Since the tesseral harmonics have a significant effect on the mean longitude of a satellite, their inclusion in the relative motion solution improves the prediction of along-track motion between two satellites in a formation. The proposed solution for the perturbed relative motion is valid for any reference elliptic orbit with an arbitrary value of the eccentricity. Accuracy verification of the proposed analytic solution is carried out by comparing the results with numerical propagation of a formation of two satellites using GMAT simulation package. [View Full Paper]

[*] Graduate Student, Department of Aerospace Engineering, Texas A&M University, College Station, Texas 77843-3141, U.S.A.

[†] Professor, Department of Aerospace Engineering, Texas A&M University, College Station, Texas 77843-3141, U.S.A.

[‡] TEES Distinguished Research Professor, Department of Aerospace Engineering, Texas A&M University, College Station, Texas 77843-3141, U.S.A.

AAS 17-496

NONLINEAR MODEL PREDICTIVE CONTROL FOR SPACECRAFT RENDEZVOUS AND DOCKING WITH A ROTATING TARGET

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

In this paper, we develop a nonlinear model predictive control (NMPC) approach for spacecraft rendezvous and docking (RVD) with a rotating target platform. A strategy to enforce and handle constraints is proposed for collision-free and soft docking while real-time computation is achieved. In the strategy, constraints on thrust, spacecraft positioning within the entry cone from the docking port, and collision avoidance are systemically treated and switched in two-phase spacecraft RVD maneuvering. Dynamically reconfigurable constraints with a switching algorithm are introduced to guide the chaser spacecraft into the docking port in the final docking phase. The performance of the developed NMPC controller is analyzed for test cases using a MATLAB/Simulink-based simulator. The controller is also implemented on an air-bearing test bed to demonstrate the capability to perform real-time computation and to satisfy constraints. [View Full Paper]

[*] Postdoctoral Research Associate, Mechanical and Aerospace Engineering, Naval Postgraduate School, Monterey, California 93943, U.S.A.

[†] Ph.D. Candidate, Mechanical and Aerospace Engineering, Naval Postgraduate School, Monterey, California 93943, U.S.A.

[‡] Ph.D. Student, Mechanical and Aerospace Engineering, Naval Postgraduate School, Monterey, California 93943, U.S.A.

[§] Associate Professor, Mechanical and Aerospace Engineering, Naval Postgraduate School, Monterey, California 93943, U.S.A.

AAS 17-498

METHODS OF RELATIVE ORBIT ESTIMATION INVOLVING SOLUTION OF POLYNOMIAL SYSTEMS

T. Alan Lovell,[*] Caroline Young,[†] Chloe Baker[‡] and Kenneth Horneman[§]

This paper presents a polynomial system approach to selected astrodynamics problems, namely, time-difference-of-arrival geolocation and angles-only initial orbit determination. Several example scenarios are generated involving both square (minimum-measurement) systems and over-determined systems. For each scenario, derivation of the polynomial system is clearly laid out, and a very stable algorithm is employed to solve the system. Methods of disambiguation are shown, for cases when multiple real solutions are obtained. [View Full Paper]

[*] Research Aerospace Engineer, U.S. Air Force Research Laboratory, Space Vehicles Directorate, 3550 Aberdeen Avenue SE, Albuquerque, New Mexico 87117, U.S.A. Associate Fellow AIAA, Senior Member AAS.
[†] Engineer, Parametric Solutions, Inc., 831 Jupiter Park Drive, Jupiter, Florida 33458, U.S.A.
[‡] Student, La Cueva High School, Albuquerque, New Mexico 87122, U.S.A.
[§] Postdoctoral Research Associate, National Research Council. Member AIAA, Member AAS.

AN INTEGRATED SOLUTION FOR DISTRIBUTED COOPERATIVE DYNAMIC MISSION PLANNING

Weinan Wu,[*] Naigang Cui[†] and Jifeng Guo[†]

This paper addresses the problems of autonomous task assignment and path planning for a fleet of heterogeneous spacecrafts in cooperative mission. In previous work many algorithms have almost run on centralized architecture and handle the task assignment decoupling with the path planning. This may result in poor solutions. Therefore, this paper investigates a novel integrated solution for spacecrafts to perform multiple consecutive tasks cooperatively on multiple targets based on distributed planning architecture. In a given scenario, the heterogeneous spacecrafts have different capabilities, kinematic constraints, and fuel constraints. Furthermore, the task has other constraints, such as task execution orders, spacecrafts conflict free constraints, etc. This paper presents details of the integrated solution which produces optimal assignment and trajectories for several given scenarios. The performance of the algorithm is compared to that of some previous methods in real-time simulation environment. The simulations results show the viability of the integrated approach, and the integrated solution has an advantage over hierarchical algorithms under the condition of dynamic mission, and the distributed architecture improves the operation efficiency of the algorithm and the robustness of the unmanned spacecraft system. [View Full Paper]

[*] Graduate for Ph.D. Degree, Department of Aerospace Engineering, Harbin Institute of Technology, Harbin 150001, China.
[†] Professor, Department of Aerospace Engineering, Harbin Institute of Technology, Harbin 150001, China.

SPACE SITUATIONAL AWARENESS

Session Chairs:

Session 4: Matthew Wilkins

Session 11: Thomas Starchville

AAS 17-216

DEBRIS AVOIDANCE MANEUVERS FOR SPACECRAFT IN A CLUSTER

Elad Denenberg[*] and Pini Gurfil[†]

Spacecraft formation flying and satellite cluster flight have seen growing interest in the last decade. However, the problem of finding the optimal debris collision avoidance maneuver for a satellite in a cluster has received little attention. This paper develops a method for choosing the timing for conducting minimum-fuel avoidance maneuvers without violating the cluster inter-satellite maximal distance limits. The mean semimajor axis difference between the maneuvering satellite and the other satellites is monitored for the assessment of a maneuver possibility. In addition, three techniques for finding optimal maneuvers under the constraints of cluster–keeping are developed. The first is an execution of an additional cluster–keeping maneuver at the debris time of closest approach, the second is a global all-cluster maneuver, and the third is a fuel-optimal maneuver, which incorporates the cluster–keeping constraints into the calculation of the evasive maneuver. The methods are demonstrated and compared. The first methodology proves to be the most fuel efficient. The global maneuver guarantees boundedness of the inter-satellite distances, as well as fuel and mass balance. However, it is rather fuel-expensive. The last method proves to be useful at certain timings, and is a compromise between fuel consumption, and the number of maneuvers. [View Full Paper]

[*] Ph.D. Student, Technion Autonomous Systems and Robotics Program, Technion, 3200003, Haifa, Israel.
[†] Associate Professor, Faculty of Aerospace Engineering, Technion, 3200003, Haifa, Israel.

AAS 17-228

AN IMPROVED MRP-BASED ITERATIVE CLOSEST POINT-TO-PLANE ALGORITHM

Benjamin Bercovici* and Jay W. McMahon†

Point-cloud registration pertains to the computation of point pairs between a source and a destination point cloud, followed by the calculation of the rigid transform minimizing a relative distance (such as the Iterative Closest Point-to-Plane distance criterion) between the set of point pairs. The work described in this paper presents an alternative parametrization of the rotational component of the rigid transform using Modified Rodrigues Parameters. The performance of this formulation is compared to that of Euler angles-based algorithms over random and structured point clouds with increasing levels of isotropic Gaussian noise. Additionally, pair matching errors were introduced to assert the performance of both algorithms when dealing with more realistic data. Monte-Carlo results along with more realistic test cases show a better performance for the new MRP formulation in terms of accuracy and speed, with convergence achieved in average 30% faster than the baseline algorithm. [View Full Paper]

* Pre-Ph.D. Candidate, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado 80309, U.S.A. AIAA Student Member.

† Assistant Research Professor, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado 80309, U.S.A. AIAA Senior Member.

AAS 17-271

TIME DEPENDENCE OF COLLISION PROBABILITIES DURING SATELLITE CONJUNCTIONS

Doyle T. Hall,* Matthew D. Hejduk† and Lauren C. Johnson‡

The NASA Conjunction Assessment Risk Analysis (CARA) team has recently implemented updated software to calculate the probability of collision (P_c) for Earth-orbiting satellites. The algorithm can employ complex dynamical models for orbital motion, and account for the effects of non-linear trajectories as well as both position and velocity uncertainties. This "3D P_c" method entails computing a 3-dimensional numerical integral for each estimated probability. Analysis indicates that the 3D method provides several new insights over the traditional "2D P_c" method, even when approximating the orbital motion using the relatively simple Keplerian two-body dynamical model. First, the formulation provides the means to estimate variations in the time derivative of the collision probability, or the *probability rate*, R_c. For close-proximity satellites, such as those orbiting in formations or clusters, R_c variations can show multiple peaks that repeat or blend with one another, providing insight into the ongoing temporal distribution of risk. For single, isolated conjunctions, R_c analysis provides the means to identify and bound the times of peak collision risk. Additionally, analysis of multiple actual archived conjunctions demonstrates that the commonly used "2D P_c" approximation can occasionally provide inaccurate estimates. These include cases in which the 2D method yields negligibly small probabilities (*e.g.*, $P_c < 10^{-10}$), but the 3D estimates are sufficiently large to prompt increased monitoring or collision mitigation (*e.g.*, $P_c \geq 10^{-5}$). Finally, the archive analysis indicates that a relatively efficient calculation can be used to identify which conjunctions will have negligibly small probabilities. This small-P_c screening test can significantly speed the overall risk analysis computation for large numbers of conjunctions. [View Full Paper]

* Senior Scientist, NASA Robotic CARA, Omitron Inc., 555 E. Pikes Peak Avenue, #205, Colorado Springs, Colorado 80903, U.S.A.

† Chief Engineer, NASA Robotic CARA, Astrorum Consulting LLC, 10006 Willow Bend Drive, Woodway, Texas 76712, U.S.A.

‡ Analysis Lead, NASA Robotic CARA, Omitron Inc., 555 E. Pikes Peak Avenue, #205, Colorado Springs, Colorado 80903, U.S.A.

AAS 17-318

INTENSITY CORRELATION IMAGING OF SPACE OBJECTS VIA NOISE REDUCING PHASE RETRIEVAL

David C. Hyland*

Intensity Correlation Imaging (ICI) offers a relatively inexpensive and robust technique to image space objects at fine angular resolution, but has been limited to bright sources. This paper describes the application of recently developed noise reducing phase retrieval algorithms to ICI. Coherence magnitude estimation via photon arrival coincidence counting, and the corresponding statistics, are explained. The phase retrieval algorithms are extended so as to incorporate *a priori* information, such as object size or outline estimates. More complex data can be encoded by choice of the integration time for each baseline. By this stratagem, the effective SNR is greatly increased. [View Full Paper]

* Professor of Aerospace Engineering, Emeritus, Dwight Look College of Engineering, Texas A&M University, TAMU 3141, College Station, Texas 77843-3141, U.S.A.

AAS 17-332

POLICY GRADIENT APPROACH FOR DYNAMIC SENSOR TASKING APPLIED TO SPACE SITUATIONAL AWARENESS

Richard Linares* and Roberto Furfaro†

This paper studies the sensors tasking and management problem for optical Space Object (SO) tracking. The tasking problem is formulated as Markov Decision Process (MDP) and solved using Reinforcement Learning (RL). This RL problem is solved using actor-critic policy gradient approach. This approach is used to find the optimal policy for tasking optical sensors to estimate SO orbits. The reward function is based reducing the uncertainty for the overall catalog to a given upper bound. The reward is negative as long as a SO exist that is about the desired catalog uncertainty. This work tests this approach in simulation and good performance is found using the actor-critic policy gradient approach.
[View Full Paper]

* Assistant Professor, Department of Aerospace Engineering and Mechanics, University of Minnesota, Twin City Campus, Minneapolis, Minnesota 55403, U.S.A. E-mail: rlinares@umn.edu. Member AIAA.
† Associate Professor, Department of Systems & Industrial Engineering, University of Arizona, Tucson, Arizona 85721, U.S.A. E-mail: robertof@email.arizona.edu.

AAS 17-354

METHOD OF EQUIVALENT CROSS SECTION AREA (MECSA) USED IN THE ANALYTICAL FORMULATION OF PROBABILITY OF COLLISION

Ken Chan*

This paper discusses the Method of Equivalent Cross Section Area (MECSA) introduced in the analytical formulation of the probability of collision between two orbiting objects. This principle was applied to approximate the elliptical area of integration in an isotropic two-dimensional Gaussian probability density distribution by a circular one with the same area and the same centroid. The results so obtained agreed to three or four significant figures with detailed computations using realistic values of the covariance and miss distance of spacecraft encounters. The reason for this extraordinary agreement is because all odd and approximately half the even order correction terms vanish in a Taylor's expansion when they are integrated over any bi-symmetric region. The second and fourth order correction terms are derived in closed form in this paper for the case in which the bi-symmetric region is an ellipse. A combination of Affine Transformation and MECSA may be applied to compute the probability of collision between a non-spherical spacecraft and a debris object. [View Full Paper]

* Chan Aerospace Consultants, 25803 Anderby Lane, South Riding, Virginia 20152, U.S.A.

ORBITAL ERROR PROPAGATION ANALYSIS USING DIRECTIONAL STATISTICS FOR SPACE OBJECTS

John T. Kent,[*] Shambo Bhattacharjee,[†] Islam I. Hussein[‡] and Moriba K. Jah[§]

As increasing numbers of optical line-of-sight observations become available for space objects, the space situational awareness community is presented with the computationally challenging problem of representing the uncertainty efficiently and accurately. The motion of a space object in orbit about the earth is described by Newtonian mechanics. More specifically, if measurements for the position and velocity at an initial time are available up to Gaussian noise, then point clouds are typically used to describe the propagated uncertainty at later times. In this paper we show that it is possible to describe succinctly the angular part of the position vector at later times using a version of the Fisher-Bingham-Kent distribution from directional statistics. [View Full Paper]

[*] Professor, Department of Statistics, University of Leeds, Leeds, LS2 9JT, United Kingdom.
[†] Department of Statistics, University of Leeds, Leeds, LS2 9JT, United Kingdom.
[‡] Applied Defense Solutions, 10440 Little Patuxent Parkway, Suite 600, Columbia, Maryland 21044, U.S.A.
[§] Professor, College of Engineering, Office for Research and Discovery, University of Arizona, Tucson, Arizona 85721, U.S.A.

AAS 17-393

ANGLES-ONLY DATA ASSOCIATION USING DIRECTIONAL DISCRIMINANT ANALYSIS

John T. Kent,[*] Shambo Bhattacharjee,[†] Islam I. Hussein[‡] and Moriba K. Jah[§]

Suppose that for a library of space objects, their predicted angular positions at the current time are available from previous observations, including an assessment of the errors. Given a new angles-only observation at the current time, the objective is to decide which object, if any, in the library corresponds to the observed object. The Fisher-Bingham-Kent distribution from directional statistics provides a powerful and tractable model to summarize uncertainty and to implement the classic methods of discriminant analysis from multivariate analysis for this data association problem. [View Full Paper]

[*] Professor, Department of Statistics, University of Leeds, Leeds, LS2 9JT, United Kingdom.
[†] Department of Statistics, University of Leeds, Leeds, LS2 9JT, United Kingdom.
[‡] Applied Defense Solutions, 10440 Little Patuxent Parkway, Suite 600, Columbia, Maryland 21044, U.S.A.
[§] Professor, College of Engineering, Office for Research and Discovery, University of Arizona, Tucson, Arizona 85721, U.S.A.

AAS 17-401

OPTICAL SENSOR FOLLOW-UP TASKING ON HIGH PRIORITY UNCORRELATED TRACK

Timothy S. Murphy,[*] Marcus J. Holzinger,[†] K. Kim Luu[‡] and Chris Sabol[‡]

This work proposes a methodology for tasking of electro-optical sensors to search an area of state space for a particular object. This work enables current space situational awareness programs to more efficiently follow-up on an unknown object. In particular, this work looks at searching for an unknown space object with prior knowledge in the form of a set, which can be defined via an uncorrelated track. The follow-up can occur from a different location at a different time, which often requires searching a large region of the sky. This work analyzes the divergence of a search region to inform a time optimal search method. Simulation work is included to explore the effects of sensor geometry, initial detection uncertainty, and handoff delay time on total time and feasibility of follow-up.

[View Full Paper]

[*] Graduate Student, The Guggenheim School of Aerospace Engineering, Georgia Institute of Technology, Georgia Institute of Technology, North Avenue NW, Atlanta, Georgia 30332, U.S.A.

[†] Assistant Professor, The Guggenheim School of Aerospace Engineering, Georgia Institute of Technology, Georgia Institute of Technology, North Avenue NW, Atlanta, Georgia 30332, U.S.A. AIAA Senior Member.

[‡] Air Force Research Laboratory, 535 Lipoa Parkway, Suite 200, Kihei, Hawaii 96753, U.S.A.

AAS 17-415

APPLICATION OF SEQUENTIAL MONTE CARLO METHODS FOR SPACE OBJECT TRACKING*

Islam I. Hussein,† Waqar Zaidi,† Weston Faber,† Christopher W. T. Roscoe,† Matthew P. Wilkins,† Paul W. Schumacher, Jr.‡ and Mark Bolden†

The problem of producing timely, accurate, and statistically meaningful space situational awareness data products from diverse data sources is one of the most challenging classes of multi-object tracking problems. The space object tracking problem, in general, is nonlinear in both state dynamics and observations, making it ill-suited to linear filtering techniques such as the Kalman filter. The more general Bayesian filtering problem is often solved using Gaussian mixtures. Additionally, given the multi-object, multi-scenario nature of the problem, space situational awareness requires multi-hypothesis tracking and management that is combinatorically challenging in nature. This paper describes the application of Sequential Monte Carlo methods for both nonlinear filtering as well as the handling of the potentially very large number of hypotheses. For nonlinear filtering, we use the novel Particle Gaussian Mixture filter. The paper discusses issues of data association and object birth, with an illustrative example. Since they make no assumptions about the underlying linearity or Gaussianity of the problem, the proposed multi-object filtering solution provides the most statistically consistent characterization of uncertainty for Bayesian filtering. [View Full Paper]

---

* DISTRIBUTION STATEMENT A. Approved for public release. Distribution is unlimited.

† Applied Defense Solutions, Inc., 10440 Little Patuxent Parkway, Suite 600, Columbia, Maryland 21044, U.S.A.

‡ Air Force Research Laboratory, 535 Lipoa Parkway, Suite 200, Kihei, Hawaii 96753, U.S.A.

AAS 17-434

DYNAMIC COORDINATE SYSTEMS FOR FASTER ORBITAL STATE PROPAGATION

Blair F. Thompson,[*] Islam I. Hussein[*] and Thomas Kelecy[*]

New coordinate systems have been developed for the specific purpose of enabling faster numerical orbital state propagation without changing integration order or method. This enhancement could find application in spacecraft flight software for autonomous rendezvous and proximity operations, formation flying, or for large constellations of satellites where long-term ephemerides must be periodically generated onboard each spacecraft for potential conjunction analysis, stationkeeping, etc. This may be especially true for smaller satellites with older, less powerful, space-proven flight computers that are operating near full computational capacity, making long-term state propagation highly impractical. The motion of the new, non-inertial coordinate systems was chosen to closely match the dynamic state of the spacecraft and, therefore, accounts for much of the orbital motion of the spacecraft. As a result, the spacecraft state changes much more slowly over time relative to the moving coordinate systems, allowing for significantly larger time steps with negligible loss of accuracy during numerical propagation. The equations of motion in the new coordinate systems permit the inclusion of any existing force models that are formulated in the more commonly used inertial coordinates, including any known maneuver thrust profiles. Initial tests and evaluation using a single step integration method show that numerical propagation speed is significantly increased, especially for low eccentricity orbits commonly used for low-earth and geosynchronous operations. Additionally, application of the new coordinate systems to non-Gaussian and non-linear particle filtering and unscented Kalman filtering might also result in significantly improved integration speeds for autonomous spacecraft navigation. The new coordinate systems may also improve numerical integration of orbital state transition matrices for faster propagation of state estimate covariance matrices. [View Full Paper]

[*] Senior Scientist, Applied Defense Solutions, 10440 Little Patuxent Parkway, Suite 600, Columbia, Maryland 21044, U.S.A.

AAS 17-477

MULTIPLE SPACE OBJECT TRACKING USING RANDOMIZED FINITE SET STATISTICS (R-FISST)

W. Faber,[*] S. Chakravorty[*] and Islam I. Hussein[†]

In multi-object tracking the amount and ambiguity of measurement returns can create scenarios where the number of possible hypotheses is computationally intractable. When ambiguous measurements are received there is uncertainty when deciding which objects to assign them to. This is known as the Data Association Problem (DAP). It is further complicated when previously unknown objects of interest or sources of clutter could produce the measurements that are received. Recent literature has proposed a technique that is particularly suited for such scenarios. This technique is called Randomized Finite Set Statistics (R-FISST). This method has shown success on various proof of concept cases however it has never been applied to real data or any realistic scenarios. This paper applies R-FISST to real data to show that the R-FISST technique performs in realistic scenarios. This paper also discusses the advantages of using the R-FISST structure. Specifically, the fact that one is not limited to using any particular measurement model, dynamic model, birth and death model, filtering technique, or object Probability Density Function (pdf) representation. Using different models within the R-FISST structure will change the accuracy of tracking error but only effects the DAP when developing measurement likelihood. As long as one uses models that are compatible then the R-FISST technique will solve the DAP and keep the multi-object tracking problem computationally tractable.

[View Full Paper]

[*] Department of Aerospace Engineering, Texas A&M University, College Station, Texas 77843-3141, U.S.A.
[†] Applied Defense Solutions, 10440 Little Patuxent Parkway, Suite 600, Columbia, Maryland 21044, U.S.A.

A SUMMARY OF EMERGING RESEARCH IN THE NEW BIG DATA SPACE SITUATIONAL AWARENESS PARADIGM

Douglas L. Hendrix,[*] Michael Bantel, William Therien, Brien R. Flewelling, Benjamin Lane, Phillip M. Cunio, Mark W. Jeffries Jr.

Orbit determination, behavioral analysis, space object characterization, and other fundamental research areas underpinning the Space Situational Awareness (SSA) mission need not be based on inferring information from sparse data collections. With the emergence of commercial observation networks with orders of magnitude more data sources observing space objects than have been available before, new research is supported by significant volumes of quality observations that are of great interest to the community. Solutions in these areas will provide important capabilities which will enable a better understanding of the behavior of objects in space. We summarize three here which are enabled by data collected by global observation networks. [View Full Paper]

[*] ExoAnalytic Solutions, 20532 El Toro Road, Suite 303, Mission Viejo, California 92692, U.S.A. (all authors).

LAUNCH AND LANDING OPERATIONS

Session Chair:

Session 5: David Spencer

AAS 17-220

TRAJECTORY ANALYSIS FOR THE UNICORN SMALL SINGLE-STAGE-TO-ORBIT LAUNCH VEHICLE

Andrew E. Turner*

Many small launchers are currently under development to address the growing miniature spacecraft market including CubeSats and other small vehicles. All such launchers employ conventional LOX-kerosene propellants in a Two Stage to Orbit (TSTO) configuration. This paper provides trajectory analysis and vehicle design background for a LOX-liquid hydrogen approach which enables a Single Stage to Orbit (SSTO) launcher, with attendant savings in production and other costs, including employment of a single large engine for all major maneuvers. SSTO avoids the in-flight stage separation and engine ignition under TSTO with its associated design complexities and failure modes, as will be discussed. [View Full Paper]

* Senior Engr. Specialist, Advanced Program & Systems, Space Systems Loral (SSL), 3825 Fabian Way, MS G-54, Palo Alto, California 94303-4604. Senior Member AIAA.

AAS 17-254

ENTRY, DESCENT, AND LANDING GUIDANCE AND CONTROL APPROACHES TO SATISFY MARS HUMAN MISSION LANDING CRITERIA

Alicia Dwyer Cianciolo* **and Richard W. Powell†**

Precision landing on Mars is a challenge. All Mars lander missions prior to the 2012 Mars Science Laboratory (MSL) had landing location uncertainty ellipses on the order of hundreds of kilometers. Sending humans to the surface of Mars will likely require multiple landers delivered in close proximity, which will in turn require orders of magnitude improvement in landing accuracy. MSL was the first Mars mission to use an Apollo-derived bank angle guidance to reduce the size of the landing ellipse. It utilized commanded bank angle magnitude to control total range and bank angle reversals to control cross range. A shortcoming of this bank angle guidance is that the open loop phase of flight created by use of bank reversals increases targeting errors. This paper presents a comparison of entry, descent and landing performance for a vehicle with a low lift-to-drag ratio using both bank angle control and an alternative guidance called Direct Force Control (DFC). DFC eliminates the open loop flight errors by directly controlling two forces independently, lift and side force. This permits independent control of down range and cross range. Performance results, evaluated using the Program to Optimize Simulated Trajectories (POST2), including propellant use and landing accuracy, are presented.

[View Full Paper]

* Aerospace Engineer, Atmospheric Flight and Entry Systems Branch (AFESB), NASA LaRC, Hampton, Virginia 23681, U.S.A.

† Aerospace Engineer, AFESB, Analytical Mechanics and Associates, MS 489, Hampton, Virginia 23681, U.S.A.

AAS 17-274

LAUNCH VEHICLE ASCENT TRAJECTORY SIMULATION USING THE PROGRAM TO OPTIMIZE SIMULATED TRAJECTORIES II (POST2)

Rafael A. Lugo,[*] Jeremy D. Shidner,[*] Richard W. Powell,[*] Steven M. Marsh,[†] James A. Hoffman,[†] Daniel K. Litton[‡] and Terri L. Schmitt[§]

The Program to Optimize Simulated Trajectories II (POST2) has been continuously developed for over 40 years and has been used in many flight and research projects. Recently, there has been an effort to improve the POST2 architecture by promoting modularity, flexibility, and ability to support multiple simultaneous projects. The purpose of this paper is to provide insight into the development of trajectory simulation in POST2 by describing methods and examples of various improved models for a launch vehicle liftoff and ascent. [View Full Paper]

[*] Aerospace Engineer, Analytical Mechanics Associates, Inc., Hampton, Virginia 23666, U.S.A.
[†] Software Engineer, Analytical Mechanics Associates, Inc., Hampton, Virginia 23666, U.S.A.
[‡] Aerospace Engineer, NASA Langley Research Center, Hampton, Virginia 23666, U.S.A.
[§] Aerospace Engineer, NASA Marshall Space Flight Center, Huntsville, Alabama 35812, U.S.A.

AAS 17-370

LANDING ON SMALL BODIES TRAJECTORY DESIGN, ROBUST NONLINEAR GUIDANCE AND CONTROL

Eric Joffre,[*] Mattia Zamaro,[†] Nuno Silva,[‡] Andrés Marcos,[§] Pedro Simplício[**] and Barbara Richardson[††]

While common Descent and Landing strategies involve extended periods of forced motion, significant fuel savings could be achieved by exploiting the natural dynamics in the vicinity of the target. However, small bodies are characterized by perturbed and poorly known dynamics environments, calling for autonomous guidance, navigation and robust control. Airbus Defence and Space and the University of Bristol have been contracted by the UK Space Agency to investigate the optimisation of landing trajectories, including novel approaches from dynamical systems theory, and robust nonlinear control techniques. This paper presents these techniques, with an application to the strategic case of a mission to Phobos. [View Full Paper]

[*] Mission Analysis and AOCS/GNC Engineer, AOCS/GNC and Flight Dynamics UK R&D Coordinator, Airbus Defence and Space Ltd., Gunnels Wood Road, Stevenage SG1 2AS, United Kingdom.
[†] Mission Analysis and AOCS/GNC Engineer, AOCS analyst, contractor for Airbus Defence and Space Ltd.
[‡] Head of AOCS/GNC and Flight Dynamics UK, Airbus Defence and Space Ltd.
[§] Head of TASC Technology for AeroSpace Control, Senior Lecturer, University of Bristol, Queen's Building, University Walk, Bristol BS8 1TR, United Kingdom.
[**] Ph.D. Researcher in Aerospace Engineering, University of Bristol.
[††] National Space Technology Programme Manager, UKSA, Polaris House, North Star Avenue, Swindon SN2 1SZ, United Kingdom.

AAS 17-399

REUSABLE BOOSTER LAUNCH VEHICLE OPTIMAL BRANCHING TRAJECTORIES*

Demyan V. Lantukh† and Shaun P. Brown‡

The trajectories and trajectory parameters of a reusable booster stage and disposable upper stage are solved simultaneously using direct transcription optimal control techniques. The combined approach enables efficient tradeoff between the stages and demonstrates key features of the resulting trajectories in an end-to-end optimization that maximizes delivered payload to different orbits. Specialized dynamics and constraints are applied in the commercial collocation tool GPOPS-II for two very different launch concepts and three target orbits: boost-back and mixed boost-glide-back first stage return; targeting low earth, polar, and geosynchronous transfer target orbits. [View Full Paper]

---

* Approved for Public Release, OTR 2017-00124.

† Member of the Technical Staff, Flight Mechanics Department, The Aerospace Corporation, El Segundo, California 90245, U.S.A.

‡ Senior Member of the Technical Staff, Flight Mechanics Department, The Aerospace Corporation, El Segundo, California 90245, U.S.A.

AAS 17-520

DESIGN ROCKET VERTICAL LANDING GUIDANCE LAW USING A GAUSS POINT DISCRETE CONVEX PROGRAMMING

Zhiguo Zhang,* Guangyou Geng,† Ying Ma,‡ Menglun Yu§ and Mingwei Yin**

The Legendre-Gauss-Lobatto (LGL) polynomial zeros point discrete convex programming is used to design the rocket's vertical recovery landing guidance law. A resulting SOCP problem is solved in both entry-powered deceleration phase and vertical landing phase, and a successive linearization relaxation technique is used to deal with highly nonlinear constrained trajectory optimization problem. Through choosing very few LGL polynomial zeros, a piecewise Lagrange interpolation approximation of the control input is used to discrete original problem into a parametric optimization problem. Finally, the guidance accuracy of different guidance methods is compared, and the results show this method has high solving efficiency and strong adaptability. [View Full Paper]

* Ph.D. Candidate, Beijing Institute of Aerospace System Engineering, China. E-mail: zhangzhiguo08@yeah.net.
† Senior Engineer, Beijing Institute of Aerospace System Engineering, China. E-mail: genggybj@163.com.
‡ Senior Engineer, Beijing Institute of Aerospace System Engineering, China. E-mail: maying@buaa.edu.cn.
§ Senior Engineer, Beijing Institute of Aerospace System Engineering, China. E-mail: yml361108@126.com.
** Ph.D. Candidate, School of Aerospace, Tsinghua University, China. E-mail: ymw13@mails.tsinghua.edu.cn.

TRAJECTORY DESIGN

Session Chair:

Session 6: Jeff Parker

AAS 17-286

TRAJECTORY DESIGN FOR A CISLUNAR CUBESAT LEVERAGING DYNAMICAL SYSTEMS TECHNIQUES: THE LUNAR ICECUBE MISSION

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

Lunar IceCube is a 6U CubeSat that is designed to detect and observe lunar volatiles from a highly inclined orbit. This spacecraft, equipped with a low-thrust engine, will be deployed from the upcoming Exploration Mission-1 vehicle in late 2018. However, significant uncertainty in the deployment conditions for secondary payloads impacts both the availability and geometry of transfers that deliver the spacecraft to the lunar vicinity. A framework that leverages dynamical systems techniques is applied to a recently updated set of deployment conditions and spacecraft parameter values for the Lunar IceCube mission, demonstrating the capability for rapid trajectory design. [View Full Paper]

[*] Post-Doctoral Research Assistant, School of Aeronautics and Astronautics, Purdue University, 701 W. Stadium Avenue, West Lafayette, Indiana 47907, U.S.A.; currently Assistant Professor, Department of Aerospace Engineering Sciences, University of Colorado Boulder, 429 UCB, Boulder, Colorado 80309, U.S.A.
[†] Graduate Student, School of Aeronautics and Astronautics, Purdue University, 701 W. Stadium Avenue, West Lafayette, Indiana 47907, U.S.A.
[‡] Hsu Lo Distinguished Professor of Aeronautics and Astronautics, School of Aeronautics and Astronautics, Purdue University, 701 W. Stadium Avenue, West Lafayette, Indiana 47907, U.S.A.
[§] Senior Fellow, NASA Goddard Space Flight Center, 8800 Greenbelt Road, Greenbelt, Maryland 20771, U.S.A.

AAS 17-344

MULTI-GOAL TRAJECTORY PLANNING FOR REDUNDANT SPACE ROBOT

Suping Zhao,[*] Zhanxia Zhu,[†] Bruno Siciliano,[‡] Alejandro Gutiérrez-Giles,[§] Jing Lang Feng[**] and Jianjun Luo[††]

The multi-goal trajectory planning problem (MTPP) for redundant space robots is studied in the paper. The robot's end-effector should go through several waypoints with minimum distance, while the sequence of the waypoints is not predefined. The problem is converted into a bilevel optimization problem. The aim of the first level is to search for an optimal path that passes through the predefined waypoints. Based on the optimal path got in the first level, the aim of the second level is to search for the appropriate joint movements. A two-layer-based heuristic algorithm is employed to solve the bilevel optimization problem. [View Full Paper]

[*] Ph.D. Candidate, National Key Laboratory of Aerospace Flight Dynamics, Northwestern Polytechnical University, 127 Youyi West Road, Xi'an, 710072, China. E-mail: suping36@mail.nwpu.edu.cn.

[†] Professor, National Key Laboratory of Aerospace Flight Dynamics, Northwestern Polytechnical University, 127 Youyi West Road, Xi'an, 710072, China. E-mail: zhuzhanxia@nwpu.edu.cn.

[‡] Professor, Department of Electrical Engineering and Information Technology, University of Naples Federico II, Via Claudio 21, 80125 Naples, Italy. E-mail: siciliano@unina.it.

[§] Dr., Consortium CREATE, University of Naples Federico II, Via Claudio 21, 80125 Naples, Italy. E-mail: alejandrogilesg@yahoo.com.mx.

[**] Dr., School of Astronomy and Space Science, Nanjing University; 163 Xianlin Road, Nanjing, 210023, China. E-mail: jinglang@nju.edu.cn.

[††] Professor, National Key Laboratory of Aerospace Flight Dynamics, Northwestern Polytechnical University, 127 Youyi West Road, Xi'an, 710072, China. E-mail: jjluo@nwpu.edu.cn.

AAS 17-356

REACHABLE DOMAIN OF SPACECRAFT WITH A SINGLE NORMAL IMPULSE

Junhua Zhang,[*] Jianping Yuan,[†] Wei Wang,[*]
Jinglang Feng[‡] and Zhanxia Zhu[†]

The reachable domain for spacecraft with a single normal impulse is studied. In this paper, the problem is addressed in an analytical approach by analyzing for either the initial maneuver point or the impulse magnitude being arbitrary. The trajectories are considered lying in the intersection of a plane and an ellipsoid of revolution, whose family can be determined in an analytical way. In addition, the related orbital parameters such as angular momentum and eccentricity are also derived in a closed form for each case. The impulse constraints and time constraints are also considered while formulating the problem. Several numerical analyses are performed in MATLAB to show the geometry of the reachable domain. [View Full Paper]

[*] Ph.D. Student, National Key Laboratory of Aerospace Flight Dynamics, Northwestern Polytechnical University, 127 West Youyi Road, Xian Shaanxi, 710072, P.R. China.
[†] Professor, National Key Laboratory of Aerospace Flight Dynamics, Northwestern Polytechnical University, 127 West Youyi Road, Xian Shaanxi, 710072, P.R. China.
[‡] Postdoctor, School of Astronomy and Space Science, Nanjing University, 163 Xianlin Road, Qixia District, Nanjing, Jiangsu Province, 210023, P.R. China.

AAS 17-372

TRAJECTORY PLANNING OF APPROACHING NON-COOPERATIVE TARGETS BASED ON GAUSS PSEUDOSPECTRAL METHOD

Shi Heng* and Zhu Jihong†

To capture a non-cooperative spacecraft whose status and information are unavailable has become a hot issue worldwide recently. This paper proposes a new trajectory planning method to solve the optimal control problem of non-cooperative target capture mission with obstacles in the final approaching phase. A continuous model based on the kinetic mechanism of spacecraft is constructed at first. Attitude of chaser craft and relative position are set as state variables. The path of avoiding obstacles is considered as constraint. Combined with terminal constraints and performance index, the parametric optimization model of algebraic constraints is established. Gauss pseudospectral method is deployed to discretize the continuous model. The problem is solved by sequential quadratic programming. Calculation and simulation module is developed to prove the feasibility of the method. [View Full Paper]

* Ph.D. Candidate, Department of Computer Science and Technology, State Key Laboratory on Intelligent Technology and Systems, Tsinghua National Laboratory for Information Science and Technology, Tsinghua University, Beijing, China.

† Professor, Department of Computer Science and Technology, State Key Laboratory on Intelligent Technology and Systems, Tsinghua National Laboratory for Information Science and Technology, Tsinghua University, Beijing, China.

AAS 17-438

STRATEGIES FOR LOW-THRUST TRANSFERS FROM ELLIPTICAL ORBITS TO GEOSTATIONARY ORBIT

Craig A. Kluever* and Scott R. Messenger†

Low-thrust transfers to geostationary-equatorial orbit (GEO) will likely start in energetic orbits in order to reduce the transfer time. One attractive option is to initiate the low-thrust transfer from a geostationary-transfer orbit (GTO). While trajectory-optimization researchers understand the low-thrust GTO-GEO transfer, they do not fully understand the spacecraft's interaction with trapped particles in the Van Allen radiation belts. This paper merges the low-thrust transfer problem with state-of-the-art models for the radiation environment and the associated solar-cell degradation. The goal is to develop the initial steps toward a general method for computing the power loss after a low-thrust transfer from an elliptical starting orbit. The method presented here quickly and accurately predicts the solar-array power degradation and the corresponding increase in transfer time without relying on running (and re-running) time-consuming, state-of-the-art solar-cell modeling software. Numerical examples illustrate this method. [View Full Paper]

* Professor, Mechanical and Aerospace Engineering Department, University of Missouri-Columbia, Columbia, Missouri 65211, U.S.A. E-mail: KlueverC@missouri.edu. Associate Fellow AIAA, Fellow AAS.
† Radiation Survivability Physicist, Northrop Grumman Corporation, Linthicum, Maryland 21090, U.S.A.
E-mail: Scott.Messenger@ngc.com.

OPTIMAL TRAJECTORY DESIGN AND CONTROL OF A PLANETARY EXPLORATION ROVER

Ameya R. Godbole,[*] V. N. V. Murali,[*] Paul Quilen[*] and Kamesh Subbarao[†]

The purpose of this paper is to combine the Navigation function path-planning algorithm with the minimum jerk trajectory design for a planetary exploration rover with some physical constraints associated with it. A new method to redesign the trajectory will be discussed when the physical constraints suddenly change. A trajectory tracking controller will be designed so as to calculate the wheel speeds. This will simplify the process of merging the framework with the experimental setup by having control law calculate the wheel speeds for tracking the trajectory of the rover. [View Full Paper]

[*] Graduate Student, Mechanical and Aerospace Engineering Department, University of Texas at Arlington, 500 W. 1st Street, Arlington, Texas 76010, U.S.A.

[†] Associate Professor, Mechanical and Aerospace Engineering Department, University of Texas at Arlington, 500 W. 1st Street, Arlington, Texas 76010, U.S.A.

AAS 17-510

A NOVEL METHODOLOGY FOR FAST AND ROBUST COMPUTATION OF LOW-THRUST ORBIT-RAISING TRAJECTORIES

Suwat Sreesawet[*] and Atri Dutta[†]

All-electric spacecraft makes numerous revolutions during the orbit-raising to the geosynchronous equatorial orbit. This paper presents a new mathematical formulation to describe the dynamics of the spacecraft under the action of continuous thrust. Furthermore, it presents a new optimization framework that considers the proposed dynamic model to solve a sequence of optimization sub-problems for rapid and robust generation of the low-thrust orbit-raising trajectories. It is considered that the spacecraft does not thrust in the shadow of the Earth. Numerical results for different orbit-raising mission scenarios are presented to illustrate the performance of the algorithm. [View Full Paper]

[*] Ph.D. Student, Aerospace Engineering, Wichita State University, 1845 Fairmount Street Box 44, Wichita, Kansas 67260, U.S.A.

[†] Assistant Professor, Aerospace Engineering, Wichita State University, 1845 Fairmount Street Box 44, Wichita, Kansas 67260, U.S.A.

DYNAMICAL SYSTEMS THEORY APPLIED TO SPACE FLIGHT

Session Chair:

Session 7: Kathleen Howell

AAS 17-464

REACHABILITY SUBSPACE EXPLORATION USING CONTINUATION METHODS

Julian Brew,* Marcus J. Holzinger† and Stefan Schuet‡

Reachability manifold computation suffers from the curse of dimensionality and for large state spaces is computationally intractable. This paper examines the use of continuation methods to address this issue by formulating the reachability subspace manifold calculation into a number of initial value problems. As a result of computing the reachability manifold for a subspace of interest, an exponential improvement in computational cost occurs. This concept is applied to a position subspace reachability problem of a spacecraft in a Keplerian orbit under maximum thrust constraints. Future work includes a comparison of the proposed method with computing reachability manifolds using viscosity solutions of the Hamilton Jacobi Bellman partial differential equation. [View Full Paper]

* Graduate Student, The Guggenheim School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, Georgia 30332, U.S.A. AIAA Student Member.
† Assistant Professor, The Guggenheim School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, Georgia 30332, U.S.A. AIAA Senior Member.
‡ Research Engineer, NASA Ames Research Center, Moffett Field, California 94035, U.S.A.

AAS 17-504

EVALUATING QUASI-PERIODIC TRAJECTORIES IN THE VICINITY OF IRREGULAR SMALL BODIES WITH ENTROPY

Yanshuo Ni,[*] Konstantin S. Turitsyn,[†] Hexi Baoyin[‡] and Junfeng Li[‡]

Discrete Fourier Transform (DFT) and the concept of entropy are used to analyze trajectories in the vicinity of 243 Ida and 6489 Golevka by measuring the periodicity of quasi-periodic trajectories. Having introduced concept of entropy, analytical derivation and numerical results indicates that entropies increase as a logarithmic function of time, that periodic trajectories usually have higher entropies and that trajectories with higher entropies means the motion is more organized and the numerical results verify these conclusions, which also indicates that applying DFT to the trajectories in the vicinity of irregular small bodies and calculating their entropy of the result after DFT provides a useful method evaluating quality of quasi-periodic trajectories by their orderliness in the periodicity of motion. Some trajectories near asteroids looking irregular have higher entropy and clearer regularity of frequency in three directions analyzed by this method. The work of this research means that one can evaluate the quality of quasi-periodic trajectories in a given time interval by quantitative analysis. [View Full Paper]

[*] Ph.D. Candidate, School of Aerospace Engineering, Tsinghua University, Beijing 100084, P.R. China.
[†] Associate Professor, Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, U.S.A.
[‡] Professor, School of Aerospace Engineering, Tsinghua University, Beijing 100084, P.R. China.

AAS 17-515

SURVEY OF MARS BALLISTIC CAPTURE TRAJECTORIES USING PERIODIC ORBITS

Diogene A. Dei Tos,[*] Ryan P. Russell[†] and Francesco Topputo[‡]

A systematic approach is devised to find ballistic captures in the planar elliptic restricted three-body problem. Simple symmetric periodic orbits around the secondary body of the circular problem, computed through a global grid search, are used as generators for ballistic captures in the elliptic problem. Combining a scaling factor that maps states from the circular to the elliptic case and restricting the motion to emanate from periodic solutions, the search space for ballistic capture is reduced to three dimensions. Results in the Sun–Mars system indicate an abundance of long time-of-flight regular solutions with a variety of characteristics, including low osculating eccentricities. [View Full Paper]

[*] Ph.D. Candidate, Department of Aerospace Science and Technology, Politecnico di Milano, Milan 20156, Italy.
[†] Associate Professor, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, Texas 78712, U.S.A.
[‡] Assistant Professor, Department of Aerospace Science and Technology, Politecnico di Milano, Milan 20156, Italy.

MAPPING CONNECTIONS BETWEEN PLANAR SUN–EARTH–MOON LIBRATION POINT ORBITS

Zubin P. Olikara[*] and Daniel J. Scheeres[†]

Natural connections between L_1 and L_2 libration point orbits in the Sun–Earth and Earth–Moon systems are prevalent. An approach is presented for mapping the full two-parameter structure of the main heteroclinic connection families. This study takes into account the phasing of the Sun, Earth, and Moon in a planar restricted four-body model. System-to-system connections are considered along with lunar-perturbed heteroclinic transfers in the Sun–Earth system. [View Full Paper]

[*] Researcher, Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado 80309, U.S.A. E-mail: zubin.olikara@colorado.edu.

[†] Distinguished Professor, A. Richard Seebass Chair, Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado 80309, U.S.A. E-mail: scheeres@colorado.edu.

AAS 17-527

ANALYTIC APPROACH ON INVARIANT MANIFOLD OF UNSTABLE EQUILIBRIUM OF RESTRICTED N+1 BODY PROBLEM

Dandan Zheng,[*] Jianjun Luo,[†] Renyong Zhang,[‡] Lei Liu,[§] Jinglang Feng[**] and Jianping Yuan[††]

This paper focusses on the analytical solutions of invariant manifold of unstable Lagrange equilibrium points of restricted N+1 body problem. Because the linear behavior of these equilibrium points is type center x center x saddle. Therefore, there exist stable manifold and unstable manifold, which are respectively tangent to the stable subspaces and unstable subspaces. We can use the improved center manifold theory to obtain Taylor series expansion of neighborhood of these points, these algebraic equation is independent of time. We obtain the geometric structure of restricted N+1 body problem. Compared with numerical integration, the results of three order expansion are consistent with the numerical results in the small neighborhood of libration point, and this approach will avoid explicit numerical differentiation. Restricted three body problem of Earth-moon is studied in detail. [View Full Paper]

[*] Graduated Student, School of Astronautics, Northwestern Polytechnical University; National Key Laboratory of Aerospace Flight Dynamics, 127 Youyi West Road,710072, Xi'an, China.

[†] Professor, School of Astronautics, Northwestern Polytechnical University; National Key Laboratory of Aerospace Flight Dynamics, 127 Youyi West Road,710072, Xi'an, China.

[‡] Engineer, Technology and Engineering Center for Space Utilization, Chinese Academy of Science, No. 9 Dengzhuang South Road, Haidian District, 100094, Beijing, China.

[§] Engineer, National Key Laboratory of Aerospace Flight Dynamics; Beijing Aerospace Control Center, 100094, Beijing, China.

[**] Postdoctoral, School of Astronomy and Space Science, Nanjing University, 163 Xinlin Road, Qixia District, 210000, Nanjing, China.

[††] Professor, School of Astronautics, Northwestern Polytechnical University; National Key Laboratory of Aerospace Flight Dynamics, 127 Youyi West Road, 710072, Xi'an, China.

SATELLITE CONSTELLATIONS

Session Chair:

Session 8: John Seago

The following paper was not available for publication:

AAS 17-471 Paper Withdrawn

AAS 17-207

MULTIPLE AGILE EARTH OBSERVATION SATELLITES SCHEDULING ALGORITHM ON AREA TARGETS

Xinwei Wang,[*] Yinrui Rao[†] and Chao Han[‡]

Limited to the time windows, it is hard for the ordinary satellite to accomplish the observation mission on the large-scale area target. However, the agile satellite with more attitude freedom could complete the task in a short period. In this paper, a division method is utilized to decompose the area target into several point targets. Then a decomposition optimization algorithm, which consists of a novel multiple satellites assignment method and the graph theory, is adopted to obtain the scheduling results. Furthermore, two typical observing modes are defined according to the practical requirements. Simulations indicate the observation missions have been completed. [View Full Paper]

[*] Ph.D. Candidate, School of Astronautics, Beihang University, Beijing, 100191, China.
E-mail: wxw4110531@gmail.com.

[†] Ph.D., Institute of Systems Engineering, China Academy of Engineering Physics, China. E-mail: 409raoyr@caep.cn.

[‡] Professor, School of Astronautics, Beihang University, Beijing, 100191, China. E-mail: hanchao@buaa.edu.cn.

AAS 17-217

CONSTELLATION DESIGN CONSIDERATIONS FOR SMALLSATS

Andrew E. Turner*

Orbits with minimum altitude and inclination reduce launch cost and can optimize observation and communications for specific regions, however requirements to observe other locations, for sun-synchronous orbits, or for rideshare opportunities may dictate higher altitudes and/or higher inclinations. Related trades are discussed. Single-plane, Walker Pattern, Streets of Coverage, Rosette and hybrids of these constellation types are evaluated for coverage of specific regions and the entire Earth. [View Full Paper]

* Senior Engr. Specialist, Advanced Program & Systems, Space Systems Loral (SSL), 3825 Fabian Way, MS G-54, Palo Alto, California 94303-4604. Senior Member AIAA.

AAS 17-234

3D LATTICE FLOWER CONSTELLATIONS USING NECKLACES

David Arnas,[*] Daniel Casanova,[†] Eva Tresaco[†] and Daniele Mortari[‡]

A new approach in satellite constellation design is presented in this paper, taking as a base the 3D Lattice Flower Constellation Theory and introducing the necklace problem in its formulation. This creates a further generalization of the Flower Constellation Theory, increasing the possibilities of constellation distribution and maintaining the characteristic symmetries of the original theory in the design. [View Full Paper]

[*] Centro Universitario de la Defensa, Zaragoza, Spain. GME - IUMA - Universidad de Zaragoza, Spain.
E-mail: darnas@unizar.es.
[†] Centro Universitario de la Defensa, Zaragoza, Spain. GME - IUMA - Universidad de Zaragoza, Spain.
[‡] Department of Aerospace Engineering, Texas A&M University, 3141 TAMU, College Station, Texas 77843-3141, U.S.A. IEEE and AAS Fellow, AIAA Associate Fellow.

AAS 17-360

PERTURBATION IN ORBITAL ELEMENTS OF A HIGH ELLIPTICAL ORBIT OF SATELLITE CONSTELLATIONS

Osama Mostafa,[*] Koki Fujita[†] and Toshiya Hanada[‡]

This work aim to study the effects of various perturbations on the motion of satellites constellation in high elliptical inclined orbit in order to make continuous coverage. A computational model developed at Space Systems Dynamics Laboratory, Kyushu University to study the effect of these perturbations on Molniya and Tundra satellite constellations for various periods one, five and 10 years. The equations of motion under effect of these perturbations forces are solved numerically using Gaussian equations. The results show that the satellites constellation in Molniya orbit have stability under effect of gravity of third body more than Tundra orbit in order to make a continuous coverage.

[View Full Paper]

[*] Ph.D. Student, Aeronautics and Astronautics Department, 819-0395, Nishi-ku, Fukuoka Motooka 744, Japan. E-mail: osama_Astro@aero.kyushu-u.ac.jp. Tel.: +81928022999.

[†] Associate professor, Aeronautics and Astronautics Department, 819-0395, Nishi-ku, Fukuoka Motooka 744, Japan. E-mail: fuji@aero.kyushu-u.ac.jp. Tel.: +81928022999.

[‡] Professor, Aeronautics and Astronautics Department, 819-0395, Nishi-ku, Fukuoka Motooka 744, Japan. E-mail: hanada.toshiya.293@m.kyushu-u.ac.jp. Tel.: +81928022999.

PLANETARY MISSIONS

Session Chair:

Session 9: Angela Bowes

AAS 17-218

DEEP SPACE RELAY TO SUPPORT COMMUNICATIONS BETWEEN EARTH AND MARS

Andrew E. Turner*

Communications between Earth and the multiple spacecraft in orbit around Mars, also the landers and rovers on the surface of the red planet, are interrupted for approximately a month roughly every two years when the sun lies between the two planets. This paper addresses a means to close this gap by employing a Deep Space Relay (DSR) spacecraft injected into an Earth-trailing orbit and/or the Sun-Earth Lagrange Point L5, which trails Earth in its orbit around the sun. DSR systems issues, enabling technologies and alternative uses are discussed. Maximizing DSR heritage from commercially-produced Earth-orbiting spacecraft is included to control costs. [View Full Paper]

* Senior Engr. Specialist, Advanced Program & Systems, Space Systems Loral (SSL), 3825 Fabian Way, MS G-54, Palo Alto, California 94303-4604. Senior Member AIAA.

WHAT GOES UP MUST COME DOWN: CASSINI MANEUVER EXPERIENCE DURING THE INCLINATION-RAISING PHASE PRIOR TO END OF MISSION

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

The Cassini spacecraft is kept on its planned reference trajectory using maneuvers designed by the Cassini Maneuver Team. The experiences of the team are documented for 2016—a span of the mission during which the orbit inclination is steadily increasing. This period contains 33 planned maneuvers and 11 Titan flybys leading up to the final orbits before Cassini's plunge into Saturn. Information about each maneuver is provided along with discussion of situations where operations deviated from the normal routine.

[View Full Paper]

[*] Corresponding Author; *Mailing Address:* Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, U.S.A. *Tel:* (818) 393-8051. *E-mail:* Frank.E.Laipert@jpl.nasa.gov.

[†] Authors are members of the Flight Path Control Group and the Cassini Navigation Team, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, U.S.A.

AAS 17-287

MARS RECONNAISSANCE ORBITER: TEN YEARS OF MANEUVER SUPPORT FOR SCIENCE OPERATIONS AND ENTRY, DESCENT, AND LANDING SEQUENCES

Sean Wagner,[*] Premkumar Menon[†] and Stuart Demcak[‡]

The Mars Reconnaissance Orbiter (MRO) was launched in August 2005 and attained an orbit around Mars in March 2006. After transitioning to its primary orbit, MRO began science operations in November 2006. Since then, nearly 50 propulsive maneuvers were executed to maintain MRO in its science orbit and position it for relay support of three arriving spacecraft: Phoenix lander in May 2008, Mars Science Laboratory in August 2012, and ExoMars Schiaparelli lander in October 2016. This paper will discuss the performance of these maneuvers and MRO's planned relay support of the InSight Entry, Descent, and Landing phase in 2018. [View Full Paper]

[*] MRO Maneuver Lead and Corresponding Author, member of the Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology. Mailing Address: Jet Propulsion Laboratory, Mail Stop 230-205, 4800 Oak Grove Drive, Pasadena, California 91109, U.S.A.

[†] MRO Navigation Team Chief, member of the Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, U.S.A.

[‡] Former MRO Navigation Team Chief, member of the Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, U.S.A.

AAS 17-308

NEW HORIZONS EXTENDED MISSION DESIGN TO THE KUIPER BELT OBJECT 2014 MU69

Yanping Guo*

After the Pluto flyby on July 14, 2015, the trajectory of the New Horizons spacecraft was adjusted through a series of four maneuvers in October-November 2015 to fly by Kuiper Belt Object (KBO) 2014 MU69 on January 1, 2019 for the first time as an extended mission. The KBO flyby will occur at a distance of 43.28 AU from the Sun and 44.26 AU from Earth with a round trip light time of 12.3 hours. This paper describes the New Horizons extended mission design to the KBO, post-Pluto trajectory adjustment by the initial KBO targeting maneuvers, and KBO flyby trajectory planning and analysis.

[View Full Paper]

* Principal Professional Staff, Space Exploration Sector, Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel, Maryland 20723-6099, U.S.A.

AAS 17-337

MARS RECONNAISSANCE ORBITER NAVIGATION STRATEGY FOR THE EXOMARS SCHIAPARELLI EDM LANDER MISSION

Premkumar R. Menon,* Sean V. Wagner,† David C. Jefferson,† Eric J. Graat,† Kyong J. Lee† and William B. Schulze†

The Mars Reconnaissance Orbiter (MRO) had planned to provide surface relay support for the brief mission of the ExoMars Schiaparelli EDM lander on Mars in October 2016. Schiaparelli was launched with the Trace Gas Orbiter (TGO) in March 2016. The two spacecraft composed the first part of the ExoMars program. To place MRO directly overhead on its third overflight of the Schiaparelli landing site, two propulsive maneuvers were performed starting three months prior to Schiaparelli's arrival at Mars. This paper documents the maneuver strategy employed by the MRO Navigation Team to support the Schiaparelli overflight campaign. [View Full Paper]

* MRO Navigation Team Chief, Jet Propulsion Laboratory, California Institute of Technology and Corresponding Author; Mailing Address: Jet Propulsion Laboratory, Mail Stop 264-282, 4800 Oak Grove Drive, Pasadena, California 91109, U.S.A. E-mail: Premkumar.R.Menon@jpl.nasa.gov. Tel: (818) 354-5093; Fax: (818) 393-3147.

† Authors are members of the Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, U.S.A.

RECURSIVE MULTI-OBJECTIVE OPTIMIZATION OF MARS-EARTH-VENUS TRAJECTORIES

Kirk S. S. Barrow* **and Marcus J. Holzinger†**

The NASA exploration roadmap envisions a sustainable human presence beyond Earth orbit with an emphasis on Mars habitation. Establishing an interplanetary transportation system in orbits that periodically intersect Earth and Mars have been under study since 1969 to meet this end, but solutions generally suffer from high Δv requirements, high approach velocities, and unfeasibly long transit times or impractical simplifying assumptions like co-planar, circular orbits. This work seeks to expand investigations to connective low-thrust, low-Δv trajectories that also take advantage of Venusian gravity assists when available to further optimize cyclic systems. By leveraging supercomputing resources, this work also seeks to diverge from studies using cycler templates and explore a larger parameter space for potential solutions that take advantage of realistic planetary ephemeris like plane change maneuvers. To optimize the process, a piecewise multi-objective Newton's method optimization is applied to combinations of planets resulting in several tours per year with less than 7 km/s Δv including Earth departure v_∞. This method is demonstrably better than an even sampling of launch and encounter dates for investigations with limited computational resources. The inclusion of Venus allows the algorithm to take advantage of fortuitous alignments of Venus for plane change maneuvers, reducing the overall cost. Venusian-inclusive tours also provide launch opportunities outside the usual Earth-Mars launch windows. [View Full Paper]

* Graduate Student, School of Physics, Georgia Institute of Technology, Atlanta, Georgia 30332, U.S.A. E-mail: kssbarrow@gatech.edu.

† Assistant Professor, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, Georgia 30332, U.S.A. E-mail: holzinger@gatech.edu.

AAS 17-437

ROBUST CAPTURE AND PUMP-DOWN DESIGN FOR NASA'S PLANNED EUROPA CLIPPER MISSION

Christopher J. Scott,[*] Martin T. Ozimek,[*] Brent Buffington,[†] Ralph Roncoli[‡] and Chen-Wan L. Yen[‡]

Missions to the planetary systems of the outer solar system generally contain a system entry sequence. These events potentially involve a propellant reducing flyby, a capture maneuver, and a subsequent set of flybys which reduce energy and set the orbital conditions necessary for a science campaign. This paper addresses the optimality, robustness, and flexibility of a design in the Jovian system with target conditions set by NASA's planned Europa Clipper Mission Concept. Robustness to spacecraft anomalies is achieved through the orbital design and not through propellant margin. The theoretical limits of the design space are derived before performing a broad trajectory search.

[View Full Paper]

[*] Senior Professional Staff, Europa Clipper Mission Design Team, The Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel, Maryland 20723, U.S.A.

[†] Europa Clipper Mission Design and Navigation Lead, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, U.S.A.

[‡] Europa Clipper Mission Design Team, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, U.S.A.

AAS 17-457

DEIMOS OBSERVATION TRAJECTORY OPTIONS FOR PHOBOS SAMPLE RETURN MISSION

Kyosuke Tawara,[*] Yasuhiro Kawakatsu[†] and Naoko Ogawa[‡]

Japan has been preparing for a Phobos sample return mission. In this mission, it is worth taking the opportunity to also observe Deimos. This paper discusses trajectory options in the case of utilizing a flyby as a Deimos-observation method. There are two problems when designing mission orbits that meet requirements. As a result of mission analysis about various options, it was revealed which mission can be conducted and how much the probe satisfies the requirements. Finally, the effective trajectory to the case that the probe has rendezvous with a satellite of Mars, and flyby with the other satellite is shown.

[View Full Paper]

[*] Ph.D. Candidate, Department of Mechanical and Aerospace Engineering, Tokyo Institute of Technology, 554, Ishikawadai 1st Bldg., 2-12-1, Ookayama, Meguro, Tokyo, 152-8552, Japan. E-mail: tawara@lss.mes.titech.ac.jp.

[†] Associate Professor, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1, Yoshinodai, Chuo, Sagamihara, Kanagawa, 252-8210, Japan. E-mail: Kawakatsu.Yasuhiro@jaxa.jp.

[‡] Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1, Yoshinodai, Chuo, Sagamihara, Kanagawa, 252-8210, Japan. E-mail: naoko.ogawa@isas.jaxa.jp.

AAS 17-522

INTERPLANETARY TRAJECTORIES FOR ICE GIANT MISSION CONCEPTS

Nitin Arora* and Anastassios E. Petropoulos†

Interplanetary Trajectory options for missions to Uranus and Neptune, launching between 2025 and 2037, are presented. Trajectories using Chemical Propulsion, Solar Electric Propulsion and Radioisotope Thermoelectric Generator Electric Propulsion, with up to four planetary flybys are investigated. The effect of different launch vehicles with or without an optimal kick stage, on flight time, inserted mass and propellant throughput, is quantified. To enable simultaneous exploration of both planets, dual-spacecraft trajectories that deliver one spacecraft to each planet from a single launch, are presented. Attractive trajectories and mission opportunities for different multi-element mission architectures are presented. [View Full Paper]

* Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, U.S.A. E-mail: Nitin.Arora@jpl.nasa.gov. Tel: 818-354-2417.

† Jet Propulsion Laboratory, California Institute of Technology. E-mail: anastassios.e.petropoulos@jpl.nasa.gov.

DYNAMICS AND CONTROL OF LARGE SPACE STRUCTURES AND TETHERS

Session Chair:

Session 12: Maruthi Akella

The following papers were not available for publication:

AAS 17-494 Paper Withdrawn

AAS 17-505 Paper Withdrawn

AAS 17-201

OBSERVER/KALMAN FILTER IDENTIFICATION BY A KALMAN FILTER OF A KALMAN FILTER (OKID^2)

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

The original Observer/Kalman filter identification (OKID) algorithm identifies a state-space model and an associated steady-state Kalman filter gain from input-output data corrupted by process and measurement noises with unknown covariances. An extension of OKID uses the estimated Kalman filter residual to convert the stochastic system identification problem into a deterministic one, then identifies a state-space model and the steady-state Kalman filter gain directly. Since the estimation of the Kalman filter residual itself is not exact, a second Kalman filter of the first Kalman filter can be employed. This paper describes a new algorithm, OKID^2 that identifies a system state-space model and the steady-state Kalman filter gains directly, optimally, and simultaneously.

[View Full Paper]

[*] Thayer School of Engineering, Dartmouth College, Hanover, New Hampshire 03755, U.S.A.
[†] Department of Acute Care Solutions, Philips Research, Cambridge, Massachusetts 02141, U.S.A.
[‡] Department of Mechanical Engineering, Columbia University, New York, New York 10027, U.S.A. Fellow AAS. Fellow AIAA.
[§] Department of Civil Engineering and Engineering Mechanics, Columbia University, New York, New York 10027, U.S.A.

AAS 17-205

CONVERTING A STATE-SPACE MODEL TO PHYSICAL COORDINATES WITHOUT A FULL SET OF SENSORS: A KRONECKER-BASED METHOD

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

This paper presents a method to convert an identified state-space model of a structure to physical coordinates. Once in physical coordinates, methods are available to recover the structure mass, stiffness, and damping matrices. The new development removes the restriction of a recently developed method that requires a full set of sensors, one per degree of freedom. With this extension, sensors can be exchanged for actuators, and at least one collocated pair of sensor and actuator is required for unique conversion to physical coordinates. [View Full Paper]

[*] Superior Information Technology, Inc., Banchiao, New Taipei City 22041, Taiwan.
[†] Thayer School of Engineering, Dartmouth College, Hanover, New Hampshire 03755, U.S.A.
[‡] Department of Mechanical Engineering, Columbia University, New York, New York 10027, U.S.A. Fellow AAS. Fellow AIAA.

AAS 17-301

A NOVEL VIBRATION DAMPER FOR SMALL SPACECRAFT WITH LARGE FLEXIBLE APPENDAGES

Robert Waelchli[*] and Dongeun Seo[†]

As small satellites become increasingly capable, opportunities now exist for them to perform complicated functions including missions beyond Earth orbit. For power, these missions may require large, flexible solar arrays that would produce dynamic loads. The research previewed in this article introduces a possible new configuration of magnetorheological fluid (MRF) damper for a small satellite application. Preliminary modeling of the proposed damper has been performed with a numerical MATLAB™ simulation to qualitatively demonstrate the feasibility of the concept and some initial results are presented. Based on the scalability of the technology, other applications could include larger spacecraft, spacecraft with solar sails, or a possible mitigation strategy against fuel sloshing.

[View Full Paper]

[*] Research Assistant in Accelerated Master's Program, Embry-Riddle Aeronautical University, 600 S. Clyde Morris Blvd., Daytona Beach, Florida 32114, U.S.A. E-mail: waelchlr@my.erau.edu.

[†] Assistant Professor, Aerospace Engineering, Embry-Riddle Aeronautical University, 600 S. Clyde Morris Blvd., Daytona Beach, Florida 32114, U.S.A. Phone: 386-226-6614. E-mail: seod@erau.edu.

AAS 17-345

DYNAMIC ANALYSIS OF THE TETHER TRANSPORTATION SYSTEM USING ABSOLUTE NODAL COORDINATE FORMULATION

Xin Sun,* Rui Zhong† and Shijie Xu‡

This paper focuses on the dynamics of the tether transportation system, which consists of two end satellites connected by a flexible tether with a movable vehicle driven by the actuator carried by itself. The Absolute Nodal Coordinate Formulation is applied to the establishment of the equation of motion in order to introduce the influence caused by the distributed mass and elasticity of the tether. Moreover, an approximated method for accelerating the calculation of the generalized gravitational forces on the tether is proposed by substituting the volume integral every step into summation of finite terms. Afterwards, dynamic evolutions of two configurations with different number of tether elements are illustrated using numerical simulations to investigate the deformation of the tether and the relative position among the two satellites and the trajectory of the crawler. Furthermore, the effect on the orbit of the system due to the crawler is revealed by the relative position of the system to an ideal constant orbital period circular motion. High-frequency transverse oscillations appear in the higher order models with more elements while lower order models are still competent during the early phase of the climber creeping.

[View Full Paper]

* Ph.D. Candidate, School of Astronautics, Beihang University, Beijing, 100191, China.

† Associate Professor, School of Astronautics, Beihang University, Beijing, 100191, China.

‡ Professor, School of Astronautics, Beihang University, Beijing, 100191, China.

AAS 17-387

TETHER-NETS FOR ACTIVE SPACE DEBRIS REMOVAL: EFFECT OF THE TETHER ON DEPLOYMENT AND CAPTURE DYNAMICS

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

A promising method to mitigate the space debris problem is to actively capture and remove debris by means of tether-nets. The chaser-tether-net-debris system is modeled with rigid bodies connected by constraints; the tether can be spooled in and out by controlling a winch on the chaser. Through dynamics simulation, this paper analyzes the effect of the tether and its tensioning on net deployment and capture dynamics of space debris. This provides interesting insight into the preferred winching of the tether and into the feasibility of using the tether as a closing mechanism. [View Full Paper]

* Ph.D. Student, Department of Mechanical Engineering, McGill University, 817 Sherbrooke Street West, Montreal, QC, H3A 0C3, Canada. E-mail: eleonora.botta@mail.mcgill.ca.

† Professor, Department of Mechanical Engineering, McGill University, 817 Sherbrooke Street West, Montreal, QC, H3A 0C3, Canada. E-mail: inna.sharf@mcgill.ca.

‡ Thomas Workman Professor, Department of Mechanical Engineering, McGill University, 817 Sherbrooke Street West, Montreal, QC, H3A 0C3, Canada. E-mail: arun.misra@mcgill.ca.

AAS 17-455

SATLEASH - PARABOLIC FLIGHT VALIDATION OF TETHERED-TUGS DYNAMICS AND CONTROL FOR RELIABLE SPACE TRANSPORTATION APPLICATIONS

Vincenzo Pesce,* Andrea Bellanca,† Michèle Lavagna,‡
Riccardo Benvenuto, Paolo Lunghi§ and Simone Rafano Carnà

The SatLeash experiment investigates the dynamics and control of tow-tethers, for space transportation. Understanding tethered towing objects in space is becoming an active research field for its range of applications. Many missions, such as Active Debris Removal, LEO satellites disposal, low-to-high energy orbit transfer and even asteroids retrieval could employ this technology. Space tugs, made of a passive orbiting target interconnected through a flexible link to an active chaser the thrusters of which excite the stack dynamics, open new challenges for guidance and control design. A wave-based control, using tension feedback, is selected as effective method to stabilize the system during tensioning and release phases. The team exploits a multibody dynamics simulator developed at PoliMi-DAER - to describe tethered-satellite-systems dynamics and synthetize their control. This is considered of primary importance to design future missions. The experiment, selected to fly in microgravity conditions by the ESA FlyYourThesis! 2016 programme, focuses on validating the adopted models and verifying the implemented control law. A reduced-scale tethered floating test bed, equipped with a stereovision system to reconstruct its 3D trajectory, has been developed for the parabolic flight campaign. Different tether stiffnesses have been tested as well as control schemes to verify their effectiveness in reducing bouncing-back effects. Developed models and control laws, together with numerical and experimental simulation results are presented in the paper.

[View Full Paper]

* Ph.D. Candidate, Department of Aerospace Science and Technology, Politecnico di Milano, via La Masa 34, 20156 Milano, Italy.

† M.Sc. Student, Department of Aerospace Science and Technology, Politecnico di Milano, via La Masa 34, 20156 Milano, Italy.

‡ Associate Professor, Department of Aerospace Science and Technology, Politecnico di Milano, via La Masa 34, 20156 Milano, Italy.

§ Research Assistant, Department of Aerospace Science and Technology, Politecnico di Milano, via La Masa 34, 20156 Milano, Italy.

ORBIT DETERMINATION AND SPACE-SURVEILLANCE TRACKING

Session Chair:

Session 14: Moriba Jah

AAS 17-215

IN-ORBIT TRACKING OF HIGH AREA-TO-MASS RATIO SPACE OBJECTS

Daniel N. Brack* **and Pini Gurfil†**

High area-to-mass ratio space objects at geosynchronous orbits pose a threat to operational satellites because of the difficulty to track them from Earth. This paper develops an in-orbit on-board algorithm for tracking high area-to-mass ratio space objects. The design utilizes relative motion dynamics and a simplified stereo-camera measurement model to estimate the tracked object's position and velocity, as well as its solar radiation pressure coefficient. An underlying assumption is the dominance of the solar radiation pressure perturbation. Two scenarios are examined: similar orbits and crossing orbits. The simulation results show that the tracking algorithm estimates the tracked object position, velocity, and solar radiation pressure coefficient in both scenarios with high accuracy. The simulations show that although shape information is lost in the measurement model, the solar radiation pressure coefficient can still be estimated. [View Full Paper]

* M.Sc. Student, Faculty of Aerospace Engineering, Technion - Israel Institute of Technology, Haifa 32000, Israel. E-mail: daniel.brack@colorado.edu.

† Associate Professor, Faculty of Aerospace Engineering, Technion - Israel Institute of Technology, Haifa 32000, Israel. E-mail: pgurfil@technion.ac.il. Associate Fellow AIAA.

AAS 17-310

CORRELATION OF OBSERVATIONS AND ORBIT RECOVERY CONSIDERING MANEUVERS

J. A. Siminski,[*] H. Fiedler[†] and T. Flohrer[‡]

Optical tracklets collected after or during a maneuver phase cannot be directly associated to any cataloged object. The observations do not provide enough information for an independent orbit determination. Thus, the new orbit remains uncertain before collecting any additional measurements. Two methods for the correlation and orbit recovery are presented. First, the solution space after the maneuver is bounded using an admissible region. Second, the historic maneuver data of each object is characterized to compute the association likelihood and predict the most likely state after a maneuver. The performance of the presented approaches is demonstrated using data of EUMETSAT satellites.

[View Full Paper]

[*] Space Debris Engineer, IMS Space Consultancy at ESA/ESOC Space Debris Office, Robert-Bosch-Str. 5, 64293 Darmstadt, Germany.

[†] Head of Space Situational Awareness group, DLR/GSOC, Münchner Str. 20, 82234 Weßling, Germany.

[‡] Space Debris Analyst, ESA/ESOC Space Debris Office, Co-Lead Space Surveillance and Tracking Segment, Space Situational Awareness Programme.

AAS 17-327

RELATIVE-MOTION APPROACH FOR DIFFERENTIAL CORRECTION IN ORBIT DETERMINATION

Andrew J. Sinclair,[*] T. Alan Lovell,[*] Kenneth Horneman,[†] Andrew Harris[‡] and Alex Sizemore[§]

This paper describes an approach for differential correction for angles-only orbit determination based on relative motion. Relative-orbit determination has traditionally been formulated for a space-based sensor in close proximity to the observed object. However, these approaches can be generalized for a distant sensor, and the motion of the observed object is described relative to some proximate reference orbit. The relative-orbit solution is used to define a new reference orbit in the next iteration, reducing approximation error in the relative-motion dynamics. The presented approach utilizes available analytic relative-motion solutions and does not introduce any linearizing approximation in the measurements. [View Full Paper]

[*] Senior Aerospace Engineer, Space Vehicles Directorate, Air Force Research Laboratory, 3550 Aberdeen Avenue SE, Kirtland AFB, New Mexico 87117, U.S.A.

[†] Research Associate, National Research Council, 3550 Aberdeen Avenue SE, Kirtland AFB, New Mexico 87117, U.S.A.

[‡] Graduate Student, Aerospace Engineering Sciences Department, University of Colorado Boulder, 429 UCB, Boulder, Colorado 80309, U.S.A.

[§] Graduate Student, Aerospace Engineering Department, University of Kansas, 1530 W 15th Street, Lawrence, Kansas 66045, U.S.A.

AAS 17-374

A NEW MULTI-TARGET TRACKING ALGORITHM FOR A LARGE NUMBER OF ORBITING OBJECTS

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

This paper demonstrates the applicability of the filter for Hypothesised and Independent Stochastic Populations (HISP), a multi-target joint detection/tracking algorithm derived from a recent estimation framework for stochastic populations, to wide area surveillance scenarios in the context of Space Situational Awareness. Designed for multi-object estimation problems where the data association between targets and collected observations is moderately ambiguous, the HISP filter has a linear complexity with the number of maintained tracks and the number of observations, and is a scalable filtering solution adapted to large-scale target tracking scenarios. It is illustrated on a challenging surveillance problem involving 30 targets on different orbits, observed by 3 sensors with limited coverage, measurement noise, false alarms, and missed detections. [View Full Paper]

[*] Research Associate, Heriot Watt University, School of Engineering & Physical Sciences, Edinburgh, United Kingdom. E-mail: E.D.Delande@hw.ac.uk.

[†] Visiting Researcher at CSIRO Data61, Eveleigh, Australia. E-mail: houssineau.j@gmail.com.

[‡] Ph.D. Student, Heriot Watt University, School of Engineering & Physical Sciences, Edinburgh, United Kingdom. E-mail: jf139@hw.ac.uk.

[§] Assistant Professor, Purdue University, School of Aeronautics & Astronautics, West Lafayette, Indiana 47907-2045, U.S.A. E-mail: cfrueh@purdue.edu. AIAA Member.

[**] Associate Professor, Heriot Watt University, School of Engineering & Physical Sciences, Edinburgh, United Kingdom. E-mail: D.E.Clark@hw.ac.uk.

AAS 17-382

DEMPSTER-SHAFER THEORY APPLIED TO ADMISSIBLE REGIONS

Johnny L. Worthy III[*] and Marcus J. Holzinger[†]

The admissible region approach is often used a bootstrap method to initialize a Bayesian state estimation scheme for too-short-arc measurements. However, there are ambiguities in how prior probabilities are assigned for states in the admissible region. Several approaches have proposed methods to assign prior probabilities, however there are inconsistencies in how the prior probabilities can be manipulated. The application of Dempster-Shafer evidential reasoning theory to the admissible region problem can avoid these ambiguities by eliminating the need to make any assumptions on the prior probabilities. Dempster-Shafer theory also enables the testing of the validity of the assumptions used to construct the admissible region. This paper introduces Dempster-Shafer theory and formulates the admissible region in terms of plausibility and belief which reduce to traditional Bayesian probability once there is sufficient information in the system.

[View Full Paper]

[*] Graduate Researcher, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, Georgia 30332, U.S.A. AIAA Student Member.

[†] Assistant Professor, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, Georgia 30332, U.S.A. AIAA Senior Member.

AAS 17-412

NONLINEAR GAUSSIAN MIXTURE SMOOTHING FOR ORBIT DETERMINATION

Kyle J. DeMars*

The forward filtering solution to the Bayesian estimation problem provides the best possible solution for a probability density function given all past and current data. The backward smoothing solution, by contrast, makes use of all data over a fixed interval, through a fixed data lag, or beyond a fixed point in order to determine an improved solution for the probability density function. Achieving a better understanding of the probabilistic description of the state in orbit determination is key to providing reliable situational awareness. This paper investigates a method of combining forward filtering and backward smoothing solutions for non-Gaussian distributions in the orbit determination problem. A simulation of a low-Earth orbit tracking scenario is considered, where a forward filter/backward smoother is applied to assess and compare the performance of filtering and smoothing recursions in a nonlinear, non-Gaussian orbit determination problem.

[View Full Paper]

* Assistant Professor, Department of Mechanical and Aerospace Engineering, Missouri University of Science and Technology, Rolla, Missouri 65409-0050, U.S.A.

AAS 17-413

PRACTICAL DEMONSTRATION OF TRACK-TO-TRACK DATA ASSOCIATION USING THE BHATTACHARYYA DIVERGENCE*

Christopher W. T. Roscoe,† Islam I. Hussein,† Joseph D. Gerber,† Jason Stauch,† Tom Kelecy,† Matthew P. Wilkins† and Paul W. Schumacher, Jr.‡

Building and maintaining a space object catalog requires rigorous methods for data association in order to maintain consistent object custody. There are three primary types of data association of interest in space surveillance: the observation-to-track association (OTTA) problem, the observation-to-observation association (OTOA) problem, and the track-to-track association (TTTA) problem. Recent work in the community has suggested the use of a number of information theoretic quantities as metrics for performing data association. This work presents a practical demonstration of using one of these quantities, the Bhattacharyya divergence, for TTTA in a small GEO catalog generation and maintenance exercise fed by data from a consortium of commercial electro-optical sensor providers. The Air Force Research Lab-developed Constrained Admissible Region–Multiple Hypothesis Filter (CAR-MHF) is used for primary orbit determination and track maintenance, including solving the OTTA and OTOA problems. [View Full Paper]

---

* DISTRIBUTION STATEMENT A. Approved for public release. Distribution is unlimited.

† Applied Defense Solutions, Inc., 10440 Little Patuxent Parkway, Suite 600, Columbia, Maryland 21044, U.S.A.

‡ Air Force Research Laboratory, 535 Lipoa Parkway, Suite 200, Kihei, Hawaii 96753, U.S.A.

AAS 17-448

ON THE EQUIVALENCE OF FISST AND MHT FOR MULTI-TARGET TRACKING

S. Chakravorty,[*] W. Faber[*] and Islam I. Hussein[†]

In this paper, we propose a hypothesis dependent derivation of the FISST equations that shows that the FISST probability density function (pdf) has a hypothesis dependent structure identical to the Multi-Hypothesis Tracking (MHT) method for multi-target tracking. The only significant difference between the two methodologies stems from the manner in which target birth and death are handled in the two methods. Furthermore, the derivation implies that the most critical element in any MTT technique is the computationally tractable handling of the large number of hypotheses that may result from the ambiguities inherent in the problem. [View Full Paper]

[*] Department of Aerospace Engineering, Texas A&M University, College Station, Texas 77843-3141, U.S.A.
[†] Applied Defense Solutions, 10440 Little Patuxent Parkway, Suite 600, Columbia, Maryland 21044, U.S.A.

AAS 17-449

COMPUTER VISION AND COMPUTATIONAL INTELLIGENCE FOR REAL-TIME MULTI-MODAL SPACE DOMAIN AWARENESS

Mark Bolden,[*] Paul Schumacher,[†] David Spencer,[‡] Islam Hussein,[§] Matthew Wilkins[**] and Christopher Roscoe[§]

This paper presents a computer vision and computational intelligence approach to space domain awareness. The approach is specifically designed to produce probabilistic density functions and state estimates in real-time for objects within the domain. PDFs are also generated for regions where there are no objects, and where there is insufficient information to assert object existence. The approach is dynamic and naturally adapts to changes of state to include maneuvering objects. The processing speed of the approach is independent of the number of objects, instead only dependent on the size of the domain, the accuracy desired in all dimensions, and the computational architecture. [View Full Paper]

[*] Senior Scientist, Applied Defense Solutions, 10440 Little Patuxent Pkwy., #600, Columbia, Maryland 21044, U.S.A.
[†] Aerospace Engineer, RDSM, Air Force Research Laboratory, 550 Lipoa Parkway, Kihei, Hawaii 96753, U.S.A.
[‡] Professor, Aerospace Engineering, The Pennsylvania State University, 229 Hammond Building, University Park, Pennsylvania 16802, U.S.A.
[§] Aerospace Engineer, Applied Defense Solutions, 10440 Little Patuxent Pkwy., #600, Columbia, Maryland 21044, U.S.A.
[**] Senior Scientist for SSA Programs, Applied Defense Solutions, 10440 Little Patuxent Pkwy., #600, Columbia, Maryland 21044, U.S.A.

INITIAL ORBIT IDENTIFICATION: COMPARISON OF ADMISSIBLE REGION MAPPING FOR TOO SHORT ARC OBSERVATIONS

Fouad Khoury,[*] Carolin Frueh[†] and Sebastian Francis[‡]

This paper investigates the orbit identification problem concerning the correlation between two sets of angle-angle rate line-of-sight (LOS) measurements taken at different times by a topo-centric observer. The tracking of these space objects, (in this case considered to be in GEO), in the form of a Too Short Arc (TSA), provides information for only small fractions of their respective orbital revolutions. The data collected as part of the TSA is known as an attributable, a 4 dimensional vector containing angle and angle rates of an observed object at an instant in time. Using the concept of the admissible region, as proposed by Andrea Milani et al., a region of attributable space can be computed from an observation at t_1 to incorporate all possible sets of range and range-rate values that, combined with angle measurements, satisfy the zero-energy condition set by employing the two-body energy equation. Once an admissible region is computed, an optimal sampling method known as the Delaunay triangulation is employed to select points, known as Virtual Space Objects (VSOs), which are propagated to some set epoch t_ε, usually corresponding to the time of the second observation t_2. The same process is repeated for a second observation at t_2, yielding a different admissible region and thus a different set of VSOs to compare against the propagated points from the first observation. Finally, the resulting propagated points from Obs. 1 and sampled points from Obs. 2 can be transformed into non-singular canonical orbital elements, which are used to generate maps comprising of the transformed position and velocity values of the VSOs from both admissible regions. When maps generated from the first observation is compared to the map generated at the second observation, correlation between the two observations can be determined if certain conditions are satisfied, as set forth by the correlation criteria.

[View Full Paper]

[*] Undergraduate Student, Department of Aeronautical and Astronautical Engineering, Purdue University, West Lafayette, Indiana 47907-2045, U.S.A.

[†] Assistant Professor, Department of Aeronautical and Astronautical Engineering, Purdue University, West Lafayette, Indiana 47907-2045, U.S.A.

[‡] National Aeronautics and Space Administration, Johnson Space Center, Flight Dynamics Division, Houston, Texas 77058, U.S.A.

ORBITAL DYNAMICS

Session Chairs:

Session 14: Roby Wilson

Session 27: Daniel Lubey

The following papers were not available for publication:

AAS 17-222 Paper Withdrawn

AAS 17-266 Paper Withdrawn

AAS 17-226

ORBIT TRANSFER OF AN EARTH ORBITING SOLAR SAIL CUBESAT

Omer Atas[*] and Ozan Tekinalp[†]

Propelling a spacecraft by using solar radiation pressure is examined in the context of orbital maneuvers. A locally optimal steering law to progressively change number of selected orbital elements together is addressed. An Earth centered cubesat satellite with solar sail is used as an example. The proper attitude maneuver mechanization is proposed to harvest highest solar radiation force in the desired direction for Earth orbiting satellites. The satellite attitude control is realized using to-go quaternion feedback control. And the effectiveness of the approach to progressively changing the orbital parameters is demonstrated. [View Full Paper]

[*] Research Assistant, Department of Aerospace Engineering, Middle East Technical University, 06800, Ankara, Turkey.
[†] Professor, Department of Aerospace Engineering, Middle East Technical University, 06800, Ankara, Turkey. Senior Member.

AAS 17-251

ON THE FORMATION AND STABILITY OF RESONANT PLANETARY SYSTEMS

Flavien Hardy[*†] and Gong Sheng Ping[‡]

We investigate the dynamics of a satellite pair pushed towards mean-motion resonance by centripetal migration due to interactions with a planetesimal disk. An analytical model of planetary systems evolving towards orbital resonance is developed to the second order in eccentricities, allowing for an assessment of the stability of the resonant equilibrium under disk interactions. Numerical applications to resonant pairs are carried out to visualize the selection of inner secondaries leading to stable resonant states by a specific outer satellite migrating inwards. The structure of the osculating phase space is analyzed and the possibilities of capture and escape from resonance are visualized accordingly. Such steps may help in predicting the evolution of a resonant planetary system and understanding its formation, while giving insights on when the driving planetesimal disk could have dissipated. Perspectives of the underlying method are briefly discussed for studies of Europa and Enceladus's migrations towards Jupiter and Saturn respectively, and to the exoplanetary system of G876. [View Full Paper]

[*] Department of Astrodynamics, School of Aerospace Engineering, Tsinghua University, Beijing, China.
[†] CentraleSupélec, Université Paris-Saclay, Châtenay-Malabry, France.
[‡] Associate professor, Department of Astrodynamics, School of Aerospace Engineering, Tsinghua University, Beijing, China.

AAS 17-261

DYNAMICS OF LIBRATION POINTS IN THE GENERAL ASYNCHRONOUS BINARY ASTEROID SYSTEM

Xiaosheng Xin,[*] Xiyun Hou[†] and Lin Liu[‡]

The Restricted Full Three-Body Problem (RF3BP) is studied in the context of asynchronous binary asteroid system in which the two asteroids are modelled as ellipsoids. We extend our previous work[1] which studies the dynamics of the libration points of the binary system in exact synchronous state to binary systems in asynchronous state. The homogeneous ellipsoids in principal-axis rotation are used to model the asteroids. Firstly, equations of motion (EOMs) truncated at 2nd order of the non-spherical terms are derived for the massless body in the binary system that revolves around each other under their mutual potential also truncated at 2nd order. Assuming a near-circular orbit for the binary system, external perturbations with two frequencies due to the non-spherical terms of the primaries contribute to the motion of the massless body. Therefore, geometrical libration points no longer exist in this asynchronous binary system. Instead, quasi-periodic orbits appear as their dynamical substitutes. Secondly we solve for the analytical solutions of the quasi-periodic orbits from the EOM and analyse their stability properties.

[View Full Paper]

[*] Ph.D. Candidate, School of Astronomy and Space Science, Nanjing University, 163 Xianlin Ave., Nanjing, Jiangsu 210023, China.

[†] Associate Professor, School of Astronomy and Space Science, Nanjing University, 163 Xianlin Ave., Nanjing, Jiangsu 210023, China.

[‡] Professor, School of Astronomy and Space Science, Nanjing University, 163 Xianlin Ave., Nanjing, Jiangsu 210023, China.

AAS 17-262

DYNAMICS AROUND EQUILIBRIUM POINTS OF UNIFORMLY ROTATING ASTEROIDS

Jinglang Feng* and Xiyun Hou†

Using tools such as periodic orbits (POs), dynamics around equilibrium points (EPs) in the body-fixed frame of uniformly rotating asteroids are studied. For EPs on the long axis, planar and vertical periodic families are computed and their stability properties are investigated. For EPs on the short axis, planar and vertical periodic families are studied, with special emphasis on the genealogy of the planar periodic families. Our studies show that dynamics around EPs are highly similar to those around libration points in the circular restricted three-body problem (CRTBP), such as halo orbits and the genealogy of planar periodic families. [View Full Paper]

* Postdoc, School of Astronomy and Space Science, Nanjing University, China, 210093.
† Associate Professor, School of Astronomy and Space Science, Nanjing University, China, 210093.

AAS 17-269

ORBIT MAINTENANCE AND NAVIGATION OF HUMAN SPACECRAFT AT CISLUNAR NEAR RECTILINEAR HALO ORBITS

Diane C. Davis,[*] Sagar A. Bhatt,[†] Kathleen C. Howell,[‡] Jiann-Woei Jang,[†] Ryan J. Whitley,[§] Fred D. Clark,[†] Davide Guzzetti,[**] Emily M. Zimovan[††] and Gregg H. Barton[†]

Multiple studies have concluded that Earth-Moon libration point orbits are attractive candidates for staging operations. The Near Rectilinear Halo Orbit (NRHO), a member of the Earth-Moon halo orbit family, has been singularly demonstrated to meet multi-mission architectural constraints. In this paper, the challenges associated with operating human spacecraft in the NRHO are evaluated. Navigation accuracies and human vehicle process noise effects are applied to various stationkeeping strategies in order to obtain a reliable orbit maintenance algorithm. Additionally, the ability to absorb missed burns, construct phasing maneuvers to avoid eclipses and conduct rendezvous and proximity operations are examined. [View Full Paper]

[*] Principal Systems Engineer, a.i. solutions, Inc., Houston, Texas 77058, U.S.A.
[†] Aerospace Engineer, The Charles Stark Draper Laboratories, Inc., Houston, Texas 77058, U.S.A.
[‡] Hsu Lo Distinguished Professor of Aeronautics and Astronautics, School of Aeronautics and Astronautics, Purdue University, 701 West Stadium Avenue, West Lafayette, Indiana 47907-2045, U.S.A.
[§] Aerospace Engineer, Exploration Mission Planning Office, NASA JSC, Houston, Texas 77058, U.S.A.
[**] Ph.D. Candidate, School of Aeronautics and Astronautics, Purdue University, 701West Stadium Avenue, West Lafayette, Indiana 47907-2045, U.S.A.
[††] Graduate Student, School of Aeronautics and Astronautics, Purdue University, 701 West Stadium Avenue, West Lafayette, Indiana 47907-2045, U.S.A.

AAS 17-278

OSCULATING KEPLERIAN ELEMENTS FOR HIGHLY NON-KEPLERIAN ORBITS

Alessandro Peloni,[*] Colin R. McInnes[†] and Matteo Ceriotti[‡]

This paper presents a mapping between the elements of highly non-Keplerian orbits and classical orbital elements. Three sets of elements are discussed and mappings are derived in closed, analytical form for both the direct and inverse problem. Advantages and drawbacks of the use of each set of elements are dis-cussed. The spacecraft thrust-induced acceleration used to generate families of highly non-Keplerian orbits is extracted from the inverse mapping from the osculating orbital elements. The key signatures of highly non-Keplerian orbits in Keplerian elements tracking data are determined through a set of representative test cases. [View Full Paper]

[*] Research Assistant, School of Engineering, University of Glasgow, Glasgow G12 8QQ, United Kingdom.
[†] Professor of Engineering Science, James Watt Chair, School of Engineering, University of Glasgow, Glasgow G12 8QQ, United Kingdom.
[‡] Lecturer in Space System Engineering, School of Engineering, University of Glasgow, Glasgow G12 8QQ, United Kingdom.

AAS 17-282

SEMI-ANALYTICAL PROPAGATION WITH DRAG COMPUTATION AND FLOW EXPANSION USING DIFFERENTIAL ALGEBRA

David J. Gondelach,[*] Roberto Armellin,[†] Hugh Lewis,[*] Juan Félix San Juan[‡] and Alexander Wittig[§]

Efficient long-term propagation of orbits is needed for e.g. the design of disposal orbits and analysis of their stability. Semi-analytical methods are suited for this as they combine accuracy and efficiency. However, the semi-analytical modelling of non-conservative forces is challenging and in general numerical quadrature is required to accurately average their effects, which reduces the efficiency of semi-analytical propagation. In this work we apply Differential Algebra (DA) for efficient evaluation of the mean element rates due to drag. The effect of drag is computed numerically in the DA arithmetic such that in subsequent integration steps the drag can be calculated by only evaluating a DA expansion. The method is tested for decaying low Earth and geostationary transfer orbits and it is shown that the method can provide accurate propagation with reduced computation time with respect to nominal semi-analytical and numerical propagation. Furthermore, the semi-analytical propagator is entirely implemented in DA to enable higher-order expansion of the flow that can be used for efficient propagation of initial conditions. The approach is applied to expand the evolution of a Galileo disposal orbit. The results show a large validity domain of the expansion which represents a promising result for the application of the method for e.g. stability analysis. [View Full Paper]

[*] Astronautics Research Group, University of Southampton, SO17 1BJ, Southampton, United Kingdom.
[†] Surrey Space Centre, University of Surrey, GU2 7XH, Guildford, United Kingdom.
[‡] Departamento de Matemáticas y Computación, Universidad de La Rioja, 26004 Logroño, Spain.
[§] Advanced Concepts Team, European Space Agency, 2200 AG Noordwijk, The Netherlands.

AAS 17-294

REVISION OF THE LIE-DEPRIT METHOD IN GENERAL PERTURBATIONS THEORIES OF ASTRODYNAMICS PROBLEMS

Juan F. San-Juan,*, Iván Pérez,† Montserrat San-Martín‡ and Rosario López§

An extension of the classical Delaunay normalization is analyzed. It takes advantage of the intrinsic arbitrariness of the Lie-Deprit method in the process of calculating its generating function. We have found that, under certain conditions, a function belonging to the null space of the Lie operator associated to the unperturbed part of the initial Hamiltonian can be added to the generating function at each order, so that the long-period terms can be removed from the transformation equations, or several angles can be eliminated simultaneously in the cases of the artificial satellite problem, Lunar theory and Planetary satellite orbiters. [View Full Paper]

* Scientific Computing Group (GRUCACI), Universidad de La Rioja, ES-26006 Logroño, Spain.
E-mail: juanfelix.sanjuan@unirioja.es.
† Scientific Computing Group (GRUCACI), Universidad de La Rioja, ES-26004 Logroño, Spain.
E-mail: ivan.perez@unirioja.es.
‡ Scientific Computing Group (GRUCACI), Universidad de Granada, ES-52005 Melilla, Spain.
E-mail: momartin@ugr.es.
§ Center for Biomedical Research of La Rioja (CIBIR) and Scientific Computing Group (GRUCACI), Universidad de La Rioja, ES-26004 Logroño, Spain. E-mail: rlgomez@riojasalud.es.

AAS 17-320

RAPID CHARGED GEOSYNCHRONOUS DEBRIS PERTURBATION MODELING OF ELECTROMAGNETIC DISTURBANCES

Joseph Hughes[*] and Hanspeter Schaub[†]

Charged space objects experience small perturbative torques and forces from their interaction with Earth's magnetic field. These small perturbations can change the orbits of lightweight, uncontrolled debris objects dramatically even over short periods. This paper investigates the effects of the isolated Lorentz force, the effects of including or neglecting this and other electromagnetic perturbations in a full propagation, and then analyzes for which objects electromagnetic effects have the most impact. It is found that electromagnetic forces have a negligible impact on their own. However, if the center of charge is not collocated with the center of mass, electromagnetic torques are produced which due impact the attitude, and thus the translation by affecting the direction and magnitude of the solar radiation pressure force. The objects for which electrostatic torques have the most influence are charged above the kilovolt level, have a difference between their center of mass and center of charge, have highly attitude-dependent cross-sectional area, and are not spinning stably about an axis of maximum inertia. Fully coupled numerical simulation illustrate the impact of electromagnetic disturbances through the solar pressure coupling. [View Full Paper]

[*] Graduate Research Assistant, Aerospace Engineering Sciences, University of Colorado.

[†] Alfred T. and Betty E. Look Professor of Engineering, Associate Chair of Graduate Affairs, Department of Aerospace Engineering Sciences, University of Colorado, 431 UCB, Colorado Center for Astrodynamics Research, Boulder, Colorado 80309-0431, U.S.A. AAS Fellow.

IMPACT OF SPECIAL PERTURBATIONS ON LAGEOS-1, AJISAI, LARES AND STELLA'S ORBIT PREDICTION ACCURACY[*]

Claire Gilbert,[†] Channing Chow,[†]
Steven Long,[‡] Jack Wetterer[‡] and Jason Baldwin[§]

Precise orbit estimation and propagation require a sophisticated dynamic model to accurately predict a spacecraft's trajectory. Selecting the most suitable force model can be challenging in low altitude orbit regimes and sparsely known space object characteristics scenarios. Limited computing power further bounds the quality of the orbit achievable in a tractable amount of processing time. This paper examines how various combinations of perturbations in the equations of motion impact orbit prediction accuracy. Four satellites in different orbits, LAGEOS-1, AJISAI, LARES and STELLA were selected for their spherical shape, passive nature, and the availability of Satellite Laser Ranging observations. One, four, and seven days worth of data were used to solve for the initial orbit, using Least-Square, Extended Kalman, and Unscented Kalman filter algorithms. The orbit was then propagated over two months using the open source Orbit Extrapolation Toolkit (Orekit) propagation software, and the differences between predicted and measured space object positions were examined when turning on or off selected forces. The accuracy of the prediction was found to depend greatly on the satellite's altitude and its sensitivity to non-gravitational perturbations. For instance, LAGEOS-1's orbit could be modeled with less than 5 m RMS position error over the whole two months propagation span, compared with 30 days for AJISAI and 11 days for STELLA. LARES, whose orbit is similar to AJISAI, could be propagated accurately for 9 days only, despite its physical characteristics rendering it immune to drag and solar radiation pressure. The effect of drag on the accuracy of each synthetic orbit was investigated using the simple exponential, Harris-Priester, DTM2000/2012/2013, and JB2006 atmospheric models, as well as different sources for the geomagnetic and solar flux indices. The type of atmospheric model selected was found to impact AJISAI's orbit the most and extended the length of time for which the satellite's position was predicted with less than 5 m RMS error by about 22 days. [View Full Paper]

---

[*] DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

[†] Senior Scientist, Integrity Applications Inc. (Pacific Defense Solutions), 535 Lipoa Parkway, Ste 101, Kihei, Hawaii 96753, U.S.A.

[‡] Principal Scientist, Integrity Applications Inc. (Pacific Defense Solutions), 535 Lipoa Parkway, Ste 101, Kihei, Hawaii 96753, U.S.A.

[§] Senior Aerospace Engineer, Air Force Research Laboratory, Space Vehicles Directorate, 3550 Aberdeen Ave SE, Kirtland AFB, New Mexico 87117, U.S.A.

AAS 17-352

AN ANALYSIS OF THE CONVERGENCE NEWTON'S ITERATIONS FOR SOLVING ELLIPTIC KEPLER'S EQUATION

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

In this note, by using Wang Xinghua's theorem [1] on optimal convergence conditions of Newton's method, the sets of super–convergence of some starters of solving the elliptic Kepler's equation with rate $q < 1$ are derived. For each starter we compute sets of super–convergence with rate $q < 1$ mainly with the values $q = 1/2$; 1/10 for eccentricity-mean anomaly $(e, M) \in 2\ [0, 1) \times [0, \pi]$. This study completes in some sense the results derived by Avendaño el al. in [2] by using Smale's α-test with $q = 1/2$. Further more insight on super-convergence are derived for rates $q < 1/2$ and new starters can be derived for super-convergence uniformly for all $(e, M) \in [0, 1) \times [0, \pi]$. [View Full Paper]

[*] Professor, Dpt. Applied Mathematics-IUMA, Universidad de Zaragoza, 50009 Zaragoza, Spain.

[†] Professor, Grupo de Mecánica Espacial-IUMA & Centro Universitario de la Defensa, Universidad de Zaragoza, 50009 Zaragoza, Spain. AAS Member. AIAA Associate Fellow.

AAS 17-355

LONG-TERM ANALYTICAL PROPAGATION OF SATELLITE RELATIVE MOTION IN PERTURBED ORBITS

Tommaso Guffanti,* Simone D'Amico† and Michèle Lavagna‡

Many scientific applications require the implementation of satellite formation-flying in various orbits both around Earth and other planetary bodies. The design and guidance of these new formations call for relative dynamics models able to accurately and efficiently incorporate secular and long-periodic effects of all relevant perturbations. This paper leverages a quasi-nonsingular relative orbital elements state representation to devise a general methodology to model both conservative and non-conservative effects on the satellite relative motion in arbitrary eccentric orbits. By augmenting the state with force model parameters and Taylor expanding the time derivative to first order in mean space, three new plant matrices capturing the effects of solar radiation pressure, Sun and Moon third-body, and geopotential zonal harmonics up to third-order are formalized. In addition, two new effects have been discovered and modeled analytically in closed form. The first is the solar radiation pressure effect on the relative eccentricity vector of formations in near-circular orbit. The second is the lunisolar third-body effect on the relative inclination vector of formations in near-circular near-equatorial orbit. The new models are validated using numerical integration. Their accuracy and computational efficiency, combined with the novel analytical insight, can be leveraged for innovative relative orbit design and guidance. [View Full Paper]

* Ph.D. Candidate, Aeronautics and Astronautics, Stanford University, 496 Lomita Mall, Stanford, California 94305, U.S.A.
† Assistant Professor, Aeronautics and Astronautics, Stanford University, 496 Lomita Mall, Stanford, California 94305, U.S.A.
‡ Associate Professor, Department of Aerospace Science and Technology, Politecnico di Milano, via La Masa 34, 20156, Milan, Italy.

AAS 17-369

MIGRATION OF THE DSST STANDALONE TO C/C++

Juan F. San-Juan,[*] Rosario López,[†] Ricardo Suanes,[‡] Iván Pérez,[§] Srinivas J. Setty[**] and Paul J. Cefola[††]

The Draper Semi-analytical Satellite Theory (DSST) Standalone orbit propagator combines the speed of analytical propagators with the accuracy of numerical propagators. The DSST exhibits linear behavior, ease of estimation, and accurate measure of orbital uncertainty over extended periods of time. DSST is publicly available in its original Fortran 77 form and in the Orekit Java library. The current project migrates the original Fortran 77 DSST code to C/C++. The original design will be maintained as much as possible in the initial version of C/C++ DSST, to facilitate use of existing test resources.

[View Full Paper]

[*] Scientific Computing Group (GRUCACI), Universidad de La Rioja, ES-26006 Logroño, Spain. E-mail: juanfelix.sanjuan@unirioja.es.

[†] Center for Biomedical Research of La Rioja (CIBIR) and Scientific Computing Group (GRUCACI), Universidad de La Rioja, ES-26004 Logroño, Spain. E-mail: rlgomez@riojasalud.es.

[‡] Student of Informatics, Universidad de La Rioja, ES-26004 Logroño, Spain. E-mail: ricardo.suanes@unirioja.es.

[§] Scientific Computing Group (GRUCACI), Universidad de La Rioja, ES-26004 Logroño, Spain. E-mail: ivan.perez@unirioja.es.

[**] Scientific Computing Group (GRUCACI), Universidad de La Rioja, ES-26004 Logroño, Spain. E-mail: srinivas.setty@dlr.de.

[††] Adjunct Professor, Department of Mechanical and Aerospace Engineering, State University of New York at Buffalo, Amherst, New York 14260, U.S.A.; also Consultant in Aerospace Systems, Spaceflight Mechanics, and Astrodynamics, Vineyard Haven, Massachusetts 02568, U.S.A. E-mail: paulcefo@buffalo.edu, paul.cefola@gmail.com.

AAS 17-389

ORBITAL MANEUVERS IN THE NON-CENTRAL GRAVITATIONAL FIELD OF PHOBOS PERTURBED BY THE GRAVITATIONAL ATTRACTION DUE TO MARS, SUN AND DEIMOS

Evandro M. Rocco,[*] Liana D. Gonçalves[†] and Rodolpho V. de Moraes[‡]

Of all known moons in the Solar System, Phobos is the one that orbits closest to its primary. This characteristic, combined with the considerable difference in mass between Phobos and Mars, makes difficulty to maintain a trajectory around Phobos for a long period of time. In addition, Phobos has a highly irregular shape, which makes its gravitational field not central. Taking into account the difficulties mentioned, the present work seeks: to present a survey of the magnitude of the main perturbations capable of altering the orbit of an artificial satellite in the vicinity of Phobos; using the Lambert problem, to calculate the velocity increment required to perform a maneuver that transfers the satellite from an orbit around Mars to an orbit close to Phobos, and to perform this maneuver; to present a strategy to keep the artificial satellite close to Phobos, first without the use of a control system, then simultaneously controlling all the orbital elements that characterize the orbit of the artificial satellite. [View Full Paper]

[*] Ph.D. Student, National Institute for Space Research (INPE-Brazil), Av. dos Astronautas, 1758. CEP 12227-070 São José dos Campos - SP - Brazil.
[†] Researcher at INPE, National Institute for Space Research (INPE-Brazil), Av. dos Astronautas, 1758. CEP 12227-070 São José dos Campos - SP - Brazil.
[‡] Researcher at UNIFESP, Federal University of São Paulo, Av. Cesare Monsueto Giulio Lattes, 1211. CEP 12231-280 São José dos Campos - SP - Brazil.

INVESTIGATION OF CRITICAL INCLINATION AND SUNSYNCHRONOUS ORBITS AROUND THE MOONS OF SATURN

Liana D. Gonçalves,[*] Maria L. G. T. X. da Costa,[†] Rodolpho V. de Moraes[‡] and Evandro M. Rocco[†]

The purpose of the present work is to investigate the possibilities of orbits with critical inclinaton and heliosynchronous orbit around some of Saturn's moons: Titan, Enceladus, Mimas, Rhea and Dione. Then, for some of the orbits encountered for Titan and Rhea, correction and transfer maneuvers are simulated, and the perturbative effects due to Saturn's gravitational potential, the gravitational attraction of the Sun and the non-uniform mass distribution of the moons are considered and analyzed. [View Full Paper]

[*] Researcher at INPE, National Institute for Space Research (INPE-Brazil), Av. dos Astronautas, 1758. CEP 12227-070 São José dos Campos - SP - Brazil.

[†] Ph.D. Student, National Institute for Space Research (INPE-Brazil), Av. dos Astronautas, 1758. CEP 12227-070 São José dos Campos - SP - Brazil.

[‡] Researcher at UNIFESP, Federal University of São Paulo, Av. Cesare Monsueto Giulio Lattes, 1211. CEP 12231-280 São José dos Campos - SP - Brazil.

AAS 17-398

DECOUPLED DIRECT STATE TRANSITION MATRIX CALCULATION WITH RUNGE-KUTTA METHODS

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

A myriad of methods, including many optimization and estimation algorithms, requires the sensitivities of a dynamic system governed by a set of ordinary differential equations (ODEs). In this paper, the decoupled direct method (DDM) is derived for the calculation of first- and second-order state transition matrices (STMs) using Runge-Kutta (RK) ODE solvers. Implications for both explicit and implicit RK methods are discussed. Emphasis is placed on the implicit class because the decoupling of the state propagation and STM calculation eliminates the need to evaluate the Jacobian and Hessian iteratively at each propagation step. Thus, significant computational savings are achievable compared to the traditional propagation of the variational equations, particularly for systems with expensive dynamics. In the current work, two implementations of the DDM are extended both to second-order STMs and to the double-integrator form of the RK equations. One of the strategies presented in this paper, newly derived to include second-order sensitivities, takes advantage of the structure of the system, allowing for the STMs of nonlinear systems to be calculated using efficient linear-algebra techniques rather than iterative methods. This linear-algebra-based approach is shown to be more efficient than the second alternative, and is also more efficient than the propagation of the variational equations for computationally intensive dynamical systems. The effects of important implicit RK customizations, such as variable-fidelity dynamics models and parallelization, are also examined.

[View Full Paper]

[*] Graduate Research Assistant, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, 210 E. 24th Street, Stop C0600, Austin, Texas 78712-1221, U.S.A. E-mail: noble.hatten@utexas.edu. Student Member AIAA.

[†] Associate Professor, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, 210 E. 24th Street, Stop C0600, Austin, Texas 78712-1221, U.S.A. E-mail: ryan.russell@utexas.edu. Associate Fellow AIAA.

AAS 17-409

EXPANSION OF THE GRAVITATIONAL POTENTIAL OF A POLYHEDRAL BODY IN INERTIAL INTEGRALS

Stefano Casotto* and Roberto Casotto†

A new method to compute the gravitational potential at field points outside the Brillouin sphere of a constant density, irregular body defined by a triangular surface mesh is presented. It is based on an expansion in Cartesian coordinates and makes us of the inertial integrals introduced by MacMillan in 1930. The novelty of the method is that a fully analytical formulation is developed for the computation of the inertial integrals to any degree by simple evaluations of line integrals based on the coordinates of the mesh points through the use of Bernstein polynomials. [View Full Paper]

* Professor, Department of Physics and Astronomy, University of Padua, Vic. Osservatorio, 3 - 35122 Padova, Italy.
† Graduate Student, Department of Physics and Astronomy, University of Padua, Via Marzolo, 8 - 35131 Padova, Italy.

AAS 17-435

STABILITY REGIONS IN THE N-BODY PROBLEM: THE DISTANT RETROGRADE ORBITS FAMILY CASE

Antonio M. Pafundi* and Michèle Lavagna†

The stability of the three body family of Distant Retrograde Orbits (DROs) is investigated under the mission scenarios of the NASA Asteroid Redirect Robotic Mission (ARRM). The full coupled orbital-attitude stability of small asteroids initialized on DROs over long time is analysed; effects of the Moon eccentricity, the Sun and major planets in the solar system attraction and the non-conservative SRP and Yarkovsky action on small size low mass and irregular shape bodies such asteroids and boulders are considered. The stability study is performed using the chaotic indicator MEGNO as tool to distinguish regular from chaotic regions. The analyses on the CR3BP case are compared with the results of two major tools adopted in the study of the three body problem, namely the Monodromy Matrix and the Poincaré maps to search for confirmation, on the long term, of the stability properties of the family when the quasi-periodic orbits around the elliptic point tend to vanish. Then, the results related to the increased complexity in the model obtained by inserting the Moon eccentricity and the asteroid ellipsoidal model are discussed. MEGNO chaotic indicator confirms the stability of DROs family also when the quasi-periodic region around the elliptic point vanishes in correspondence of the intersection with the triple periodic orbit of the same family. The model enhancements show a progressive reduction of the global stability of the family, a strong component due to the rotational state of the rigid body. [View Full Paper]

* Research Assistant, Aerospace Science and Technology Department, Politecnico di Milano, via La Masa 34, 20156, Milano, Italy.
† Associate Professor, Aerospace Science and Technology Department, Politecnico di Milano, via La Masa 34, 20156, Milano, Italy.

AAS 17-463

A COMPARATIVE STUDY OF DISPLACED NON-KEPLERIAN ORBITS WITH IMPULSIVE AND CONTINUOUS THRUST

Jules Simo[*]

A study of novel families of highly non-Keplerian orbits (NKO) for spacecraft utilizing either solar sail or solar electric propulsion (SEP) at linear order are investigated in the circular restricted three-body problem (CRTBP). In addition to a detailed investigation of the dynamics and control of highly NKO, effort will be devoted to develop a strategy that uses maneuvers executed impulsively at discrete time intervals. Thus, impulse control is investigated as a means of generating displaced orbits. In order to compare the continuous thrust and impulse control orbits, linearized equations of motion will be considered for small displacements. The requirements for impulse control and continuous thrust for different values of out-of-plane distance are presented. [View Full Paper]

[*] Lecturer, School of Engineering, University of Central Lancashire, Preston, PR1 1XJ, United Kingdom.
E-mail: jsimo@uclan.ac.uk.

DEVELOPMENT OF AN ANALYTIC EXPRESSION FOR ESTIMATING THE TIME WHEN THE UNCERTAINTY BECOMES NON-GAUSSIAN

Inkwan Park[*] and Kyle T. Alfriend[†]

The objective of this research is to develop an analytic method for estimating the time when the uncertainty becomes non-Gaussian for specific initial conditions. The method is based on an extended Mahalanobis distance, that includes the nonlinear effects of the dynamics of the 2-dimensional semi-major axis – mean-anomaly space for Keplerian motion. It is hypothesized that there exists a specific ratio of the cumulative probability densities of the linear and nonlinear propagated uncertainties that determines when the uncertainty becomes non-Gaussian. Then based on this hypothesis an analytic method is derived to determine when the uncertainty becomes non-Gaussian. Using numerical simulation, it is shown that the error using the analytic method is less than 3%.

[View Full Paper]

[*] Postdoctorate Research Associate, Department of Aerospace Engineering, H. R. Bright Building, Texas A&M University, College Station, Texas 77843-3141, U.S.A.

[†] Professor, Department of Aerospace Engineering, H. R. Bright Building, Texas A&M University, College Station, Texas 77843-3141, U.S.A.

AAS 17-473

EXACT NORMALIZATION OF THE TESSERAL HARMONICS

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

An exact Delaunay normalization of the tesseral and sectorial harmonics using a nonconservative canonical transformation is presented. The main problem is reduced to a linear partial differential equation for the short-period generating function in two variables, mean anomaly and time, which is solved using the method of characteristics. This direct approach avoids the use of series expansions in the eccentricity and is unlike the iterative method of relegation. As a result, artificial satellite theories with tesseral and sectorial harmonics constructed using the proposed approach are valid for elliptic orbits of arbitrary eccentricity. Additionally, the proposed approach results in a significantly compact theory, valid for both subsynchronous and supersynchronous orbits simultaneously, and without singularities for resonant orbits. The analytic formulae for short-period and m-daily variations of classical as well as equinoctial orbital elements due to an arbitrary tesseral or sectorial harmonic are provided. The accuracy of the proposed satellite theory is compared with the solution obtained from numerical propagation and the results are presented for several types of orbits. [View Full Paper]

[*] Graduate Student, Department of Aerospace Engineering, Texas A&M University, College Station, Texas 77843-3141, U.S.A.
[†] Professor, Department of Aerospace Engineering, Texas A&M University, College Station, Texas 77843-3141, U.S.A.
[‡] TEES Distinguished Research Professor, Department of Aerospace Engineering, Texas A&M University, College Station, Texas 77843-3141, U.S.A.

ATTITUDE DYNAMICS AND CONTROL

Session Chairs:

Session 16: Roberto Furfaro

Session 20: Kyle DeMars

Session 29: Manoranjan Majji

The following papers were not available for publication:

AAS 17-302 Paper Withdrawn

AAS 17-351 Paper Withdrawn

AAS 17-500 Paper Withdrawn

AAS 17-211

FINITE-TIME ATTITUDE TRACKING CONTROL FOR SPACECRAFT WITHOUT ANGULAR VELOCITY MEASUREMENT

Boyan Jiang,[*] Chuanjiang Li,[†] Yanning Guo[‡] and Hongyang Dong[§]

This paper investigates the finite-time output feedback problem of attitude tracking control for spacecraft. It is assumed that the angular velocity information is not available for the controller design. An adding a power integrator technique based filter is designed to generate the pseudo-angular-velocity estimates, then a finite-time output feedback attitude tracking controller is developed with relative-attitude-only measurement. Overall finite-time stability of the entire closed-loop system is given, which shows the attitude tracking errors will converge into a region of zero in the presence of external disturbance. The simulation results illustrate the highly precision and robust attitude control performance of the proposed controllers. [View Full Paper]

[*] Ph.D., Department of Control Science and Engineering, Harbin Institute of Technology, Harbin 150001, China. E-mail: boyanjiang_hit@163.com.
[†] Professor, Department of Control Science and Engineering, Harbin Institute of Technology, Harbin 150001, China. E-mail: lichuan@hit.edu.cn.
[‡] Assistant Professor, Department of Control Science and Engineering, Harbin Institute of Technology, Harbin 150001, China. E-mail: guoyn@hit.edu.cn.
[§] Ph.D., Department of Control Science and Engineering, Harbin Institute of Technology, Harbin 150001, China. E-mail: donghongyang@hit.edu.cn.

AAS 17-225

ATTITUDE QUATERNION ESTIMATION USING A SPECTRAL PERTURBATION APPROACH

Adam L. Bruce*

All quaternion methods for static attitude determination currently rely on either the spectral decomposition of a 4×4 matrix (q-Method) or finding the maximum eigenvalue of a 4th-order characteristic equation (QUEST). Using a spectral perturbation approach, we show it is possible to analytically estimate the attitude quaternion to high accuracy and recursively calculate the maximum-likelihood attitude quaternion to arbitrary numerical precision. Analytic or recursive estimation removes several numerical difficulties which are inherent to state-of-the-art algorithms, suggesting our results may substantially benefit high frequency and limited memory embedded software implementations, such as those commonly used on spacecraft computers. [View Full Paper]

* This research was completed while the author was a graduate student at Purdue University and is being released as a university work product qualifying as fundamental research under ITAR 120.11(a)(8). The author is currently Systems Engineer II, Guidance, Navigation, and Control Center, Raytheon Missile Systems, 1151 E. Hermans Road, Tucson, Arizona 85756, U.S.A.

SPIN PARAMETERS AND NONLINEAR KALMAN FILTERING FOR SPINNING SPACECRAFT ATTITUDE ESTIMATION

Halil Ersin Soken,[*] Shin-ichiro Sakai,[†] Kazushi Asamura,[‡] Yosuke Nakamura[§] and Takeshi Takashima[†]

When quaternions are used for representing the attitude of a spinning spacecraft in an attitude estimation filter, several problems appear due to their rapid variations. These problems include numerical integration errors and violation of the linear approximations for the filter. In this study, we propose representing the attitude of a spinning spacecraft using a set of spin parameters. These parameters consist of the spin-axis orientation unit vector in the inertial frame and the spin phase angle. This representation is advantageous as the spin axis direction components in the inertial frame do not change rapidly and the phase angle changes with a constant rate in the absence of a torque. The attitude matrix and the kinematics equations are derived in terms of spin parameters. As the equations are highly nonlinear an Unscented Kalman Filter (UKF) is implemented to estimate the spacecraft's attitude in spin parameters. The estimation results are compared with those of a quaternion based UKF in different scenarios using the simulated data for JAXA's ERG spacecraft. [View Full Paper]

[*] Aerospace Project Research Associate, Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA), Yoshinodai 3-1-1 Chuo-ku, Sagamihara 252-5210, Japan.
[†] Associate Professor, ISAS/JAXA, Yoshinodai 3-1-1 Chuo-ku, Sagamihara 252-5210, Japan.
[‡] Assistant Professor, ISAS/JAXA, Yoshinodai 3-1-1 Chuo-ku, Sagamihara 252-5210, Japan.
[§] ERG Project Submanager, ISAS/JAXA, Yoshinodai 3-1-1 Chuo-ku, Sagamihara 252-5210, Japan.

AAS 17-250

SPIN-AXIS TILT ESTIMATION ALGORITHM WITH VALIDATION BY REAL DATA

Halil Ersin Soken,[*] Jozef C. Van der Ha[†] and Shin-ichiro Sakai[‡]

The spin-axis tilt (SAT), which is also known as dynamic imbalance or coning error, is one of the dominant errors deteriorating the attitude determination accuracy of spinning spacecraft. It is experienced as the misalignment of the major principal axis of the spacecraft from the intended body spin axis. This paper evaluates a straightforward SAT estimation algorithm by means of real in-flight data. The algorithm is based on the Singular Value Decomposition (SVD) method and makes use of the attitude rates estimated by an attitude determination filter. The accuracy of the algorithm is investigated by using telemetry data gathered by the CONTOUR spacecraft in 2002. The results are compared with those obtained by an averaging method for the SAT determination. The SVD-based SAT estimation algorithm (SVD-SAT) provides robust estimation results without being significantly affected by sensor biases. This is in contrast with the averaging method, which is shown to be more sensitive to other errors. [View Full Paper]

[*] Aerospace Project Research Associate, Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA), Yoshinodai 3-1-1 Chuo-ku, Sagamihara 252-5210, Japan.
[†] Aerospace Engineering Consultant, Satellite Mission Design and Operations, 5808 Bell Creek Road, Deming, Washington 98244, U.S.A.
[‡] Associate Professor, Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA), Yoshinodai 3-1-1 Chuo-ku, Sagamihara 252-5210, Japan.

AAS 17-255

THE THEORY OF CONNECTIONS. PART 1: CONNECTING POINTS

Daniele Mortari*

Dedicated to John Lee Junkins

This study introduces a procedure to obtain general expressions, $y = f(x)$, subject to linear constraints on the function and its derivatives defined at specified values. These *constrained expressions* can be used to describe functions with embedded specific constraints. The paper first shows how to express the most general explicit function passing through a single point in three distinct ways: linear, additive, and rational. Then, functions with constraints on single, two, or multiple points are introduced as well as those satisfying relative constraints. This capability allows to obtain general expressions to solve linear differential equations with no need to satisfy constraints (the "subject to:" conditions) as the constraints are already embedded in the *constrained expression*. In particular, for expressions passing through a set of points, a generalization of the Waring's interpolation form, is introduced. The general form of additive *constrained expressions* is introduced as well as a procedure to derive its coefficient functions, requiring the inversion of a matrix with dimensions as the number of constraints. [View Full Paper]

---

* Department of Aerospace Engineering, Texas A&M University, 3141 TAMU, College Station, Texas 77843-3141, U.S.A. E-mail: mortari@tamu.edu. IEEE and AAS Fellow, AIAA Associate Fellow.

AAS 17-264

STABILITY OF PERMANENT ROTATIONS OF A HEAVY ASYMMETRIC GYROSTAT

M. Iñarrea,[*] V. Lanchares,[†] A. I. Pascual[‡] and A. Elipe[§]

We consider the motion of a gyrostat under the attraction of a Newtonian field. For this problem, we obtain the possible permanent rotations, that is, the equilibria of the system. The stability of those permanent rotations is analyzed by means of the Energy-Casimir method. We are able to give necessary and sufficient conditions for some of the permanent rotations. The geometry of the gyrostat and the value of the gyrostatic moment are relevant in order to get stable permanent rotations. Moreover, it seems that the necessary conditions are also sufficient, but, however, this fact can only be proved partially.

[View Full Paper]

[*] Assistant Professor, Área de Física aplicada, Universidad de La Rioja, 26004 Logroño, Spain.
[†] Associate Professor, Dpto. Matemáticas y Computación, Universidad de La Rioja, 26004 Logroño, Spain.
[‡] Assistant Professor, Dpto. Matemáticas y Computación, Universidad de La Rioja, 26004 Logroño, Spain.
[§] Professor, Grupo de Mecánica Espacial-IUMA & Centro Universitario de la Defensa, Universidad de Zaragoza, 50009 Zaragoza, Spain. AAS Member. AIAA Associate Fellow.

MINIMUM POWER SLEWS AND THE JAMES WEBB SPACE TELESCOPE

Mark Karpenko,[*] Cornelius J. Dennehy,[†] Harleigh C. Marsh[‡] and Qi Gong[§]

Power is a precious commodity in space flight. Reducing the power demands of reaction wheels during spacecraft attitude slews can have multiple benefits both in the up-front spacecraft design phase as well as during in-flight operations. In an effort to reduce power requirements of momentum control systems, many authors have contemplated the use of proxies for reaction wheel power to design *minimal effort* slews. Proxies for power are used because the power input equation is non-smooth leading to a seemingly unsolvable problem in optimal control. In this paper we show, through the application of various transformations and the introduction of appropriate functional constraints, that a smooth cost functional for reaction wheel input power can indeed be built. Standard techniques can then be used to solve and analyze the power optimal slew problem. The concept is applied to reduce the power requirements for a typical large-angle slew of the James Webb Space Telescope. The energy reduction (~ 20%) is obtained by finding a minimum power momentum distribution that achieves the necessary control effort while simultaneously reducing power input to the individual wheels. [View Full Paper]

[*] Research Associate Professor and corresponding author, Department of Mechanical and Aerospace Engineering, Naval Postgraduate School, Monterey, California 93943, U.S.A. E-mail: mkarpenk@nps.edu.

[†] NASA Technical Fellow, Guidance, Navigation and Control, NASA Engineering and Safety Center, NASA Goddard Space Flight Center (GSFC), Greenbelt, Maryland 20771, U.S.A.

[‡] Graduate Student., Department of Applied Mathematics and Statistics, University of California Santa Cruz, Santa Cruz, California 95064, U.S.A.

[§] Associate Professor, Department of Applied Mathematics and Statistics, University of California Santa Cruz, Santa Cruz, California 95064, U.S.A.

AAS 17-292

PERFORMANCE ANALYSIS OF SPACECRAFT MANEUVER TO CALIBRATE ATTITUDE DETERMINATION SUBSYSTEM

SooYung Byeon,[*] D. W. Koh,[†] H. W. Woo[‡] and Amer Mohammad Al Sayegh[§]

This paper presents performance analysis of spacecraft maneuvers to calibrate attitude determination subsystem (ADS). The purpose of a calibration is to improve the accuracy of the model parameters of an ADS and that of attitude knowledge. A calibration process deals with bias, scale factor error, and misalignment of gyros and also misalignment of star-trackers. Extended Kalman filter (EKF) based approach allows calibration process to converge within relatively short time compared with other methods such as least-square based filter. The persistent excitation condition for maneuver is known for necessary condition for ADS calibration process using EKF based approach but it is not known exactly what kinds of attitude maneuver are beneficial to the ADS calibration in terms of observability. In this paper, several three-axis periodic spacecraft maneuvers for ADS calibration are investigated and analyzed how the calibration performance changes as the parameters of each maneuver are modified. For this, observability measures are addressed as an analytic method, and calibration simulations are conducted to verify that the expected results are actually obtained. Finally, based on the flight data of the DubaiSat-2 operating in-orbit since 2013, it is confirmed through the star-tracker residual values that the ADS calibration is performed successfully. [View Full Paper]

[*] Associate Research Engineer, R&D Center, Satrec Initiative, Daejeon, 34054, Republic of Korea.
[†] Senior Research Engineer, R&D Center, Satrec Initiative, Daejeon, 34054, Republic of Korea.
[‡] Team Leader, R&D Center, Satrec Initiative, Daejeon, 34054, Republic of Korea.
[§] Deputy Director, Space Systems Development Department, Mohammed bin Rashid Space Centre (MBRSC), PO Box 211833, Dubai, United Arab Emirates.

AAS 17-300

ADAPTIVE SAILCRAFT ATTITUDE STABILIZATION VIA PHOTONIC PRESSURE TORQUE

Erik Proano[*] and Dongeun Seo[†]

This paper is intended to demonstrate attitude stabilization for a sailcraft with a heliogyro-like configuration of solar sails by taking advantage of solar- and laser-emitted photons. An adaptive nonlinear controller with saturation is able to correct and perform attitude maneuvers during the lifetime of a mission. The designed control is compared with a PD controller based on the linearized model. A newly developed adaptive controller is used in order to compensate for the changes in the moment of inertia matrix due to the tilting of the wings. In addition, saturation due to limited intensity is considered. It is shown that the main advantage of the adaptive over the PD controller is that the former is capable of stabilize the sailcraft faster with a high-frequency output while the latter shows an overdamped behavior with a higher settling time. However, the adaptive controller requires faster actuation of the tilting sails and faster computations which in turn requires high electrical energy and processing speed. [View Full Paper]

[*] Graduate Research Assistant, Embry-Riddle Aeronautical University, 600 S. Clyde Morris Blvd., Daytona Beach, Florida 32114, U.S.A. E-mail: proanoe@erau.edu.

[†] Assistant Professor, Aerospace Engineering, Embry-Riddle Aeronautical University, 600 S. Clyde Morris Blvd., Daytona Beach, Florida 32114, U.S.A. Phone: 386-226-6614. E-mail: seod@erau.edu.

AAS 17-307

FAULT TOLERANT CONTROL FOR SPACECRAFT ASSEMBLED WITH SGCMGS BASED ON THE FAULT DECOUPLING

Fuzhen Zhang,* Lei Jin† and Shijie Xu‡

A fault tolerant control method for rigid spacecraft assembled with SGCMGs as actuator is presented. First of all, considering partial failure of the SGCMG, the spacecraft model and the CMG model are described. In order to achieve the attitude stability of the spacecraft, the PD controller is designed to get the expected control torque without considering the fault of the SGCMGs firstly. Then, the Singular Robustness Escape/Avoidance steering law is adopted to obtain the expected gimbal rate. The fault tolerant control method for each SGCMG is designed to track the expected gimbal rate without knowing the prior information of the fault. The simulation results indicate the effectiveness of the algorithm for attitude control of the spacecraft. [View Full Paper]

* Ph.D. Candidate, Department of Aerospacecraft Technology, Beihang University, Beijing, 100191, China. E-mail: zhangfuzhen9288@buaa.edu.cn
† Associate Professor, Department of Guidance Navigation and Control, Beihang University, Beijing, 100191, China. E-mail: jinleibuaa@163.com.
‡ Professor, Department of Aerospacecraft Technology, Beihang University, Beijing, 100191, China. E-mail: starsjxu@163.com.

AAS 17-311

PERFORMANCE TESTS OF PYRAMID STAR-ID ALGORITHM WITH MEMORY ADAPTIVE K-VECTOR

Marcio A. A. Fialho* **and Daniele Mortari†**

This paper presents results obtained with a C/C++ implementation of the Pyramid star identification algorithm enhanced by the memory adaptive k-vector. Specifically, the paper focuses in the benchmark results of Pyramid run time versus the amount of memory allocated for the k-vector. A discussion about the tradeoff relations between memory allocated for the k-vector and speed, and the impact of cache misses in modern processors for very long k-vectors is presented. [View Full Paper]

* Doctorate Student, Divisão de Eletrônica Aeroespacial, INPE - Instituto Nacional de Pesquisas Espaciais, São José dos Campos, SP, Brazil CEP: 12227-010. E-mail: marcio.fialho@inpe.br.

† Professor, Department of Aerospace Engineering, Texas A&M University, 746C H.R. Bright Building, College Station, Texas 77843-3141, U.S.A. Tel.: (979) 845-0734. E-mail: mortari@tamu.edu. IEEE and AAS Fellow, AIAA Associate Fellow.

AAS 17-312

NEW PRACTICAL RESULTS FOR FLAT-SPIN RECOVERY BY EQUATORIAL TORQUES

Frank L. Janssens* and Jozef C. Van der Ha†

The paper studies the motion of a spinning rigid asymmetric body under an equatorial torque (i.e., normal to spin axis). Through extensive simulations, starting from pure flat-spin motion, four types of motion are identified and visualized as zones within the plane formed by the two torque components. The zone "No Recovery" describes a new type of unstable motion. The zone "Slow flat spin recovery" gives new insights into the efficiency of a recovery strategy by an equatorial torque. For the zone "Fast Recovery" a new approximate analytical model involving Fresnel integrals has been established for modeling the asymptotic rotational motion. [View Full Paper]

* Consultant, Wilhelminastraat 29, 2201 KA Noordwijk, The Netherlands. E-mail: f.janssens@ziggo.nl.
† Consultant, 5808 Bell Creek Road, Deming, Washington 98244, U.S.A. E-mail: jvdha@aol.com.

AAS 17-313

RETHINKING ORTHOGONAL REACTION WHEEL CONFIGURATIONS FOR SMALL SATELLITES

Jeffery T. King[*] and Mark Karpenko[†]

Rigid-body agility is limited by the maximum torque and orientation of the reaction wheels. Maximizing the inscribed sphere of the torque envelope can underestimate the true capability of the system because spacecraft inertia properties are not considered. We show that simple reorientation of the reaction wheel assembly while maintaining orthogonality can increase agility while maintaining spherical acceleration limits. This paper utilizes the associated concept of the agility envelope to develop analytical equations for finding ideal reaction wheel orientations that provide up to 40% more capability than conventional methods. The equations and corresponding design curves are presented for typical small satellites. [View Full Paper]

[*] Assistant Professor, Department of Aerospace Engineering, United States Naval Academy, Annapolis, Maryland, 21402, U.S.A.

[†] Research Associate Professor, Control and Optimization Laboratories, Naval Postgraduate School, Monterey, California 93943, U.S.A.

AAS 17-324

BAYESIAN ATTITUDE ESTIMATION ON SO(3) WITH MATRIX FISHER MIXTURES

Shankar Kulumani and Taeyoung Lee*

This paper presents a Bayesian attitude estimation for a rigid body on the special orthogonal group. The matrix Fisher distribution provides a compact form of unimodal probability densities for attitude uncertainty, and it has been utilized in attitude estimation on the special orthogonal group. This paper aims to extend such results to a general class of uncertainties with a mixture of matrix Fisher distributions. Stochastic attitude estimators are constructed in an intrinsic fashion directly on the special orthogonal group with matrix Fisher mixtures, and it is shown that the proposed approach is particularly useful for challenging attitude estimation problems with arbitrarily large uncertainties.

[View Full Paper]

* Mechanical and Aerospace Engineering, George Washington University, 800 22nd Street NW, Washington, DC 20052, U.S.A. Tel: 202-994-8710. E-mail: {fskulumani,tyleeg}@gwu.edu.

GEOMETRIC SWITCHING SCHEME FOR ATTITUDE CONTROL OF AN UNDERACTUATED SPACECRAFT WITH TWO CONTROL MOMENT GYROS

Chris Petersen,[*] Frederick Leve[†] and Ilya Kolmanovsky[‡]

A switching feedback controller is developed for the attitude control of an underactuated spacecraft equipped with two control moment gyros (CMGs). The overall method exploits the separation of the system states into inner-loop base variables and outer-loop fiber variables. The base variables, which in this paper are the gimbal angles, track periodic reference trajectories. The amplitude of the base variables is governed by parameters that are adjusted to induce an appropriate change in the fiber variable, which in this paper is the attitude of the spacecraft described by a matrix representation of $SO(3)$, towards the desired pointing configuration. [View Full Paper]

[*] Graduate Student, Department of Aerospace Engineering, The University of Michigan, 1320 Beal Avenue, Ann Arbor, Michigan 48109, U.S.A. E-mail: cdpete@umich.edu.

[†] Air Force Research Laboratory (AFRL), Space Vehicles Directorate, 3550 Aberdeen Avenue SE, Kirtland AFB, New Mexico 87117-5776, U.S.A. E-mails: AFRL.RVSV@us.af.mil.

[‡] Professor, Department of Aerospace Engineering, The University of Michigan, 1320 Beal Avenue, Ann Arbor, Michigan 48109, U.S.A. E-mail: ilya@umich.edu.

AAS 17-343

REPETITIVE MODEL PREDICTIVE CONTROLLER DESIGN BASED ON MARKOV PARAMETERS

Jianzhong Zhu* and Richard W. Longman†

The authors and co-workers have developed a method of producing a stable inverse of systems that have zeros outside the unit circle so the full inverse is unstable. The methods produce zero tracking error except at one or more initial time steps. The purpose of this paper is to outline a set of uses for such a stable inverse in control applications, including Linear Model Predictive Control (LMPC), and LMPC applied to Repetitive Control RC-LMPC, and a generalized form of one step ahead control. An important characteristic is that the approach has the property that it can converge to zero tracking error in a small number of time steps, which is finite time convergence instead of asymptotic convergence as time tends to infinity. The majority of discrete time systems in the world obtained from discretizing differential equation systems fed by a zero order hold have unstable inverses. The existence of a stable inverse that produces zero tracking error at addressed time steps opens up a range of new possibilities in control theory.

[View Full Paper]

* Doctoral Candidate, Department of Mechanical Engineering Department, Columbia University, MC4703, 500 West 120th Street, New York, New York 10027, U.S.A. E-mail: jianzhong.zhu07@gmail.com.

† Professor of Mechanical Engineering, Professor of Civil Engineering and Engineering Mechanics, Columbia University, MC 4703, 500 West 120th Street, New York, New York 10027, U.S.A. E-mail: RWL4@columbia.edu.

AAS 17-373

THE ECCENTRIC CASE OF A FAST-ROTATING, GRAVITY-GRADIENT-PERTURBED SATELLITE ATTITUDE SOLUTION

Noble Hatten* and Ryan P. Russell†

A closed-form perturbation solution for the attitude evolution of a triaxial space object in an elliptical orbit is presented. The solution, derived using the Lie-Deprit method, takes into account gravity-gradient torque and is facilitated by an assumption of fast rotation of the object. The formulation builds on the earlier implementation of Lara and Ferrer, which assumes a circular orbit. The previously presented work – which assumes spin about an object's axis of maximum inertia – is further extended by the explicit presentation of the transformations required to apply the solution to an object spinning about its axis of minimum inertia. Additionally, several numerical analyses are presented to more completely assess the utility of the solution. These studies (1) validate the elliptical solution, (2) assess the impact of varying the small parameter of the perturbation procedure, (3) analyze the assumption of fast rotation, and (4) apply the solution to the common and important scenario of a tumbling rocket body. [View Full Paper]

* Graduate research assistant, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, 210 E. 24th Street, Stop C0600, Austin, Texas 78712-1221, U.S.A. E-mail: noble.hatten@utexas.edu. Student member AIAA.

† Associate Professor, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, 210 E. 24th Street, Stop C0600, Austin, Texas 78712-1221, U.S.A. E-mail: ryan.russell@utexas.edu. Associate Fellow AIAA.

AAS 17-376

A SEMIANALYTICAL TECHNIQUE FOR SIX-DEGREE-OF-FREEDOM SPACE OBJECT PROPAGATION

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

The cannonball assumption of three-degree-of-freedom (3DOF) space object state prediction can lead to large inaccuracies if the sphericity assumption is violated, while numerical propagation of both the translational and rotational (6DOF) equations of motion is computationally expensive. In this paper, a middle ground is proposed, in which the translational equations of motion are propagated numerically using approximate attitude predictions obtained via a closed-form perturbation solution. The capabilities of this semianalytical "hybrid" of special and general perturbation techniques are illustrated using a specific attitude solution, which assumes a fast-rotating, triaxial rigid body in an elliptical orbit subject to gravity-gradient torque. Even when these assumptions are mildly violated – such as when modeling higher-fidelity forces and torques – the approximate attitude predictions allow for more accurate modeling of body forces than a 3DOF cannonball propagation. In numerical examples, the hybrid method produces position predictions one or more orders of magnitude more accurate than a 3DOF cannonball propagation while requiring approximately one-third of the CPU time of a full 6DOF propagation for certain accuracy tolerance levels. Relative speedups achievable by the hybrid method are shown to increase as the rotation rate of the body increases. [View Full Paper]

[*] Graduate Research Assistant, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, 210 E. 24th Street, Stop C0600, Austin, Texas 78712-1221, U.S.A. E-mail: noble.hatten@utexas.edu. Student Member AIAA.

[†] Associate Professor, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, 210 E. 24th Street, Stop C0600, Austin, Texas 78712-1221, U.S.A. E-mail: ryan.russell@utexas.edu. Associate Fellow AIAA.

AAS 17-386

TIME-OPTIMAL REORIENTATION OF AN AUTONOMOUS AGILE EARTH OBSERVING SATELLITE

Mingwei Yin,* Hongwei Yang† and Hexi Baoyin‡

This paper proposes a rapid parameterized algorithm for the time-optimal reorientation of an autonomous agile satellite. This kind of satellites is presently studied by China. The smoothness and continuity of the controls is required for the engineering implementation. It means that the classical bang-bang control is not feasible. The reorientation problem is firstly formulated by the modified Rodrigues parameters. Then, the attitude angles, angular velocities, available control torques are all parameterized analytically by polynomials. Radau Pseudo-spectral method is exploited to solve this problem whose solutions are smooth. Finally, instead of the two-point boundary value problem, it is described as a constrained nonlinear programming problem, which can be optimized by the nonlinear programming solver. This smooth polynomial optimization algorithm is suitable to solve the three-axis reorientation problem for both symmetric and asymmetric rigid bodies. It enables us to deal with the singular and nonsingular cases in a unified way. Numerical simulations illustrate that the algorithm is fast enough for the online computation onboard. The smooth controls are consistent with the mission requirement.

[View Full Paper]

* Ph.D. Candidate, School of Aerospace Engineering, Tsinghua University, Beijing 100084, China.
E-mail: ymw13@mails.tsinghua.edu.cn.
† Ph.D. Candidate, School of Aerospace Engineering, Tsinghua University, Beijing 100084, China.
E-mail: yang.hw.thu@gmail.com.
‡ Professor, School of Aerospace Engineering, Tsinghua University, Beijing 100084, China.
E-mail: baoyin@tsinghua.edu.cn. Senior Member AIAA.

HIGH ACCURACY ATTITUDE DETERMINATION ESTIMATOR SYSTEM FOR IRASSI INTERFEROMETER SPACECRAFT

Divya Bhatia,[*] Ulf Bestmann[†] and Peter Hecker[‡]

High accuracy attitude determination is becoming a norm for future space missions. Hence, this work describes development of an Attitude Determination Estimator System (ADES) which achieves an unprecedented stringent attitude estimation accuracy of 0.04 arcsec. This is accomplished by carefully selected high accuracy commercial-off-the shelf (COTS) sensors and implementing state-of-the-art optimal attitude estimation algorithm for sensor data fusion in MATLAB. During fine-pointing mission mode of IRASSI, data from two simultaneously operating star trackers are fused with gyroscope via a Multiplicative Extended Kalman Filter (MEKF). For coarse attitude acquisition mode, measurements from Sun Sensor and Gyroscope are fused via MEKF. [View Full Paper]

[*] Research Associate, Institute of Flight Guidance (IFF), Technische Universität Braunschweig, 38108 Germany.
[†] Navigation Team Leader, Institute of Flight Guidance (IFF), Technische Universität Braunschweig, 38108 Germany.
[‡] Managing Director, Institute of Flight Guidance (IFF), Technische Universität Braunschweig, 38108 Germany.

AAS 17-428

PRECISION ATTITUDE STABILIZATION: INPUTS SCALED BY PERSISTENTLY EXCITING DIAGONAL MATRICES

Hongyang Dong[*] and Maruthi R. Akella[†]

In this paper, a certain type of spacecraft attitude stabilization problem is addressed. Under this setting, the control inputs are scaled by time-varying, singular gains in the form of a diagonal matrix. These control scaling gains are supposed to satisfy persistency of excitation conditions, and could be singular at time instants or even stay singular for large time intervals. Based on a novel state-dependent filter, a feedback control structure is proposed to achieve the stabilization objective. A significant contribution of this result is that the states errors of the closed-loop system are guaranteed to converge to a predetermined small region around the origin exponentially. To illustrate the effectiveness of the proposed method, an attitude stabilization problem for spacecraft with a single, gimbaling-based thruster is studied, while incorporating rise and fall times and on-off schedules of the thruster are also considered. [View Full Paper]

[*] Ph.D. Candidate, Department of Control Science and Engineering, Harbin Institute of Technology, Harbin, 150001, China. E-mail: donghongyang91@gmail.com.
[†] Professor and Myron L. Begeman Fellow in Engineering, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, Austin, Texas, 78712, U.S.A. E-mail: makella@mail.utexas.edu. AAS Fellow.

AAS 17-446

NONLINEAR ATTITUDE DYNAMICS OF A RIGID BODY AT THE LAGRANGIAN POINTS

Lorenzo Bucci[*] and Michèle Lavagna[†]

The paper presents an exact, analytical solution for the planar attitude dynamics of a rigid body, located at an equilibrium point of the Circular Restricted Three-Body Problem. The dynamics equations are proved to be analogous to the nonlinear dynamics of a swinging pendulum, for which exact solution exists in literature, and is thus applied to the present case. Three-dimensional attitude stability of the rotating body is investigated, both for oscillations (no net swing over) and for multiple swings, extending the literature results on the topic. Eventually, three-dimensional periodic solutions are presented and analyzed.

[View Full Paper]

[*] Ph.D. Student, Aerospace Science and Technology Department, Politecnico di Milano, via La Masa 34, 20156, Milano, Italy. E-mail: lorenzo.bucci@polimi.it.

[†] Associate Professor, Aerospace Science and Technology Department, Politecnico di Milano, via La Masa 34, 20156, Milano, Italy.

AAS 17-451

VOLUME MULTI-SPHERE-MODEL DEVELOPMENT USING ELECTRIC FIELD MATCHING

Gabriel Ingram,[*] Joseph Hughes,[*] Trevor Bennett,[*]
Christine Reilly[†] and Hanspeter Schaub[‡]

Electrostatic modeling of spacecraft has wide-reaching applications such as detumbling space debris in the Geosynchronous Earth Orbit regime before docking or servicing and tugging space debris to graveyard orbits. The viability of electrostatic actuation control applications relies on faster-than-realtime characterization of the electrostatic interaction. The Volume Multi-Sphere Method (VMSM) seeks the optimal placement and radii of a small number of equipotential spheres to accurately model the electrostatic force and torque on a conducting space object. Current VMSM models tuned using force and torque comparisons with commercially available finite element software are subject to the modeled probe size and numerical errors of the software. This paper investigates fitting of VMSM models to Surface-MSM (SMSM) generated electrical field data, removing modeling dependence on probe geometry while significantly increasing performance and speed. A proposed electric field matching cost function is compared to a force and torque cost function, the inclusion of a self-capacitance constraint is explored and 4 degree-of-freedom VMSM models generated using electric field matching are investigated. The resulting E-field based VMSM development framework is illustrated on a box-shaped hub with a single solar panel. Despite the complex non-symmetric spacecraft geometry, elegantly simple 2-sphere VMSM solutions provide force and torque fits within a few percent. [View Full Paper]

[*] Graduate Research Assistant, Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado, U.S.A.
[†] Undergraduate Researcher, Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado, U.S.A.
[‡] Alfred T. and Betty E. Look Professor of Engineering, Associate Chair of Graduate Affairs, Department of Aerospace Engineering Sciences, University of Colorado, 431 UCB, Colorado Center for Astrodynamics Research, Boulder, Colorado 80309-0431, U.S.A. AAS Fellow.

AAS 17-458

ON THE ROBUST ATTITUDE REGULATION FOR EARTH OBSERVATION SPACECRAFT UNDER HYBRID ACTUATION

Dimitrios Pylorof,[*] Srinivas Bettadpur[†] and Efstathios Bakolas[‡]

Mission requirements for Earth observation spacecraft often influence the design philosophy of the latter and may additionally impose constraints and performance objectives on their attitude control functionality. We study the robust attitude regulation problem for such spacecraft, characterized primarily by hybrid actuation consisting of magnetic actuators and thrusters, assuming noisy attitude feedback. In our problem formulation, the angular accelerations induced by the attitude stabilization have to remain sufficiently small due to payload requirements. A linear robust control law is developed, which is tailored to the hybrid actuation scheme by appropriately complementing the directionally constrained magnetic torque with the thrusters. [View Full Paper]

[*] Graduate Student, Center for Space Research & Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, 210 East 24th Street, Austin, Texas 78712, U.S.A.

[†] Associate Professor, Center for Space Research & Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, 210 East 24th Street, Austin, Texas 78712, U.S.A.

[‡] Assistant Professor, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, 210 East 24th Street, Austin, Texas 78712, U.S.A.

AAS 17-468

A SIMPLIFIED MODEL FOR VIBRATING MASS CONTROL MOMENT GYROSCOPE

Burak Akbulut,[*] Ferhat Arberkli,[†] Kivanc Azgin[‡] and Ozan Tekinalp[§]

A novel satellite attitude actuator based on vibrating masses was previously proposed. Its governing equations were obtained and simulated. In this study, the resulting mathematical model is validated via energy as well as the conservation of angular momentum methods. Additionally, the mathematical model for the complete system was too complicated for analysis. In this work, a representative simplified set of equations describing vibrating mass control moment gyroscope (vCMG) dynamics in high fidelity are also obtained. It is shown that the simplified model may be used to simulate the complex vCMG dynamics under certain conditions. [View Full Paper]

[*] Ph.D. Candidate, Aerospace Engineering Department, Middle East Technical University, Ankara, 06800, Turkey. E-mail: e134632@metu.edu.tr.
[†] M.Sc. Student., Mechanical Engineering Department, Middle East Technical University, Ankara, 06800, Turkey.
[‡] Assistant Professor Dr., Mechanical Engineering Department, Middle East Technical University, Ankara, 06800, Turkey.
[§] Professor Dr., Aerospace Engineering Department, Middle East Technical University, Ankara, 06800, Turkey.

AAS 17-478

REAL-TIME ATTITUDE CONTROL FOR LARGE-ANGLE AGILE MANEUVERS OF A SPACECRAFT WITH CONTROL MOMENT GYROS

Shota Kawajiri[*] and Saburo Matunaga[†]

In this paper, a real-time control method satisfying mechanical constraints using control moment gyros is studied for an agile maneuver. It is known that there exists a coasting period in which the gimbal rates become zero for an agile large-angle maneuver. The gimbals are driven such that the coasting period is generated in the proposed method. This allows the problem to be converted into obtaining only a coasting time and gimbal angles which give the spacecraft the maximum angular velocity along the rotational axis of the maneuver during the coasting. The effectiveness of the proposed method is demonstrated by numerical simulations. It is found that the proposed method can shorten the settling time by 20–70% compared with a traditional feedback method. Also, comparison with an existing path planning method shows that the proposed method achieves low computational complexity and a certain level of the shortness of the settling time.

[View Full Paper]

[*] Ph.D. Student, Department of Mechanical and Aerospace Engineering, Tokyo Institute of Technology, 152-8550, Japan.

[†] Professor, Department of Mechanical Engineering, Tokyo Institute of Technology, 152-8550, Japan.

NON LINEAR K-VECTOR

Marcio A. A. Fialho* **and Daniele Mortari†**

The *k*-vector search technique is a general purpose search method that is capable of locating entries in a sorted array with complexity independent from the database size. It is based on an *m*-long vector of integers, called the *k*-vector, that keeps record of the sorted database nonlinearities. The traditional *k*-vector best performs for almost linear sorted databases. In this paper we extend the *k*-vector technique by the use of non-linear mapping functions, and show how this approach can potentially solve performance and memory limitations of the traditional *k*-vector for searches in arrays with strongly non-uniform distributions. [View Full Paper]

* Doctorate Student, Divisão de Eletrônica Aeroespacial, INPE - Instituto Nacional de Pesquisas Espaciais, São José dos Campos, SP, Brazil CEP: 12227-010. E-mail: marcio.fialho@inpe.br.

† Professor, 746C H.R. Bright Building, Aerospace Engineering, Texas A&M University, College Station, Texas 77843-3141, U.S.A. Tel.: (979) 845-0734. E-mail: mortari@tamu.edu. IEEE and AAS Fellow.

AAS 17-490

DESIGN AND VALIDATION OF HYBRID ATTITUDE DETERMINATION AND CONTROL SYSTEM FOR CUBESAT THROUGH HARDWARE-IN-THE-LOOP SIMULATION

Dae Young Lee,[*] Hyeongjun Park,[†] Marcello Romano[‡] and James Cutler[§]

More accurate and flexible attitude maneuvering capability is demanded for extending applications of miniaturized satellites. In this paper, an autonomous condition-based switching method among a family of control and estimation algorithms is proposed to extract required attitude maneuvering performance with low-price sensors, small-sized actuators, and low-powered processors. A hybrid automaton design for multi-algorithmic hybrid ADCS is proposed by defining a set of operative modes, domain mapping, set of edges, and guard mapping. In addition, experimental analysis is pursued using CubeSat Three-Axis Simulator (CubeTAS) to simulate a frictionless and torque-free environment. By implementing the hybrid ADCS on the real-time test bed, the performance of the proposed method is validated with real sensors, actuators, and computing resources.

[View Full Paper]

[*] Postdoctoral Research Associate, Center for Space Research, University of Texas, Austin, Texas 78759, U.S.A.
[†] Postdoctoral Research Associate, Mechanical and Aerospace Engineering, Naval Postgraduate School, Monterey, California 93943, U.S.A.
[‡] Associate Professor, Mechanical and Aerospace Engineering, Naval Postgraduate School, Monterey, California 93943, U.S.A.
[§] Associate Professor, Aerospace Engineering, University of Michigan, Ann Arbor, Michigan 48109, U.S.A.

AAS 17-493

OPTIMAL ATTITUDE DETERMINATION AND CONTROL SYSTEM DESIGN FOR LAICE AND CUBESAIL

Vedant,* Erik Kroeker† and Alexander Ghosh‡

This paper investigates the optimization of the Attitude Determination and Control System (ADCS) for LAICE and CubeSail, two nanosatellites based on the Illinisat-2 bus. The ADC system is divided into two separate, but interlinked subsystems: attitude determination and attitude control. The coupled system is limited in available mass and power and must use inexpensive components. In the case of IlliniSat-2, the system uses the Earth's magnetic field for both attitude determination (through the use of a magnetometer) and for attitude control (through the use of magnetic torque coil actuators). Previous work has seen these two systems independently optimized. This study optimizes the coupled system to generate an optimal pointing method for IlliniSat-2 satellites. In these previous studies, it was assumed that there were no constraints on the duration or intensity of the magnetic torque utilization beyond the physical limits of the hardware in question. In this investigation, the energy stored in the battery and available for use by the ADCS will be considered. [View Full Paper]

* Graduate Student, Aerospace Engineering Department, University of Illinois at Urbana-Champaign, Illinois 61801, U.S.A.
† Adjunct Lecturer, Aerospace Engineering Department, University of Illinois at Urbana-Champaign, Illinois 61801, U.S.A.
‡ Adjunct Research Assistant Professor, Aerospace Engineering Department, University of Illinois at Urbana-Champaign, Illinois 61801, U.S.A.

AAS 17-497

EXTENDING SOFTWARE CAPABILITIES OF CUBESIM: A HARDWARE IN THE LOOP SIMULATION PACKAGE

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

The University of Illinois has developed a hardware-in-loop (HIL) attitude simulation platform called CubeSim for the testing and calibration of attitude determination and control systems (ADCS) for NanoSatellites. This system is currently being used to calibrate the LAICE and CubeSail satellites, both based on the Il-liniSat-2 bus, which are scheduled for launch in early 2017. It consists of hardware elements (Helmholtz cage (HC3), custom power supply) and a software package. To further improve the capabilities of CubeSim, this study introduces two main modifications to the CubeSim software package improving simulation accuracy. The first would discuss calibration techniques developed for CubeSim that enable robust and fast calibration of magnetometers. Subsequently the study would evaluate the inclusion of the Enhanced Magnetic Model (EMM) instead of the International Geomagnetic Reference Field (IGRF) model for production higher fidelity of magnetic field. [View Full Paper]

---

[*] Graduate Student, Aerospace Engineering Department, University of Illinois at Urbana-Champaign, Illinois 61801, U.S.A.

[†] Adjunct Lecturer, Aerospace Engineering Department, University of Illinois at Urbana-Champaign, Illinois 61801, U.S.A.

[‡] Adjunct Research Assistant Professor, Aerospace Engineering Department, University of Illinois at Urbana-Champaign, Illinois 61801, U.S.A.

AAS 17-507

EFFECT OF SUN SHADE PERFORMANCE ON ICESAT-2 LASER REFERENCE SENSOR ALIGNMENT ESTIMATION

Chirag R. Patel,* Noah H. Smith,† Sungkoo Bae‡ and Bob E. Schutz§

Laser pointing knowledge for the Ice, Cloud, and land Elevation Satellite 2 is based on star observations from the laser reference sensor (LRS), which simultaneously observes stars and laser altimeter measurements in a single instrument coordinate frame. The LRS is modeled in this paper by two functions of the angle between star tracker zenith and the sun: pointing motion relative to the spacecraft; and sensitivity, or magnitude of the dimmest trackable star. The objective is to track thermally induced motion driven by the sun using star observations that are simultaneously degraded by the sun. Sun blinding is modeled as zero sensitivity with sunshade performance, that is the extent to which the shade prevents the sun from affecting star observations, determining the detailed sensitivity curve between sunrise and blinding. Star tracking sensitivity is relatively low due to imager issues, and sunshade issues can further reduce sensitivity in sunlight. Effects of a range of possible sensitivities and sun shades on laser pointing knowledge (and consequently geolocation of the laser spot) are characterized in this paper. [View Full Paper]

* Research Assistant, Center for Space Research, University of Texas, Austin, Texas 78712, U.S.A.
† Software Engineer, Voipfuture GmbH, 20097 Hamburg, Germany (contributing work performed while at Center for Space Research, Austin, Texas).
‡ Research Associate, Applied Research Laboratories, University of Texas, Austin, Texas 78758, U.S.A.
§ Professor and Associate Director, Center for Space Research, University of Texas, Austin, Texas 78712, U.S.A. (deceased).

AAS 17-513

MIN-MAX MERGED WITH QUADRATIC COST FOR REPETITIVE CONTROL OF NON-MINIMUM PHASE SYSTEMS

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

Repetitive control (RC) aims to eliminate the effects of a periodic disturbance to a control system. Spacecraft application include active vibration isolation from slight imbalance in CMG's or reaction wheels. Non-minimum phase systems present a design challenge. Previous work addressed this challenge, by using a Min-Max cost function to force faster learning at DC and low frequencies. This addresses the primary difficulty, but it is very sensitive to the common model error at high frequencies. To obtain robustness to high frequency model error it is best to learn slowly, but Min-Max aims for roughly uniform learning rate at all frequencies. This paper addresses these new difficulties in two ways. A merged cost function is created that has the good low frequency performance of Min-Max and the robustness of quadratic cost design at high frequencies, and this can be solved using Quadratically Constrained Quadratic Program software. The alternative is to use Min-Max up to a frequency and apply a zero-phase cutoff filter above this frequency. These results make the Min-Max design practical, and allow one to design effective repetitive controllers for non-minimum phase systems. [View Full Paper]

[*] Doctoral Candidate, Department of Electrical Engineering, Columbia University, 500 West 120th Street, New York, New York 10027, U.S.A.

[†] Professor Mechanical Engineering, also Professor of Civil Engineering and Engineering Mechanics, Columbia University, MC4703, 500 West 120th Street, New York, New York 10027, U.S.A.

EARTH AND LUNAR MISSIONS

Session Chair:

Session 17: Zubin Olikara

AAS 17-238

SPACE-ENHANCED SOLAR POWER FOR EQUATORIAL REGIONS

Federica Bonetti*[*] and Colin R. McInnes[†]

This paper examines the concept of solar mirrors in an Earth orbit to provide solar farms with additional solar power during the hours of darkness. The design of the orbit is key for the purposes of the mission: the mirror needs continuous access to the Sun and the solar farm simultaneously. Therefore, orbits with high-eccentricity will be considered to increase the visibility time. Also, since the most convenient locations for solar power farms are about the equator, a suitable orbit should have a low inclination. This issue can be addressed through the concept of anti-heliotropic orbits that exploits mainly solar radiation pressure perturbations to generate highly-eccentric equatorial orbits able to maintain the orientation with respect to the Sun. The considered configuration consists in two space mirrors in a flower constellation rotating with the Earth to deliver a repeat ground track.

[View Full Paper]

[*] School of Engineering, University of Glasgow, Glasgow, G12 8QQ, United Kingdom.
E-mail: F.Bonetti.1@research.gla.ac.uk.
[†] School of Engineering, University of Glasgow, Glasgow, G12 8QQ, United Kingdom.
E-mail: Colin.McInnes@glasgow.ac.uk.

AAS 17-259

MOON AGE AND REGOLITH EXPLORER (MARE) MISSION DESIGN AND PERFORMANCE

Gerald L. Condon,* David E. Lee* and John M. Carson III*

On December 11, 1972, Apollo 17 marked the last controlled U.S. lunar landing and was followed by an absence of methodical in-situ investigation of the lunar surface. The Moon Age and Regolith Explorer (MARE) proposal provides scientific measurement of the age and composition of a relatively young portion of the lunar surface near Aristarchus Plateau and the first post-Apollo U.S. soft lunar landing. It includes the first demonstration of a crew survivability-enhancing autonomous hazard detection and avoidance system. This report focuses on the mission design and performance associated with the MARE robotic lunar landing subject to mission and trajectory constraints.

[View Full Paper]

* Senior Engineer, Aeroscience and Flight Mechanics Division, NASA Johnson Space Center, Houston, Texas 77058, U.S.A.

AAS 17-267

TARGETING CISLUNAR NEAR RECTILINEAR HALO ORBITS FOR HUMAN SPACE EXPLORATION

Jacob Williams,[*] David E. Lee,[†] Ryan J. Whitley,[‡] Kevin A. Bokelmann,[§] Diane C. Davis[**] and Christopher F. Berry[†]

Part of the challenge of charting a human exploration space architecture is finding locations to stage missions to multiple destinations. To that end, a specific subset of Earth-Moon halo orbits, known as Near Rectilinear Halo Orbits (NRHOs) are evaluated. In this paper, a systematic process for generating full ephemeris based ballistic NRHOs is outlined, different size NRHOs are examined for their favorability to avoid eclipses, the performance requirements for missions to and from NRHOs are calculated, and disposal options are evaluated. Combined, these studies confirm the feasibility of cislunar NRHOs to enable human exploration in the cislunar proving ground. [View Full Paper]

[*] Aerospace Engineer, ERC Inc. (JSC Engineering, Science, and Technology Contract), Houston, Texas 77058, U.S.A.
[†] Aerospace Engineer, Flight Mechanics and Trajectory Design Branch, NASA JSC, Houston, Texas 77058, U.S.A.
[‡] Aerospace Engineer, Exploration Mission Planning Office, NASA JSC, Houston, Texas 77058, U.S.A.
[§] Ph.D. Student, Aerospace Engineering and Engineering Mechanics, University of Texas, Austin, Texas 78712, U.S.A.
[**] Aerospace Engineer, a.i. solutions, Inc., Houston, Texas 77058, U.S.A.

AAS 17-290

DESIGN OF LOW-THRUST TRANSFER ORBIT TO EARTH-MOON LAGRANGE ORBIT VIA ELECTRIC DELTA-V LUNAR GRAVITY ASSIST

Toshinori Ikenaga,[*] Naomi Murakami,[*] Satoshi Ueda,[†] Masayoshi Utashima,[‡] Naoki Satoh[§] and Nobuaki Ishii[**]

The International Space Exploration Coordination Group, ISECG addresses the use of a cislunar habitat for future space exploration such as Lunar and Mars exploration. For the transportation to the cislunar, there three types of transfer options: 1) in-direct transfer via Powered Lunar swing-by, 2) Weak Stability Boundary Transfer in which Solar gravity perturbation is utilized, and 3) low-thrust orbit raising to Lunar orbit. The in-direct transfer requires roughly 500 m/s order of delta-V however the Time-of-Flight, TOF from Earth to Cislunar is practically short i.e., roughly 5~7 days. This type of transfer is assumed for human transportations. The WSB transfer will significantly decrease the required delta-V, however the TOF will be 2~6 months and it will largely change depending on the launch epoch. The low-thrust orbit raising will increase the payload mass, however it will take 6~12 months to get to the destination. Considering such situation, this paper focuses on a new type of low-thrust transfer option which fulfils the significant gap between the two transfer methods. The proposed method is called Electric Delta-V Lunar Gravity Assist, EDV-LGA. The use of electric propulsion will reduce the fuel mass for the transfer, besides the TOF of EDV-LGA is roughly 1 month which is almost equivalent to the life-support capability of Orion. As another merit of the low-thrust transfer, the author thinks it may also increase the safety of human transportation to the habitat. If some trouble occurs at the impulsive delta-V in the in-direct transfer, the manned space ship may not be able to come back to the Earth within the duration of a life support system. However, the low-thrust transfer is relatively easily restored from such kinds of troubles. These characteristics of the proposed transfer method will provide a new transfer option for future deep-space habitat. [View Full Paper]

[*] Researcher, Research Unit-I, Japan Aerospace Exploration Agency, 2-1-1, Sengen, Tsukuba, Ibaraki, 305-8505, Japan.

[†] Associate Senior Researcher, Research Unit-I, Japan Aerospace Exploration Agency, 3-1-1, Yoshinodai, Chuo-ku, Sagamihara, Kanagawa, 252-5210, Japan.

[‡] Advisor, Research Unit-I, Japan Aerospace Exploration Agency, 2-1-1, Sengen, Tsukuba, Ibaraki, 305-8505, Japan.

[§] Senior Engineer, HTV Technology Center, Japan Aerospace Exploration Agency, 2-1-1, Sengen, Tsukuba, Ibaraki, 305-8505, Japan.

[**] Professor, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1, Yoshinodai, Chuo-ku, Sagamihara, Kanagawa, 252-5210, Japan.

AAS 17-319

THE LUNAR ICECUBE MISSION CHALLENGE: ATTAINING SCIENCE ORBIT PARAMETERS FROM A CONSTRAINED APPROACH TRAJECTORY

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

The challenges of targeting specific lunar science orbit parameters from a concomitant Sun-Earth/Moon system trajectory are examined. While the concept of ballistic lunar capture is well-studied, achieving and controlling the time evolution of the orbital elements to satisfy mission constraints is especially problematic when the spacecraft is equipped with a low-thrust propulsion system. Satisfying these requirements on the lunar approach and capture segments is critical to the success of the Lunar IceCube mission, a 6U CubeSat that will prospect for water in solid (ice), liquid, and vapor forms and other lunar volatiles from a low-periapsis, highly inclined elliptical lunar orbit. [View Full Paper]

[*] Senior Fellow, NASA Goddard Space Flight Center, Greenbelt, Maryland 20771, U.S.A.
[†] Post-Doctoral Research Assistant, School of Aeronautics and Astronautics, Purdue University, 701 W. Stadium Avenue, West Lafayette, Indiana 47907, U.S.A.; currently Assistant Professor, Department of Aerospace Engineering Sciences, University of Colorado Boulder, 429 UCB, Boulder, Colorado 80309, U.S.A.
[‡] Graduate Student, School of Aeronautics and Astronautics, Purdue University, 701 W. Stadium Avenue, West Lafayette, Indiana 47907, U.S.A.
[§] Hsu Lo Distinguished Professor of Aeronautics and Astronautics, School of Aeronautics and Astronautics, Purdue University, 701 W. Stadium Avenue, West Lafayette, Indiana 47907, U.S.A.

AAS 17-333

DARE MISSION DESIGN: LOW RFI OBSERVATIONS FROM A LOW-ALTITUDE FROZEN LUNAR ORBIT

Laura Plice,[*] Ken Galal[†] and Jack O. Burns[‡]

The Dark Ages Radio Explorer (DARE) seeks to study the cosmic Dark Ages approximately 80 to 420 million years after the Big Bang. Observations require truly quiet radio conditions, shielded from Sun and Earth electromagnetic (EM) emissions, on the far side of the Moon. DARE's science orbit is a frozen orbit with respect to lunar gravitational perturbations. The altitude and orientation of the orbit remain nearly fixed indefinitely, maximizing science time without the need for maintenance. DARE's observation targets avoid the galactic center and enable investigation of the universe's first stars and galaxies. [View Full Paper]

[*] Systems Engineer V, Metis Technology Solutions, NASA/Ames Research Center, Mission Design Division, Moffett Field, California 94035, U.S.A.

[†] Aerospace Engineer, Ames Associate, NASA/Ames Research Center, Moffett Field, California 94035, U.S.A.

[‡] Professor, Center for Astrophysics and Space Astronomy, Department of Astrophysical and Planetary Sciences, University of Colorado, Boulder, Colorado 80309, U.S.A.

AAS 17-395

STATIONKEEPING ANALYSIS FOR SPACECRAFT IN LUNAR NEAR RECTILINEAR HALO ORBITS

Davide Guzzetti,[*] Emily M. Zimovan,[†]
Kathleen C. Howell[‡] and Diane C. Davis[§]

Near Rectilinear Halo Orbits (NRHOs), a subset of the halo orbits characterized by favorable stability properties, are strong candidates for a future inhabited facility in the lunar vicinity. To maintain such orbits in this regime, however, requires a reliable maintenance strategy. Two low-cost, reliable, stationkeeping strategies for maintaining long-term NRHO-like behavior in the ephemeris regime are investigated. Orbit determination errors, orbital perturbations, and spacecraft noise are incorporated into the higher-fidelity simulation environment. As a complement, a real-time warning in the event of a diverging path is presented. [View Full Paper]

[*] Ph.D. Candidate, School of Aeronautics and Astronautics, Purdue University, Armstrong Hall of Engineering, 701 W. Stadium Avenue, West Lafayette, Indiana 47907-2045, U.S.A.
[†] Graduate Student, School of Aeronautics and Astronautics, Purdue University, Armstrong Hall of Engineering, 701 W. Stadium Avenue, West Lafayette, Indiana 47907-2045, U.S.A. Member AAS; Member AIAA.
[‡] Hsu Lo Distinguished Professor, School of Aeronautics and Astronautics, Purdue University, Armstrong Hall of Engineering, 701 W. Stadium Avenue, West Lafayette, Indiana 47907-2045, U.S.A. Fellow AAS; Fellow AIAA.
[§] Principal Systems Engineer, a.i. solutions, Inc., 2224 Bay Area Blvd., Houston, Texas 77058, U.S.A. Member AAS.

AAS 17-456

TRAJECTORY DESIGN FOR THE LUNAR POLAR HYDROGEN MAPPER MISSION

Anthony L. Genova[*] [†] and David W. Dunham[‡]

The presented trajectory was designed for the Lunar Polar Hydrogen Mapper (LunaH-Map) 6U CubeSat, which was awarded a ride on NASA's Space Launch System (SLS) with Exploration Mission 1 (EM-1) via NASA's 2015 SIMPLEX proposal call. After deployment from EM-1's upper stage (which is planned to enter heliocentric space via a lunar flyby), the LunaH-Map CubeSat will alter its trajectory via its low-thrust ion engine to target a lunar flyby that yields a Sun-Earth-Moon weak stability boundary transfer to set up a ballistic lunar capture. Finally, the orbit energy is lowered to reach the required quasi-frozen science orbit with periselene above the lunar south pole. [View Full Paper]

[*] Trajectory Designer, Mission Design Division, NASA Ames Research Center, Moffett Field, California 94035, U.S.A.

[†] Ph.D. Student, Mechanical & Aerospace Engineering Department, Florida Institute of Technology, Melbourne, Florida 32901, U.S.A.

[‡] Chief Mission Design Engineer, KinetX, Inc., 7913 Kara Court, Greenbelt, Maryland 20770, U.S.A.

NAVIGATION

Session Chair:

Session 18: Renato Zanetti

The following paper was not available for publication:

AAS 17-358 Paper Withdrawn

AAS 17-230

SMALL BODY NAVIGATION AND GRAVITY ESTIMATION USING ANGLE AND FDOA OBSERVABLES

Jeroen L. Geeraert,* Jay W. McMahon† and Siamak G. Hesar‡

In this proof of concept study we examine the use of angles, namely azimuth and elevation in addition to Frequency Difference of Arrival (FDOA) measurements to estimate the gravity field of 433 Eros. The setup includes two beacons orbiting in close proximity to Eros with the main spacecraft in a trailing orbit to the asteroid, 1500 *km* away. FDOA is a double differenced observable therefore any translation oscillation errors in the beacons and receiver errors in the main satellite cancel. This is the motivation to explore the potential use of FDOA, cheaper components may be used as measurement biases and errors would not affect performance unlike other observables such as range or range-rate/Doppler. We show that with a 1-α uncertainty on the angles of 2e-5 *rad* and a 0.1 *mHz* uncertainty on FDOA the Cramér-Rao Lower Bound (CRLB) allows for a gravity field of degree and order 5 to be estimated within 8 days. Furthermore, the 1-α 3D RMS uncertainty for position and velocity of beacon 1 is 1.89 *m* and 0.26 *mm/s* respectively and 3.17 *m* and 0.74 *mm/s* for beacon 2 after 8 days of observation processing. To contrast the FDOA observable, the same simulation is performed with two range-rate measurements to each of the beacons, the purpose is to serve as a benchmark for comparison. We find that the results using uncertainties on range-rate of 1 *cm/s* and 1 *mm/s* correspond to within several percent of the FDOA results using uncertainties of 0.1 *mHz* and 0.01 *mHz* respectively. Finally, we introduce a bias, representative of beacon oscillator error and show the effect on the simulation with angles and range-rate which leaves angles and FDOA unaffected. [View Full Paper]

* Ph.D. Candidate, Colorado Center for Astrodynamics Research, University of Colorado, Boulder, Colorado 80309.
† Assistant Professor, Colorado Center for Astrodynamics Research, University of Colorado, Boulder, Colorado 80309.
‡ Research Associate, Colorado Center for Astrodynamics Research, University of Colorado, Boulder, Colorado 80309.

AAS 17-323

B-PLANE EVOLUTION UNDER HIGHLY NON-KEPLERIAN DYNAMICS

Yu Takahashi,[*] Davide Farnocchia,[*] Paul Thompson,[*] Nicholas Bradley,[*] Shadan Ardalan[†] and John Bordi[‡]

Juno is the second of a series of New Frontiers missions and was launched in 2011. The spacecraft was set en route to Jupiter, and its Jupiter Orbit Insertion occurred on 2016-07-04 PST after a five-year cruise in deep space. The mission phase just prior to this large maneuver is called approach. As navigation team, we were responsible for precise orbit determination of the Juno spacecraft to ensure a successful orbit insertion. To evaluate the navigation performance, we employed the B-plane mapping, where the incoming hyperbolic velocity defines the plane perpendicular to it, and the time to go to hit the plane will directly map into the uncertainties of the target point. The B-plane is a convenient tool when assessing the navigation performance as it is not affected by non-linearities due to the gravitational pull of the targeted body. However, as the Jupiter Orbit Insertion approached we started to realize that the B-plane mapping uncertainties were significantly larger than expected. We found that the B-plane mapping time had tremendous influence on the covariance inflation in the B-plane. Because of the close approach distance during the Jupiter Orbit Insertion and the strong interaction with J_2 spherical harmonic coefficient, the Juno dynamics were too far from a Keplerian one assumed for the B-plane mapping. We first discuss the analytical approach of the B-plane mapping uncertainty and perform a numerical analysis to isolate the components of the Juno dynamics that cause the B-plane covariance inflation. [View Full Paper]

[*] Orbit Determination Analyst, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, California 91109, U.S.A.
[†] Juno Orbit Determination Team Lead, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, California 91109, U.S.A.
[‡] Juno Navigation Team Lead, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, California 91109, U.S.A.

AAS 17-325

THE EVOLUTION OF DEEP SPACE NAVIGATION: 2004-2006*

Lincoln J. Wood†

The exploration of the planets of the solar system using robotic vehicles has been underway since the early 1960s. During this time the navigational capabilities employed have increased greatly in accuracy, as required by the scientific objectives of the missions and as enabled by improvements in technology. This paper is the fourth in a chronological sequence dealing with the evolution of deep space navigation. The time interval covered extends from roughly 2004 to 2006. The paper focuses on the observational techniques that have been used to obtain navigational information, propellant-efficient means for modifying spacecraft trajectories, and the computational methods that have been employed, tracing their evolution through eleven planetary missions. [View Full Paper]

† Principal Engineer, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, Mail Stop 301-121, 4800 Oak Grove Drive, Pasadena, California 91109, U.S.A.

AAS 17-329

A DEEP LEARNING APPROACH FOR OPTICAL AUTONOMOUS PLANETARY RELATIVE TERRAIN NAVIGATION

Tanner Campbell,[*] Roberto Furfaro,[†] Richard Linares[‡] and David Gaylor[§]

Autonomous relative terrain navigation is a problem at the forefront of many space missions involving close proximity operations which does not have any definitive answer. There are many techniques to help cope with this issue using both passive and active sensors, but almost all require very sophisticated dynamical models. Convolutional Neural Networks (CNNs) trained with images rendered from a digital terrain map (DTM) can provide a way to side-step the issue of unknown or complex dynamics while still providing reliable autonomous navigation by directly mapping an image to position. The portability of trained CNNs allows offline training that can yield a matured network capable of being loaded onto a spacecraft for real-time position acquisition. [View Full Paper]

[*] Graduate Student, Department of Aerospace and Mechanical Engineering, University of Arizona, Tucson, Arizona 85721, U.S.A.

[†] Associate Professor, Department of Systems and Industrial Engineering, Department of Aerospace and Mechanical Engineering, University of Arizona, Tucson, Arizona 85721, U.S.A.

[‡] Assistant Professor, Department of Aerospace Engineering and Mechanics, University of Minnesota, Minneapolis, Minnesota 55455, U.S.A.

[§] Associate Professor, Department of Aerospace and Mechanical Engineering, University of Arizona, Tucson, Arizona 85721, U.S.A.

AAS 17-331

JPL NAVIGATION SUPPORT FOR THE JAXA AKATSUKI (PLANET-C) RETURN TO VENUS*

Mark S. Ryne, Neil A. Mottinger, Eunice Lau, Maximilian Schadegg, Cliff Helfrich, Paul Stumpf and Brian Young†

This paper details the orbit determination activities undertaken at JPL in support of the Akatsuki (a.k.a. Planet-C) mission's return to Venus. The JPL navigation team's role was to provide independent navigation support as a point of comparison with the JAXA generated orbit determination solutions. Topics covered will include a mission and spacecraft overview; small forces modeling; cruise, approach, and Venus phase orbit determination results; and the international teaming arrangement. A discussion of the preparations for the Venus orbit insertion maneuver, which was successfully executed on December 7, 2015, is also covered in detail in the paper. [View Full Paper]

* This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California under contract to the National Aeronautics and Space Administration.

† All authors: Navigation Engineer, Mission Design & Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, U.S.A.

AAS 17-459

JUNO NAVIGATION FOR JUPITER ORBIT INSERTION*

Paul F. Thompson,† Shadan Ardalan,‡ John Bordi,§ Nicholas Bradley, Davide Farnocchia** and Yu Takahashi****

Juno arrived at Jupiter on 05 July 2016 UTC, achieving orbit with the execution of the Jupiter Orbit Insertion (JOI) maneuver. Thanks to a dynamically well-behaved spacecraft, the delivery of Juno to JOI was done largely with only a maneuver to setup an Earth gravity assist (EGA), an EGA, an EGA clean-up maneuver, and a JOI targeting maneuver. During the last several weeks of the approach to JOI, the dominant uncertainties in the predicted trajectory were from the Jupiter barycenter ephemeris. In this paper, we discuss the maneuver and orbit determination (OD) strategy for successfully arriving at JOI, the challenges of calculating a correction to the Jupiter barycenter ephemeris using only radiometric data types, and how the ephemeris estimates during approach to JOI compare to a post-JOI trajectory reconstruction. [View Full Paper]

---

† Juno Orbit Determination Analyst.

‡ Juno Orbit Determination Lead.

§ Juno Navigation Team Chief.

** Juno Orbit Determination Analyst.

All authors in the Mission Design and Navigation Section at Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, U.S.A.

AAS 17-489

OPTICAL NAVIGATION CONCEPT OF OPERATIONS FOR THE OSIRIS-REX MISSION

Coralie D. Jackman,* Derek S. Nelson,* Leilah K. McCarthy,* Tiffany J. Finley,† Andrew J. Liounis,‡ Kenneth M. Getzandanner,† Peter G. Antreasian* and Michael C. Moreau†

The OSIRIS-REx sample return mission will begin proximity operations at asteroid Bennu in late 2018. Optical Navigation (OpNav), a sub-function of the Flight Dynamics System, uses information extracted from spacecraft images to assist in the orbit determination of the spacecraft. Star-based OpNav is utilized in early mission phases, before global imaging data and digital terrain maps are available. Once these maps are available, landmark navigation is utilized in order to achieve the required navigation performance requirements. This paper will discuss the optical navigation concept of operations for each mission phase, details about imaging plans, and operational OpNav techniques.

[View Full Paper]

* Space Navigation and Flight Dynamics Practice, KinetX, Inc., 21 W. Easy Street, Ste. 108, Simi Valley, California 93065, U.S.A.

† Southwest Research Institute, 1050 Walnut Street, Suite 300, Boulder, Colorado 80302, U.S.A.

‡ Navigation and Mission Design Branch (Code 595), NASA Goddard Spaceflight Center, Greenbelt, Maryland 20771, U.S.A.

AAS 17-529

ORBIT DETERMINATION ANALYSIS OF VENUS SPACE PROBE "AKATSUKI (PLANET-C)"

Tsutomu Ichikawa,[*] Nobuaki Ishii,[*] Chikako Hirose,[*] Hiroshi Takeuchi,[*] Sho Taniguchi,[†] Tomoko Yagami[†] and Takafumi Ohnishi[†]

First Japanese probe orbiting Venus known as "AKATSUKI (Planet-C)", has been launched on May 21, 2010 on H-IIA booster from Tanegashima Space Center (TSC), Kagoshima, Japan. It arrived at Venus on December 7, 2010, but due to a malfunction of the thruster system, the Venus orbit insertion failed. Using the reaction control systems instead of the broken orbital maneuvering engine, the recovery maneuver was operated on December 7, 2015, and AKATSUKI was finally inserted into an orbit around Venus with a 0.36 million km apoapsis and a 10.5 day. It is described the strategy, analysis, and evaluation for the orbit determination to orbit Venus. [View Full Paper]

[*] Japan Aerospace Exploration Agency (JAXA), 3-1-1, Yoshinodai, Chuo-ku, Kanagawa 252-5210, Japan.
[†] Fujitsu Limited, 3-10 Higashikanda 2, Chiyoda-ku, Tokyo 101-0031, Japan.

ORBITAL DEBRIS

Session Chair:

Session 22: Puneet Singla

AAS 17-233

CNES ACTIVITES ON POLYNOMIAL CHAOS EXPANSION FOR UNCERTAINTY PROPAGATION

Vincent Morand,[*] Guillaume Prigent, Emmanuel Bignon,[†] Pierre Mercier and Pietro Marco Congedo[‡]

Dealing with initial uncertainties, or models uncertainties, and their evolution over time has become a point of greater interest over the last years. In particular, the increasing number of space debris strengthens the need for more efficient technics for risk assessment, both on orbit (collision risk) and on ground (casualty risk). One of the most common non-intrusive methods for uncertainty propagation is called Polynomial chaos expansion (PCE). The paper will briefly review some fundamentals of the PCE and the framework that have been adopted during an ongoing R&T study. Test cases will be presented, covering concrete day-to-day work of a spaceflight engineer. Current results will be presented and discussed. [View Full Paper]

[*] Centre National d'Etudes Spatiales (CNES), Toulouse, France.
[†] Thales Services CIS, Toulouse, France.
[‡] I INRIA Bordeaux Sud-Ouest, France.

AAS 17-237

OBSERVABILITY ANALYSIS APPLIED TO ARTIFICIAL NEAR-EARTH OBJECTS WITH NOISE

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

Observability analysis is a method for determining whether a chosen state of a system can be determined from the output or measurements. A system is better understood with the information gained from observability analysis, which leads to improved sensor tasking for observation of orbital debris and better control of active spacecraft. This research performs numerical observability analysis of artificial near-Earth objects. Analysis of linearization methods and state transition matrices (STM) is performed to determine the viability of applying linear observability methods to the nonlinear orbit problem. In addition, through the use of pre-whitening, the measurement matrix and output of the systems being tested can be reformulated to include measurement noise. The observability analysis is performed again including measurement noise for the artificial near-Earth objects. In order to compare observability analysis results with and without measurement noise, quantitative measures of observability are investigated and implemented. With observability analysis quantitative measures, the consequences of measurement noise on observability analysis of a linearized orbit problem are presented. [View Full Paper]

[*] Graduate Research Assistant, School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana 47907, U.S.A.

[†] Assistant Professor, School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana 47907, U.S.A.

AAS 17-244

IS THE COLLISION PROBABILITY OF A SPACECRAFT TRAVERSING THROUGH A DEBRIS CLOUD DESCRIBED BY A POISSON DISTRIBUTION?

Ken Chan*

This paper answers in detail the question whether the probability of collision of a spacecraft traversing through a debris cloud is described by the Poisson distribution when given the debris collision fluxes obtained from the NASA ORDEM 3.0, ESA MASTER and "N=IJK" Models. The N=IJK Model, originally developed for the Iridium Program in 1996, is applied to the steady state cloud of Earth-orbiting debris objects. It accounts for the debris population with actual inclined orbits, thus resulting in a variation of debris density with latitude and altitude. In all previous published literature, whenever the Poisson distribution was invoked, the reason for justification was similarity to the Kinetic Theory of Gases Model. This comparison is unjustified because the density of the gaseous molecules is statistically uniform whereas the density of the debris objects is not. In order to proceed with the analysis in these papers, the assumption is made that the debris objects are then spread uniformly throughout the Earth's environment. But the differences do not end there. The intermolecular collisions give rise to molecular chaos whereas the disciplined motion of the debris objects is governed mainly by the Earth's gravitational force which results in almost Keplerian orbits. The variation in density of the debris objects persists and manifests itself in specific latitude bands corresponding to the inclinations of their orbits. Moreover, for spacecraft with highly inclined orbits the probability of collision is much greater at the polar regions because the debris density there is several orders of magnitude higher. Results of this study indicate that debris collision fluxes obtained from the NASA ORDEM 3.0 and the ESA MASTER Models cannot be simply and directly used to yield the probability of collision described by Poisson statistics. In contrast, the debris collision fluxes obtained from the N=IJK Model can be modified so as to be amenable to such a description. [View Full Paper]

* Chan Aerospace Consultants, 25803 Anderby Lane, South Riding, Virginia 20152, U.S.A.
E-mail: ChanAerospace@verizon.net.

COMPARISON OF DEBRIS COLLISION FLUXES FOR THE INTERNATIONAL SPACE STATION

Ken Chan* and Wei-Ping Zhou†

This paper is concerned with the calculation of the debris fluxes experienced by the International Space Station (ISS) traversing through a cloud of orbiting debris. This study uses on the "N=IJK" Model which is formulated on the concept of Inclination Classes that the debris objects are grouped into. For each Inclination Class, it considers two cases of modeling the orbits of the debris within a thin spherical shell straddling the ISS orbit: (1) the debris objects have "almost" circular orbits; (2) the actual elliptical debris orbits are used. It accounts for the actual debris population with various inclined orbits, thus resulting in a variation of debris density with latitude. The Number of Collisions N per year thus obtained compares favorably to those obtained by the NASA ORDEM 3.0 and the ESA MASTER Models. The N=IJK Model reveals that N depends on the ratio (h/σ) where h is the thickness of the spherical shell and σ is the average positional uncertainty of the combined spacecraft and debris objects under consideration. Moreover, it yields a minimum value and an asymptotic upper bound for the value of N. These values are consistent with the bounds obtained in the other two models. [View Full Paper]

* Chan Aerospace Consultants, 25803 Anderby Lane, South Riding, Virginia 20152, U.S.A.
E-mail: ChanAerospace@verizon.net.
† Ph.D. Student, National Astronomical Observatories, Chinese Academy of Sciences, Beijing, 100049, China.

AAS 17-298

ENVIRONMENTAL ESTIMATION ON SUB-MILLIMETER-SIZE DEBRIS USING IN-SITU MEASUREMENT DATA

Masahiro Furumoto,[*] Shin'ya Nakano,[†] Koki Fujita[*] and Toshiya Hanada[*]

Space debris smaller than 1 mm in size still have enough energy to cause a fatal damage on a spacecraft, but such tiny debris cannot be followed or tracked from the ground. Therefore, IDEA the project for In-situ Debris Environmental Awareness, which aims to detect sub-millimeter-size debris using a group of micro satellites, has been initiated at Kyushu University. The IDEA project aims to construct the dynamic environmental model that provides a better definition of the current orbital debris environment. This study proposes data assimilation method to estimate the environment of sub-millimeter-size debris using in-situ measurement data. This paper also verifies the proposed model by simulating the measurement and the estimation. The simulation demonstrates that the estimation model can determine the orbital plane of the detected debris approximately.

[View Full Paper]

[*] Department of Aeronautics and Astronautics, Kyushu University, Fukuoka 819-0395, Japan.

[†] The Institute of Statistical Mathematics, Research Organization of Information and Systems, Tachikawa, Tokyo 190-8562, Japan.

DESIGN OF A SYNTHETIC POPULATION OF GEOSTATIONARY SPACE DEBRIS BY STATISTICAL MEANS

Alexis Petit,[*] Daniel Casanova,[†] Morgane Dumont[‡] and Anne Lemaitre[§]

We can observe and track objects located at the geostationary region with a size of approximately 1 meter by telescope means. However, a huge population of space debris still remains unknown for us. In this work, we propose to generate a synthetic (artificial) population of individual space debris, whose global characteristics are the same as the real one. We use two different tools; the first one, a combination of orbit propagators, fragmentation models, and historical data, and the second one, an Iterative Proportional Fitting (IPF) procedure, which allows to reconstruct the current population from partial data and statistical information. [View Full Paper]

[*] University of Namur, 5000 Namur, Belgium. E-mail: alexis.petit@unamur.be.
[†] Centro Universitario de la Defensa, 50090 Zaragoza, Spain. E-mail: casanov@unizar.es.
[‡] University of Namur, 5000 Namur, Belgium. E-mail: morgane.dumont@unamur.be.
[§] University of Namur, 5000 Namur, Belgium. E-mail: anne.lemaitre@unamur.be.

SPACECRAFT ELECTROSTATIC FORCE AND TORQUE EXPANSIONS YIELDING APPROPRIATE FIDELITY MEASURES

Joseph Hughes[*] and Hanspeter Schaub[†]

Charged spacecraft experience electrostatic forces and torques from both charged neighboring spacecraft and the local space environment. These forces and torques can be used for a variety of novel touchless actuation concepts. In contrast to the multipole method which provides an expansion of the potential field, this paper presents a direct binomial series expansion of the forces and torques called the Appropriate Fidelity Measures (AFMs) method. A two-stage process is presented where first the force and torque vectors are expanded assuming a known charge distribution, followed by a second stage which provides an approximation of the charge distribution through the susceptibilities of the measures. AFMs provide a direct analytical solution and thus provide new insight for charged single- and two-body configurations. The accuracy of a truncated expansion is numerically studied and validated. With a second-order AFM solution, the errors drop below 5% at separations greater than ~ 6 craft diameters. This new method is well-suited for control analysis due to the analytical solutions produced. An AFM solution of the torque on a axis-symmetric cylinder is developed that yields closed form analytic solutions that match prior numerically fit solutions. [View Full Paper]

[*] Graduate Research Assistant, Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado.

[†] Alfred T. and Betty E. Look Professor of Engineering, Associate Chair of Graduate Affairs, Department of Aerospace Engineering Sciences, University of Colorado, 431 UCB, Colorado Center for Astrodynamics Research, Boulder, Colorado 80309-0431, U.S.A. AAS Fellow.

AAS 17-461

EXTRACTION AND ASSIGNMENT OF TUMBLING ASTEROID AND DEFUNCT SATELLITE ROTATION PERIODS FROM SIMULATED LIGHT-CURVE OBSERVATIONS

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

Fourier transform analysis and Fourier series fitting methods for extracting the fundamental rotation periods of tumbling bodies from simulated light-curves are discussed and expanded. Methods leveraging the analytical dynamics and information about the body's moments of inertia, shape, and orientation are then explored for assigning extracted periods to the rotation and precession motion. These methods are then tested on simulated tumbling light-curves with all parameters known a priori for verification. While extraction was found to be challenging, dynamical relationships and body information helped significantly constrain the possible period solutions and in some cases the fundamental periods were conclusively determined. Applications for these methods include light-curve analysis for asteroids and defunct satellites with known or estimated moments of inertia and geometries. These methods provide initial rotation state estimates which can then be used in the full light-curve inversion process to obtain a complete rotation state solution.

[View Full Paper]

[*] Department of Aerospace Engineering Sciences, University of Colorado at Boulder, 429 UCB, Boulder, Colorado 80309, U.S.A.

AAS 17-483

ELECTROSTATICALLY CHARGED SPACECRAFT FORMATION ESTIMATION USING LINEARIZED RELATIVE ORBIT ELEMENTS

Trevor Bennett[*] and Hanspeter Schaub[†]

Touchless methods of actuating and detumbling large Earth-orbiting objects are of increasing importance to active satellite servicing and debris mitigation strategies. Electrostatic detumble, the process of using electrostatic interaction between two spacecraft, is able to touchlessly detumble large targets in Geostationary orbit. This is of interest for reducing tumble rates of several degrees per second down to rates conducive to capture and servicing. The effectiveness of the electrostatic detumble control is dependent upon the electrostatic potential of both craft and the relative separation. This study develops the estimation approach to obtain the electrostatic potential of the target object using only relative motion measurements. The sensitivity to electrostatic perturbations are developed using the Linearized Relative Orbit Elements relative motion description. The analytical conclusions are validated using a two-time-scale Kalman filter numerical simulation.

[View Full Paper]

[*] Graduate Research Assistant and NSTRF Fellow, Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado.

[†] Alfred T. and Betty E. Look Professor of Engineering, Associate Chair of Graduate Affairs, Department of Aerospace Engineering Sciences, University of Colorado, 431 UCB, Colorado Center for Astrodynamics Research, Boulder, Colorado 80309-0431, U.S.A.

AAS 17-501

DE-ORBIT TIME OF ON-ORBIT DEBRIS FOR LASER-BASED REMOVAL METHODS

Prathyusha Karampudi* **and Atri Dutta†**

The amount of space debris in the near-Earth space environment poses a major challenge for current and future space missions. Controlling the growth of on-orbit debris utilizing on-orbit debris removal missions is of great importance for sustained space operations. This paper focusses on the laser-based removal of on-orbit debris utilizing the physical process of ablation. We consider the momentum change of the debris due to laser ablation and investigate the de-orbit times for debris that has cubic and spherical shapes. Our focus is on modeling the de-orbiting process as a low-thrust transfer under the action of continuous perturbation forces. We present numerical results for a variety of starting orbits for the debris. [View Full Paper]

* M.S. Student, Aerospace Engineering, Wichita State University, 1845 Fairmount Box 44, Wichita, Kansas 67260, U.S.A.

† Assistant Professor, Aerospace Engineering, Wichita State University, 1845 Fairmount Street, Box 44, Wichita, Kansas 67260, U.S.A.

FORMATION FLYING
AND RELATIVE MOTION

Session Chair:

Session 23: Rodney Anderson

AAS 17-202

COMPARISON OF RELATIVE ORBITAL MOTION PERTURBATION SOLUTIONS IN CARTESIAN AND SPHERICAL COORDINATES

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

Previously shown perturbation approaches for unperturbed spacecraft relative motion solutions in Cartesian and spherical coordinates, in which both the chief eccentricity and the normalized separation were treated as order ε, are extended in this work to allow for higher chief orbit eccentricity. The relative accuracies of the solutions obtained in Cartesian versus spherical coordinates are explored for a wide range of relative orbit scenarios and perturbation orders. While the use of spherical coordinates eliminates many of the secular terms in the Cartesian solution and extends the range of in-track separations, certain scenarios are found to result in less accuracy. [View Full Paper]

[*] Associate Professor, Aerospace and Mechanical Engineering, University of Arizona, Tucson, Arizona 85721, U.S.A. E-mail: ebutcher@email.arizona.edu.
[†] Graduate Student, Aerospace and Mechanical Engineering, University of Arizona, Tucson, Arizona 85721, U.S.A.
[‡] Research Aerospace Engineer, Air Force Research Laboratory, Space Vehicles Directorate, Kirtland AFB, Albuquerque, New Mexico 87117, U.S.A.

AAS 17-209

A CAPTURE METHOD OF ORBITAL NET-CAPTURE SYSTEM BASED ON COOPERATIVE FORMATION FLYING CONTROL

Liangming Chen,* Yannning Guo† and Chuanjiang Li‡

To cope with the space debris removal mission, a capture method based on spacecraft formation flying is investigated for the orbital net-capture system. Firstly, the relative orbit motion dynamics for each payload are modeled in the local-vertical and local-horizontal rotating frame. Secondly, the flying capture trajectory for each payload is planned by the four-order polynomial. Then, a cooperative saturated PD control algorithm with computed feedforward is proposed such that all payloads can track the planned flying trajectories. This realizes the closed-loop orbital net-capture process. Finally, the simulation example of four payloads installed at the net capturing one static space debris illustrates the effectiveness of the proposed capture method.

[View Full Paper]

* Ph.D. Student, Department of Control Science and Engineering, Harbin Institute of Technology, Harbin, 150001, China. E-mail: chenliangmng@hit.edu.cn.

† Associate Professor, Department of Control Science and Engineering, Harbin Institute of Technology, Harbin, 150001, China. Corresponding author. E-mail: guoyn@hit.edu.cn.

‡ Professor, Department of Control Science and Engineering, Harbin Institute of Technology, Harbin, 150001, China. E-mail: lichuan@hit.edu.cn.

AAS 17-291

CONSTRAINED LOW-THRUST SATELLITE FORMATION-FLYING USING RELATIVE ORBIT ELEMENTS

Lukas M. Steindorf,[*] Simone D'Amico,[†] Julian Scharnagl,[‡] Florian Kempf[§] and Klaus Schilling[**]

This paper proposes a continuous low-thrust guidance and control strategy for constrained satellite formation-flying in perturbed orbits of arbitrary eccentricity. The controller feeds back mean relative orbit elements (ROE) and is based on Lyapunov theory. A novel feedback gain matrix, which enables the spacecraft to autonomously apply thrust at fuel efficient locations is presented. The guidance strategy makes use of a reference governor, which is designed in ROE state-space in order to ensure that all constraints imposed on the formation-flying mission are satisfied. The reference governor can enforce wall, thrust and time constraints. To achieve near-optimal fuel consumption, an autonomous algorithm to leverage Keplerian dynamics is developed. Orbit perturbations include the differential Earth oblateness effect J_2 and aerodynamic drag. The control and guidance strategy is developed for the nanosatellite formation-flying mission NetSat, which is developed by the Zentrum für Telematik e.V. NetSat will launch four identical spacecraft into a low Earth orbit to demonstrate fully autonomous guidance, navigation and control with low-thrust electrical propulsion. [View Full Paper]

[*] Research Scholar, Stanford University, Department of Aeronautics and Astronautics, Space Rendezvous Laboratory, Durand Building, 496 Lomita Mall, Stanford, California 94305-4035, U.S.A.

[†] Assistant Professor, Stanford University, Department of Aeronautics and Astronautics, Space Rendezvous Laboratory, Durand Building, 496 Lomita Mall, Stanford, California 94305-4035, U.S.A.

[‡] Doctoral Candidate, Zentrum für Telematik, Magdalene-Schoch-Straße 5, 97074 Würzburg, Germany.

[§] Doctoral Candidate, University of Würzburg, Department of Computer Sciences, Am Hubland, 97074 Würzburg, Germany.

[**] Professor, University of Würzburg, Department of Computer Sciences, Am Hubland, 97074 Würzburg, Germany.

AAS 17-328

RECTIFICATION OF THE SECOND-ORDER SOLUTIONS FOR ASTRODYNAMICS PROBLEMS

Andrew J. Sinclair[*] and R. Scott Erwin[†]

Whereas linearizations of astrodynamics problems are often used, study of higher-order solutions is motivated by a desire for greater accuracy. Carleman linearization is one approach to develop these higher-order approximations. A property of these solutions is that treating a point along the solution as a new initial condition produces an alternate solution differing from the original solution. This motivates a rectification process for long-term evaluation of higher-order solutions. At intervals, the instantaneous solution defines a new initial condition for continued propagation of the solution. For polynomial systems, rectification can provide improved accuracy, but drawbacks are seen for non-polynomial systems.

[View Full Paper]

[*] Senior Aerospace Engineer, Air Force Research Laboratory, Space Vehicles Directorate, Kirtland AFB, New Mexico 87117, U.S.A.

[†] Principal Aerospace Engineer, Air Force Research Laboratory, Space Vehicles Directorate, Kirtland AFB, New Mexico 87117, U.S.A.

SPACECRAFT PROXIMITY FORMATION FLYING: A HOMOTOPY BRIDGE FROM ENERGY-OPTIMAL TO FUEL-OPTIMAL SOLUTIONS USING LOW-THRUST

Marco Gulino* and Maruthi R. Akella†

This paper focuses on finding the low-thrust fuel optimal solution to a class of spacecraft proximity operations subject to path constraints. The mission is for a service spacecraft to perform a surveying orbit relative to a reference within a prescribed period, without violating a no fly zone represented by a sphere centered on the reference vehicle. Clohessy-Wiltshire equations are used, together with the controllability Gramian of the resulting linear system, to obtain an analytical solution to the energy optimal problem. A homotopic approach is subsequently shown to serve as an effective bridge from the energy optimal solution toward the fuel optimal solution. [View Full Paper]

* Graduate Student, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, 210 East 24th Street WRW, 1 University Station, C0600, Austin, Texas 78712, U.S.A.
E-mail: marco.gulino@utexas.edu.
† Professor, Myron L. Begeman Fellow in Engineering, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, 210 East 24th Street WRW, 1 University Station, C0600, Austin, Texas 78712, U.S.A. E-mail: makella@mail.utexas.edu. AAS Fellow.

AAS 17-353

RIGID BODY CONSENSUS UNDER RELATIVE MEASUREMENT BIAS

Devyesh Tandon[*] and Srikant Sukumar[†]

We study the problem of achieving position consensus in a multi-agent rigid-body system operating under measurement bias. It is assumed that the agents measure relative positions of each other with a constant sensor bias. A Lyapunov function based approach is utilized to develop a novel adaptive controller to estimate measurement bias and attempt to achieve consensus. The results show convergence of all agents to a neighborhood.

[View Full Paper]

[*] Undergraduate Student, Department of Aerospace Engineering, Indian Institute of Technology, Bombay, India. E-mail: devyeshtandon@gmail.com.

[†] Assistant Professor, Systems and Control Engineering, Indian Institute of Technology, Bombay, India. E-mail: srikant@sc.iitb.ac.in.

AAS 17-359

SPACECRAFT FORCED FLY-AROUND FORMATION DESIGN AND CONTROL BASED ON RELATIVE ORBIT ELEMENTS

Ran Zhang,[*] Qichen Zhao[†] and Chao Han[‡]

In on-orbit servicing missions, fly-around technology is widely applied to keep the chasing satellite flying around the reference satellite at specified period. Flying-around formation is obtained by designing the chaser absolute orbit, and a set of relative orbit elements is introduced to describe the fly-around formation. Explicit geometric meaning makes it convenient to apply the fly-around formation in practical engineering problems. Moreover, based on relative orbit elements, an impulsive control strategy is proposed to complete the fly-around formation. Numerical simulations are conducted to demonstrate the efficacy of these proposed methods. [View Full Paper]

[*] Ph.D. Candidate, School of Astronautics, Beihang University, No 37, Xueyuan Road, Beijing, China, 100191. Contact at E-mail: buaazhangran@buaa.edu.cn.
[†] Master, School of Astronautics, Beihang University, No 37, Xueyuan Road, Beijing, China, 100191. Contact at E-mail: zhaoqichen@buaa.edu.cn.
[‡] Professor, School of Astronautics, Beihang University, No 37, Xueyuan Road, Beijing, China, 100191. Contact at E-mail: hanchao@buaa.edu.cn.

AAS 17-383

NONLINEAR ROBUST CONTROL FOR SATELLITE FORMATION FLYING VIA ADAPTIVE SECOND-ORDER SLIDING MODES

Hancheol Cho[*] and Gaëtan Kerschen[†]

This paper presents a robust adaptive control methodology based on the concept of second-order sliding modes for satellite formation control in the presence of unknown, but bounded uncertainties. By introducing two sliding variables to achieve the concept of second-order sliding modes, a robust controller is designed so that it forces the first sliding variable to converge to a desired error box in a finite time. Then, the second sliding variable is automatically bounded in a much smaller region by sliding mode control theory, thereby considerably improving the control accuracy. The proposed control scheme is of a smooth form and effectively alleviates chattering. An adaptive law that updates the control gain is also presented without *a priori* knowledge of the uncertainties. Numerical simulations, in which a desired formation configuration is required to be precisely maintained under uncertain mass and external disturbances, are carried out to validate the efficiency and the accuracy of the proposed robust adaptive control scheme developed herein. [View Full Paper]

[*] Marie Curie COFUND Postdoctoral Fellow, Department of Aerospace and Mechanical Engineering, University of Liège, 4000 Liège, Belgium. E-mail: hancheol.cho@ulg.ac.be.

[†] Professor, Department of Aerospace and Mechanical Engineering, University of Liège, 4000 Liège, Belgium.
E-mail: g.kerschen@ulg.ac.be.

AAS 17-396

GEOMETRIC SNAPSHOT METHOD FOR THE AUTONOMOUS RELATIVE POSITIONING OF FORMATION FLYING SATELLITES IN REAL-TIME

Kathrin Frankl,[*] Meltem Eren Copur[†] and Bernd Eissfeller[‡]

The autonomous relative positioning of formation flying satellites is of major importance for a safe operation of the satellite formation. To this end, several challenges are faced: a stringent position accuracy requirement, the real-time capability of the positioning algorithm and the deviation of the measured satellite distances between ranging sensors from the desired distance between the telescope reference points. In this work, these challenges are approached by developing two autonomous relative positioning algorithms. In the serial algorithm, the distance measurements are transferred to the telescope reference positions before an optimization problem including the transferred distance measurements is set up and solved. In the incorporated algorithm, the measurement transformation is integrated in the optimization problem besides the angular and attitude measurements that are also included. Both algorithms are applied to two different case studies and evaluated with respect to the stated challenges. [View Full Paper]

[*] Kathrin Frankl, Institute of Space Technology and Space Applications, Universität der Bundeswehr München, Werner-Heisenberg-Weg 39, 85577 Neubiberg, Germany.
[†] Meltem Eren Copur, Institute of Space Technology and Space Applications, Universität der Bundeswehr München, Werner-Heisenberg-Weg 39, 85577 Neubiberg, Germany.
[‡] Prof. Dr.-Ing. Bernd Eissfeller, Institute of Space Technology and Space Applications, Universität der Bundeswehr München, Werner-Heisenberg-Weg 39, 85577 Neubiberg, Germany.

AAS 17-425

ADAPTIVE FAULT-TOLERANT CONTROL FOR SPACECRAFT FORMATION FLYING WHILE ENSURING COLLISION AVOIDANCE

Hongyang Dong,[*] Guangfu Ma,[†] Yueyong Lv[‡] and Maruthi R. Akella[§]

This paper addresses the target tracking and configuration maintaining problems for spacecraft formation flying systems. In particular, a potential function guidance scheme is designed in conjunction with a time-varying sliding manifold to enable the spacecraft formation can maintain the predetermined configuration while tracking a target, and avoid all possible collisions among members in formation or with respect to a dynamic obstacle. Additionally, by employing special adaptive laws, the proposed method also guarantees that all control objectives can still be achieved even in the presence of severe actuator faults. Stability of the closed-loop system is demonstrated by Lyapunov-based method. Numerical simulation results are performed to illustrate the effectiveness, robustness, collision/obstacle avoidance feature, and fault-tolerant capability of the proposed method. [View Full Paper]

[*] Ph.D. Candidate, Department of Control Science and Engineering, Harbin Institute of Technology, Harbin, 150001, China. E-mail: donghongyang91@gmail.com.
[†] Professor, Department of Control Science and Engineering, Harbin Institute of Technology, Harbin, 150001, China. E-mail: magf@hit.edu.cn.
[‡] Research Assistant, Department of Control Science and Engineering, Harbin Institute of Technology, Harbin, 150001, China. E-mail: lvyy@hit.edu.cn.
[§] Professor and Myron L. Begeman Fellow in Engineering, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, Austin, Texas, 78712, U.S.A. E-mail: makella@mail.utexas.edu. AAS Fellow.

AAS 17-450

RELATIVE SATELLITE NAVIGATION WITH ANGLES-LOS MEASUREMENTS USING RELATIVE ORBITAL ELEMENTS AND ADMISSIBLE REGIONS

Fouad Khoury[*] and T. Alan Lovell[†]

This paper investigates the derivation, computation, and implementation of the relative constrained admissible region (RCAR) as a relative satellite motion navigation tool that collects angles-only measurements from a reference spacecraft to perform initial relative orbit determination of a target space object in Earth orbit. This research addresses the need for a computationally inexpensive and accurate on-board space based navigation and orbit determination technique for use in future rendezvous, formation flight, and space-based observation missions. Using relative motion as characterized by relative orbital elements, the RCAR is computed, sampled, and constrained to provide a range of different orbits satisfying the angle LOS measurements from the reference spacecraft at time t_1 and the two-body energy condition. The use of relative orbital elements is justified because of the clear geometrical insight that the elements provide to understand and work with the relative orbit geometry and LOS measurements. The computed region is then propagated and compared to a second RCAR computed at a different observation time t_2 to reveal the region where the actual orbit of the object is most probably located within the attributable space. Finally, a preliminary design for a space based navigation/orbit determination algorithm involving admissible regions will be assessed and validated using high-fidelity simulations.

[View Full Paper]

[*] Undergraduate Student, Department of Aeronautical/Astronautical Engineering, Purdue University, West Lafayette, Indiana 47906, U.S.A. AFRL Scholar, Space Vehicles Directorate.

[†] Research Aerospace Engineer, U.S. Air Force Research Laboratory, Space Vehicles Directorate, Guidance Navigation and Control Group. 3550 Aberdeen Avenue SE, Albuquerque, New Mexico 87117, U.S.A. Associate Fellow AIAA, Senior Member AAS.

GUIDANCE AND CONTROL

Session Chair:

Session 24: Sean Wagner

The following paper was not available for publication:

AAS 17-203 Paper Withdrawn

AAS 17-223

USE OF MULTICOPTERS FOR LAUNCHERS PROBLEMATIC INVESTIGATIONS

Olivier Boisneau,* Eric Bourgeois,* Jean Desmariaux,* David-Alexis Handschuh,* Amaya Espinosa* and Julien Franc†

Multicopters have many similarities with launchers for what concerns Guidance, Navigation and Flight Control. Their accessibility and their price make them ideal tools for launchers problematic investigations. A review of different domains has been performed to identify when multicopters will be or not representative of a launcher. CNES launchers directorate initiated a project to use multicopter as test bench for launchers problematic investigations. The first application is to study, in flight, analogy between propellant sloshing and the equivalent pendulum models. A device has been design and a quadcopter has been used to prepare and demonstrate the feasibility of the concept.

[View Full Paper]

* CNES, Launchers Directorate. France. Contact E-mail: olivier.boisneau@cnes.fr.
† AERACCESS.

AAS 17-227

OPTIMIZATION METHOD OF INSTALLATION ORIENTATION AND BAFFLE DESIGN FOR DUAL-FOVS STAR TRACKER

Geng Wang,[*] [†] Fei Xing,[*] [†] Minsong Wei,[‡] Ting Sun[*] [†] and Zheng You[*] [†]

The star tracker is an optical attitude sensor with high accuracy, which is susceptible to the stray light, and the suppression of the stray light is very important for the star tracker. In this work, an orientation method of dual- FOVs star trackers for sun-synchronous orbit was proposed, based on the coordinate-transformation matrix and considering the perturbative force, the vector- areas free from stray light in the body coordinate system of satellite were derived under multi-maneuver attitudes, meanwhile, the orientation of star tracker and the corresponding exclusive angle of the sunlight and the earthlight were optimized based on boundary equations. The simulation results indicated that the optimization method for installation orientation and baffle design of dual- FOVs star tracker was precise and effective, and it can provide a basis for the orientation of sun sensor simultaneously. [View Full Paper]

[*] Department of Precision Instrument, Tsinghua University, Beijing 100084, China.
[†] State Key Laboratory of Precision Measurement Technology and Instruments, Tsinghua University, Beijing 100084, China.
[‡] Department of Mechanical Engineering, University of California, Berkeley, California 94720, U.S.A.

AAS 17-296

A NEW STEERING LAW FOR VARIABLE SPEED CONTROL MOMENT GYROS

Qingqing Dang,[*] Lei Jin[†] and Shijie Xu[‡]

In this paper, a new steering law that calculates the gimbal rates and wheel acceleration separately is proposed for variable speed control moment gyros (VSCMGs). The relationship between control moment gyros (CMG) mode singularity and Reaction wheels (RW) mode singularity is analyzed. Singular direction avoidance steering (SDA) law based on singular value decomposition (AVD) is used for CMGs mode. When CMGs mode is close to singularity, the resulting torque error is compensated by RW mode. In order to avoid the wheel speeds difference is too large and makes full use of the configuration redundancy, the null motion is introduced and the desired wheel speeds are given dynamically according to the angular momentum of the VSCMGs. In order to improve the control accuracy of VSCMGs, the gimbal rates dead zone and ignore item are compensated by wheel acceleration. The simulations demonstrate the excellent performance of this steering law. [View Full Paper]

[*] Ph.D. Candidate, School of Astronautics, No. 37 Xueyuan Road, Haidian District, Beijing, 100191, China.
[†] Associate Professor, School of Astronautics, No. 37 Xueyuan Road, Haidian District, Beijing, 100191, China.
[‡] Professor, School of Astronautics, No. 37 Xueyuan Road, Haidian District, Beijing, 100191, China.

AAS 17-339

INITIAL ATTITUDE CONTROL CHALLENGES FOR THE SOLAR PROBE PLUS SPACECRAFT

Robin M. Vaughan,[*] Daniel J. O'Shaughnessy[*] and John H. Wirzburger[†]

The Solar Probe Plus (SPP) mission plans to launch a spacecraft to explore the Sun in 2018. Attitude control is maintained with a 3-axis stabilized, closed-loop control system. One of the first tasks for this system is acquiring attitude knowledge and establishing attitude control after separation from the launch vehicle. Once control is established, the spacecraft must be moved through a sequence of attitudes to meet power and thermal constraints and reach a power-positive state. This paper describes the options selected for the sequence of initial attitudes and gives results for expected performance for nominal and contingency timelines after separation. [View Full Paper]

[*] Principal Professional Staff, Space Department, The Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel, Maryland 20723, U.S.A.

[†] Senior Professional Staff, Space Department, The Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel, Maryland 20723, U.S.A.

AAS 17-341

SUN DIRECTION DETERMINATION FOR THE SOLAR PROBE PLUS SPACECRAFT

Robin M. Vaughan,[*] John H. Wirzburger,[†] Timothy G. McGee,[†] Hongxing S. Shapiro[†] and Daniel J. O'Shaughnessy[*]

The Solar Probe Plus (SPP) mission plans to launch a spacecraft to explore the Sun in 2018. This paper presents the process applied in the attitude control flight software for the spacecraft to determine the best Sun direction from Sun sensor data or a vector derived from on-board ephemeris models and the estimated attitude. Self-consistency checks applied to determine validity of these different knowledge sources are explained, with emphasis on processing of solar limb sensor data. Consistency checks between the available data sources are described. The paper concludes with a presentation of the logical hierarchy that determines which source to select from among the available and valid sources and results of the consistency checks between them. [View Full Paper]

[*] Principal Professional Staff, Space Department, The Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel, Maryland 20723, U.S.A.

[†] Senior Professional Staff, Space Department, The Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel, Maryland 20723, U.S.A.

AAS 17-342

ON TRANSLATIONAL AND ROTATIONAL CONTROL OF A RIGID SPACECRAFT IN A CENTRAL GRAVITY FIELD WITH ONLY ATTITUDE CONTROL

Chris Petersen,[*] Frederick Leve[†] and Ilya Kolmanovsky[‡]

A set of coupled translational and rotational equations of motion for a spacecraft in a central gravity field is derived. The spacecraft is assumed to have only internal attitude actuators and the equations of motion are such that they are relative with respect to an equilibrium orbit. These equations are then approximated, and for certain orbits, yield dynamics similar to Hill-Clohessy-Wiltshire (HCW) dynamics. Under reasonable assumptions on the spacecraft configuration and equilibrium orbit, it is proven that the coupled dynamics are small-time locally controllable (STLC), which opens a path to utilizing conventional control techniques to move translationally in space by employing attitude control only. [View Full Paper]

[*] Graduate Student, Department of Aerospace Engineering, The University of Michigan, 1320 Beal Avenue, Ann Arbor, Michigan 48109, U.S.A. E-mail: cdpete@umich.edu.

[†] Air Force Research Laboratory (AFRL), Space Vehicles Directorate, 3550 Aberdeen Avenue SE, Kirtland AFB, New Mexico 87117-5776, U.S.A. E-mails: AFRL.RVSV@us.af.mil.

[‡] Professor, Department of Aerospace Engineering, The University of Michigan, 1320 Beal Avenue, Ann Arbor, Michigan 48109, U.S.A. E-mail: ilya@umich.edu.

AAS 17-420

NEAR-OPTIMAL REAL-TIME SPACECRAFT GUIDANCE AND CONTROL USING HARMONIC POTENTIAL FUNCTIONS AND A MODIFIED RRT*

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

A primary requirement for any rendezvous and proximity (RPO) guidance algorithm is to ensure mission safety through the generation of collision-free trajectories in a fuel-efficient manner. This work presents a real-time hybrid guidance method which fuses the flexibility and robustness of Harmonic Potential Functions with the asymptotically-optimal Rapidly-expanding Random Tree Star method. The proposed method allows to plan trajectories on cluttered environments while producing near-fuel-optimal trajectories. To quantify and validate the performance of this method an experimental campaign is performed utilizing the Naval Postgraduate School POSEIDYN test bed. Lastly, implementation considerations and experimental results are discussed. [View Full Paper]

[*] Ph.D. Candidate, Mechanical and Aerospace Department, Naval Postgraduate School, 1 University Circle, Monterey, California 93940, U.S.A.

[†] Postdoctoral Research Associate, Naval Postgraduate School, 1 University Circle, Monterey, California 93940, U.S.A.

[‡] Associate Professor, Naval Postgraduate School, 1 University Circle, Monterey, California 93940, U.S.A.

AAS 17-424

A SYSTEMATIC APPROACH TO DETERMINING THE MINIMUM SAMPLING RATE FOR REAL-TIME SPACECRAFT CONTROL

Richard Zappulla II[*] and Marcello Romano[†]

Typical controller design and analysis methods utilize techniques for continuous-time systems. However, digital computation is the favored approach to implementing the resulting controllers. This leads to the natural question of choosing an appropriate sampling rate for the controller. There exist several “Rules of Thumbs” for choosing a sample rate derived from primarily frequency domain properties of the system. A metric to estimate the sample rate based on the system properties rooted from first principles is developed. It is then validated via several case studies using representative mechanical systems, actuators, and controllers. Lastly, the paper concludes with a discussion on the applications of this metric. [View Full Paper]

[*] Ph.D. Candidate, Mechanical and Aerospace Department, Naval Postgraduate School, 1 University Circle, Monterey, California 93940, U.S.A.

[†] Associate Professor, Mechanical and Aerospace Department, Naval Postgraduate School, 1 University Circle, Monterey, California 93940, U.S.A.

LQ ATTITUDE CONTROL OF A 2U CUBESAT BY MAGNETIC ACTUATION

Richard Sutherland,[*] Ilya Kolmanovsky[†] and Anouck Girard[‡]

The paper describes the development of the attitude control subsystem for a 2U QB50 cubesat. Due to the gravity gradient torques, the satellite dynamics are open-loop unstable at the desired pointing configuration but can be shown to be controllable with the magnetic torque rod actuators. The control laws for magnetic torque rod actuators are derived based on linear quadratic regulator theory applied to a discrete-time linearized model. Simulation results, employing the 2015 IGRF tilted dipole model of the Earth's magnetic field, demonstrate successful stabilization to the desired equilibrium. To improve the system capability to handle disturbances, four air drag "dart" panels are added to the satellite. The controller for the magnetic torque rods is redesigned for this configuration based on a reduced-order model to improve computational feasibility. Simulation results confirm the controller ability to meet pointing requirements of the mission even in the presence of the simulated disturbance. [View Full Paper]

[*] Graduate Student, Department of Aerospace Engineering, University of Michigan, 1320 Beal Avenue, Ann Arbor, Michigan 48109-2140, U.S.A.
[†] Professor, Department of Aerospace Engineering, University of Michigan, 1320 Beal Avenue, Ann Arbor, Michigan 48109-2140, U.S.A.
[‡] Associate Professor, Department of Aerospace Engineering, University of Michigan, 1320 Beal Avenue, Ann Arbor, Michigan 48109-2140, U.S.A.

AAS 17-465

RECEDING HORIZON DRIFT COUNTERACTION AND ITS APPLICATION TO SPACECRAFT ATTITUDE CONTROL

Robert A. E. Zidek,* Christopher D. Petersen,* Alberto Bemporad† and Ilya V. Kolmanovsky*

In this paper, a recently developed model predictive control (MPC) approach for drift counteraction optimal control (DCOC) is applied to attitude control of fully actuated and underactuated spacecraft with reaction wheels (RWs). The objective is to maximize the time that prescribed constraints on spacecraft orientation and RW spin rates are satisfied given disturbance torques due to solar radiation pressure. While the MPC/DCOC approach is based on linear programming, all closed-loop simulations are performed using the nonlinear model. In case constraints are violated, a control strategy is presented that recovers constraint satisfaction (if possible). We consider the cases where either one, two, or three RWs are operable. The numerical results show that the proposed controller successfully counteracts drift in order to satisfy constraints for as long as possible.

[View Full Paper]

* Department of Aerospace Engineering, University of Michigan, 1320 Beal Avenue, Ann Arbor, Michigan 48109-2140, U.S.A.

† IMT – Institute for Advanced Studies, Piazza S. Francesco, 19, 55100 Lucca LU, Italy.

AAS 17-491

ATTITUDE CONTROL OF SPACECRAFT FORMATIONS SUBJECT TO DISTRIBUTED COMMUNICATION DELAYS

Siddharth Nair[*] and Kamesh Subbarao[†]

This paper considers the problem of achieving attitude consensus in spacecraft formations with bounded, time-varying communication delays between spacecraft connected as specified by a strongly connected topology. A state feedback controller is proposed and investigated using a time domain approach (via LMIs) and a frequency domain approach (via the small-gain theorem) to obtain delay dependent stability criteria to achieve the desired consensus. Simulations are presented to demonstrate the application of the strategy in a specific scenario. [View Full Paper]

[*] Undergraduate, Department of Aerospace Engineering, Indian Institute of Technology, Bombay, 400076, India. This work was performed as part of an internship at the Aerospace Systems Laboratory in UT Arlington in Summer 2016.

[†] Associate Professor, Department of Mechanical & Aerospace Engineering, The University of Texas at Arlington, Texas 76010, U.S.A. AAS Senior Member.

TRAJECTORY DESIGN AND OPTIMIZATION

Session Chair:

Session 26: Martin Ozimek

AAS 17-204

VALIDATION OF A LOW-THRUST MISSION DESIGN TOOL USING OPERATIONAL NAVIGATION SOFTWARE

Jacob A. Englander,[*] Jeremy M. Knittel,[†] Ken Williams,[‡] Dale Stanbridge[§] and Donald H. Ellison[**]

Design of flight trajectories for missions employing solar-electric propulsion requires a suitably high-fidelity design tool. In this work, the Evolutionary Mission Trajectory Generator (EMTG) is presented as a medium-high fidelity design tool that is suitable for mission proposals. EMTG is validated against the high-heritage deep-space navigation tool MIRAGE, demonstrating both the accuracy of EMTG's model and an operational mission design and navigation procedure using both tools. The validation is performed using a benchmark mission to the Jupiter Trojans. [View Full Paper]

[*] Aerospace Engineer, Navigation and Mission Design Branch, NASA Goddard Space Flight Center, Greenbelt, Maryland 20771, U.S.A. Member AAS.

[†] Aerospace Engineer, Navigation and Mission Design Branch, NASA Goddard Space Flight Center, Greenbelt, Maryland 20771, U.S.A.

[‡] Flight Director, Space Navigation and Flight Dynamics Practice, KinetX Aerospace, Simi Valley, California 93065, U.S.A.

[§] Senior Navigation Analyst, Space Navigation and Flight Dynamics Practice, KinetX Aerospace, Simi Valley, California 93065, U.S.A.

[**] Ph.D. Candidate, Department of Aerospace Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, U.S.A.

AAS 17-347

CUDA-ENHANCED INTEGRATION FOR QUICK POINCARÉ SURFACE INTERSECTIONS IN A GLOBAL OPTIMIZATION FRAMEWORK FOR LOW ENERGY TRANSFERS

Joshua Aurich,* Ryne Beeson† and Victoria Coverstone‡

Identifying homoclinic and heteroclinic intersections of manifolds associated with libration point periodic orbits has proven to be an effective design methodology for generating low-energy trajectory solutions in the restricted three-body problem. The method of intersection identification upon Poincaré surfaces of section has been previously automated by the authors; this paper extends that work by incorporating the algorithm into an automated global optimization framework. The second half of this paper then focuses on the important issue of making the automated detection process numerically efficient; otherwise run-time performance of the global optimizer could be excessive. We accomplish this by using graphics processing units (GPU) and CUDA programming. We discuss run-time performance, implementation improvements, and demonstrate the aforementioned capabilities on a variant of the Hiten mission. [View Full Paper]

* Masters Student, Aerospace Engineering, University of Illinois at Urbana-Champaign, 104 S. Wright Street, Urbana, Illinois 61801, U.S.A.

† Ph.D. Candidate, Aerospace Engineering, University of Illinois at Urbana-Champaign, 104 S. Wright Street, Urbana, Illinois 61801, U.S.A.

‡ Adjunct Professor, Aerospace Engineering, University of Illinois at Urbana-Champaign, 104 S. Wright Street, Urbana, Illinois 61801, U.S.A.

A SOLUTION TO THE THREE-BODY LAMBERT PROBLEM BASED ON CUBATURE KALMAN FILTER PARAMETER ESTIMATION

Qichen Zhao,* Hongli Zhang,† Ran Zhang‡ and Chao Han§

The three-body Lambert problem is to find out an orbit determined from two position vectors and transfer time in the three-body system. Its solution is generally divided into two steps: initial guess based on the two-body model and final solution using cubature kalman filter parameter estimation (CPE). CPE is based on the theory of probability without the gradient matrixes which are hard to calculate. Moreover, by using CPE the demand for the accuracy of the initial values for the three-body Lambert problem is modified. Results show CPE is efficient, robust and has a larger convergence domain compared with other methods. [View Full Paper]

* Master Degree Candidate, School of Astronautics, Beihang University, Beijing, 100191, China.
† Ph.D. Beijing Electro-Mechanical Engineering Institute, Beijing, 100000, China.
‡ Ph.D. Candidate, School of Astronautics, Beihang University, Beijing, 100191, China.
§ Professor, School of Astronautics, Beihang University, Beijing, 100191, China.

AAS 17-460

OPTIMAL COPLANAR ORBIT TRANSFER IN LEVI CIVITA COORDINATES

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

This paper addresses optimal planar orbit transfers using Levi-Civita coordinates through continuation. The Levi-Civita coordinates is a useful orbit representation due to the fact that, for a body traveling through a trajectory with fixed semi-major axis, the equations of motion for these coordinates are represented by linear dynamics. In fact, the solution to the unperturbed EOM it that of a simple harmonic oscillator with the oscillation frequency as function of the semi-major axis itself. Another relevant aspect of Levi-Civita coordinates is that the unperturbed dynamics presents equally segmented position steps for fixed time step segments, which makes fixed step numerical propagation easier for highly eccentric orbits. These properties of the Levi-Civita coordinates motivate this work, which uses Sequential Quadratic Programming to obtain optimal coplanar orbit transfer in these coordinates. We apply the optimization method to different orbit transfer scenarios and evaluate the performance of the algorithm. The near-linear characteristics of Levi-Civita allows Sequential Quadratic Programming methods to converge quickly and reliably if there is tolerance for slight errors in the final orbital elements.

[View Full Paper]

[*] Graduate Research Assistant, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, 210 East 24th Street WRW, 1 University Station, C0600, Austin, Texas 78712, U.S.A. E-mail: marcelino.malmeidan@utexas.edu.

[†] Professor and Myron L. Begeman Fellow in Engineering, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, 210 East 24th Street WRW, 1 University Station, C0600, Austin, Texas 78712, U.S.A. E-mail: makella@mail.utexas.edu.

AAS 17-479

ITERATIVE FIVE-ELEMENT LYAPUNOV CONTROL FOR LOW THRUST RENDEZVOUS WITH MODIFIED CHEBYSHEV PICARD ITERATION

Nathan I. Budd,* Julie L. Read,* Robyn M. Woollands* and John L. Junkins†

We present an iterative five-element Lyapunov control for low thrust rendezvous that uses Modified Chebyshev Picard Iteration (MCPI), an iterative solver of linear and nonlinear ordinary differential equations (ODEs). MCPI uses Chebyshev polynomials to approximate the orbital trajectory and then uses Picard iteration to improve the approximation iteratively. We discuss simulations of two rendezvous test cases, which illustrate the effectiveness of this method as a computationally cheap alternative to relatively expensive optimal control solutions. [View Full Paper]

* Graduate Research Assistant, Department of Aerospace Engineering, Texas A&M University, College Station, Texas 77843-3141, U.S.A.

† Distinguished Professor, Department of Aerospace Engineering, Texas A&M University, College Station, Texas 77843-3141, U.S.A.

AAS 17-480

ACTIVE VIBRATION CONTROL OF GYROELASTIC BODY WITH OPTIMAL PLACEMENT OF ACTUATORS

Shiyuan Jia,* Yinghong Jia† and Shijie Xu‡

This paper studies the optimal placement of discrete actuators on the gyroelastic body based on the linear quadratic regulator (LQR) control. The dynamics of the cantilevered gyroelastic system with different installation directions of control moment gyros (CMGs) is derived. The LQR performance is considered as the objective for finding the optimal configuration of actuators. The optimal placement of actuators is formulated in the frame of combinatorial integer optimization problem. Genetic algorithms (GAs) are used to solve the combination problem of the gyroelastic body with a fixed number of actuators. The effectiveness of the optimized configurations for different cases with different installation directions of CMG actuators in active vibration suppression using LQR control is studied. Numerical results show that the cantilevered gyroelastic body with hybrid installation directions of actuators enables fast vibration suppression with less control effort when compared to the situations with the same directions of all CMG actuators.

[View Full Paper]

* Ph.D. Candidate, School of Astronautics, Beihang University, Beijing, China 100191. E-mail: jiashi.yuan@163.com.
† Associate Professor, School of Astronautics, Beihang University. E-mail: jia_yingh@163.com.
‡ Professor, School of Astronautics, Beihang University. E-mail: starsjxu@163.com.

AAS 17-487

TRAJECTORY AND NAVIGATION DESIGN FOR AN IMPACTOR MISSION CONCEPT

Andres Dono Perez,[*] Roland Burton,[†] Jan Stupl[‡] and David Mauro[§]

This paper introduces a trajectory design for a secondary spacecraft concept to augment the science return in interplanetary missions. The concept consists of a small probe with a kinetic impactor on board that generates an artificial plume to perform in-situ sampling. A Monte Carlo simulation was used to validate the nominal trajectory design for a particular case study that samples ejecta particles from Jupiter's moon Europa. Details regarding the navigation, targeting, and disposal challenges related to this concept are presented herein. [View Full Paper]

[*] Trajectory Analyst, Millennium Engineering and Integration Services, NASA Ames Research Center, Moffett Field, California 94035, U.S.A.

[†] Consultant, Millennium Engineering and Integration Services, NASA Ames Research Center, Moffett Field, California 94035, U.S.A.

[‡] Research scientist, Stinger Ghaffarian Technologies Inc., NASA Ames Research Center, Moffett Field, California 94035, U.S.A.

[§] Systems Engineer, Stinger Ghaffarian Technologies Inc., NASA Ames Research Center, Moffett Field, California 94035, U.S.A.

AAS 17-502

COOPERATIVE GUIDANCE WITH IMPACT ANGLE CONSTRAINT BASED ON LEADER-FOLLOWER STRATEGY

Teng Lyu,* Yueyong Lyu† and Chuanjiang Li‡

A new time-cooperative guidance law against a stationary target is proposed in this paper, which can be applied to salvo attack of anti-ship missiles with the impact angle constraint. Firstly, the nonlinear motion equations of missiles are linearized and various constraints are formulated. Secondly, centralized leader-follower topology based guidance laws of the leader and followers are presented. Finally, closed-form trajectory solutions are given to demonstrate that the zero miss distance and desired impact angle performance of all the missiles can be achieved. Simulation results demonstrate the effectiveness of the proposed guidance law. [View Full Paper]

* Ph.D., Department of Control Science and Engineering, Harbin Institute of Technology, Harbin 150001, China. E-mail: lvtenghit@gmail.com.

† Corresponding author, Assistant Professor, Department of Control Science and Engineering, Harbin Institute of Technology, Harbin 150001, China. E-mail: lvyy_hit@163.com.

‡ Professor, Department of Control Science and Engineering, Harbin Institute of Technology, Harbin 150001, China. E-mail: lichuan@hit.edu.cn.

ORBIT MANIPULATION BY USE OF LUNAR SWING-BY ON A HYPERBOLIC TRAJECTORY

Shuntaro Suda,[*] Yasuhiro Kawakatsu,[†] Shujiro Sawai,[†] Harunori Nagata[‡] and Tsuyoshi Totani[§]

In the modern space development, small-scale deep space mission should be realized to promote frequent and challenging deep space mission. Therefore, the efficient and quick design method to construct Earth escape trajectory with high flexibility in the boundary condition such as escape velocity, direction and timing is strongly demanded. In this paper, the families of Moon-to-Moon transfers with sequential lunar swing-by on a hyperbolic orbit are computed and stored in a database. These families are useful to enhance the Earth escape energy and to change escape direction which could lead a spacecraft to further destinations. [View Full Paper]

[*] Graduate Student, Mechanical and Space Engineering, Graduate School of Engineering, Hokkaido University, 060-8628, Japan.
[†] Associate Professor, Department of Space Flight Systems, ISAS/JAXA, 252-5210, Japan.
[‡] Professor, Mechanical and Space Engineering, Faculty of Engineering, Hokkaido University, 060-8628, Japan.
[§] Associate Professor, Mechanical and Space Engineering, Faculty of Engineering, Hokkaido University, 060-8628, Japan.

AAS 17-528

THE USE OF LUNI-SOLAR GRAVITY ASSISTS FOR ASTEROID RETRIEVAL

Hongru Chen*

This paper proposes the use of luni-solar gravity assists for asteroid retrieval. The joint lunar and solar gravity assist can be approximated by a sequence of Moon-Moon transfers, in which the solar perturbation is effective, and lunar swingbys. The trajectory design is to find a sequence that can reduce the v_∞ of the asteroid with respect to the Moon to a low level, such that the asteroid can be inserted to a lunar orbit with little effort. In this way, the Earth is kept safe from the asteroid. To aid the trajectory design, a database of Sun-perturbed Moon-Moon transfers is used. However, it is burdensome to compute optimal heliocentric transfer trajectories and capture trajectories for every asteroid in the large near-Earth asteroid database. This paper presents analyses revealing the capture capacity of luni-solar gravity capture in terms of Jacobi constant, the magnitude and declination of the v_∞ of the asteroid with respect to the Earth. With this information known, the asteroid candidates can be easily selected out. It is found that there are 13 asteroids that can be retrieved by a mission during the period from 2020 to 2030.

[View Full Paper]

* Research Associate, Key Laboratory of Space Utilization, Technology and Engineering Center for Space Utilization, Chinese Academy of Sciences, Beijing, China 100094.

ORBIT DETERMINATION

Session Chair:

Session 28: Cameron Meek

AAS 17-235

OPTIMAL *K*-VECTOR TO INVERT NONLINEAR FUNCTIONS

David Arnas[*] and Daniele Mortari[†]

This work proposes a numerical technique that can be used to invert one dimensional analytic or tabulated nonlinear functions in assigned ranges of interest. The approach proposed is based on an "optimal" version of the *k*-vector range searching technique. The optimality consists of retrieving a prescribed number of data (1, 2, $\cdots$) to initiate the root solver. This allows flexibility to adopt a variety of root solvers (bisection, Newton, regula falsi, etc.) to obtain machine error precision. The method is suitable when extensive inversions of the same function must be done, as for instance to build an inverse function toolbox. The method is extremely fast, but it requires a one-time preprocessing effort for each distinct nonlinear function and range of interest. This method can be also applied to provide inversion estimates of tabulated data of unknown functions. Numerical examples are provided for some nonlinear analytic and tabulated functions. [View Full Paper]

[*] Centro Universitario de la Defensa, Zaragoza, Spain. GME - IUMA - Universidad de Zaragoza, 50009 Zaragoza, Spain. E-mail: darnas@unizar.es.

[†] Department of Aerospace Engineering, Texas A&M University, 3141 TAMU, College Station, Texas 77843-3141, U.S.A. E-mail: mortari@tamu.edu. IEEE and AAS Fellow, AIAA Associate Fellow.

AAS 17-236

VARIABLE EXPANSION POINTS FOR SERIES SOLUTIONS OF THE LAMBERT PROBLEM

James D. Thorne[*] and Dennis F. DeRiggi[†]

Lambert's problem, to find the unique conic trajectory that connects two points in a spherical gravity field in a given time, is represented by a set of transcendental equations due to Lagrange. The associated Lagrange equations for the orbital transfer time of flight may be expressed as series expansions for all cases. Power series solutions have been previously published that reverse the functionality of the Lagrange equations to provide direct expressions for the unknown semi-major axis as an explicit function of the transfer time. In this paper, convergence of the series solutions is achieved for certain problematic cases through the introduction of variable expansion points as a simple function of the input parameters of the problem. The resulting series expression for the transfer time may be reversed to produce convergent series solutions for the unknown semi-major axis over the full domain of interest. [View Full Paper]

[*] Research Staff Member, System Evaluation Division, Institute for Defense Analyses, 4850 Mark Center Drive, Alexandria, Virginia 22311, U.S.A. E-mail: jthorne@ida.org.

[†] Research Staff Member, System Evaluation Division, Institute for Defense Analyses, 4850 Mark Center Drive, Alexandria, Virginia 22311, U.S.A. E-mail: dderiggi@ida.org.

AAS 17-256

LEAST-SQUARES SOLUTIONS OF LINEAR DIFFERENTIAL EQUATIONS

Daniele Mortari[*]

Dedicated to John Lee Junkins

This study shows how to obtain *least-squares solutions* to initial and boundary value problems to nonhomogeneous linear differential equations with nonconstant coefficients of *any* order. However, without loss of generality, the approach has been applied to second order differential equations. The proposed method has two steps. The first step consists of writing a *constrained expression*, introduced in Ref. [1], that has embedded the differential equation constraints. These expressions are given in term of a new unknown function, $g(t)$, and they satisfy the constraints, no matter what $g(t)$ is. The second step consists of expressing $g(t)$ as a linear combination of m independent known basis functions, $g(t) = \boldsymbol{\xi}^{\mathrm{T}}\boldsymbol{h}(t)$. Specifically, Chebyshev orthogonal polynomials of the first kind are adopted for the basis functions. This choice requires rewriting the differential equation and the constraints in term of a new independent variable, $x \in [-1, +1]$. The procedure leads to a set of linear equations in terms of the unknown coefficients vector, $\boldsymbol{\xi}$, that is then computed by *least-squares*. Numerical examples are provided to quantify the solutions accuracy. [View Full Paper]

[*] Department of Aerospace Engineering, Texas A&M University, 3141 TAMU, College Station, Texas 77843-3141, U.S.A. E-mail: mortari@tamu.edu. IEEE and AAS Fellow, AIAA Associate Fellow.

RANDOM NUMBER GENERATION USING *K*-VECTOR

David Arnas[*] and Daniele Mortari[†]

This work focuses on random number generation with any prescribed nonlinear distribution using the *k*-vector methodology. Two approaches are introduced. The first is based on inverse transform sampling using an optimal *k*-vector to generate the numbers by the inversion of the cumulative distribution. The second generates samples using random searching in a pre-generated large database built by massive inversion of the prescribed nonlinear distribution using the *k*-vector. [View Full Paper]

[*] Centro Universitario de la Defensa, Zaragoza, Spain. GME - IUMA - Universidad de Zaragoza, 50009 Zaragoza, Spain. E-mail: darnas@unizar.es.

[†] Department of Aerospace Engineering, Texas A&M University, 3141 TAMU, College Station, Texas 77843-3141, U.S.A. E-mail: mortari@tamu.edu. IEEE and AAS Fellow, AIAA Associate Fellow.

AAS 17-304

ON THE RESOLUTION OF THE LAMBERT'S PROBLEM WITH THE SDG-CODE

Virginia Raposo-Pulido* and Jesús Peláez†

Based on the Lambert's problem, once identified the one-parameter family of orbits that verify the geometric constraints of the problem, we must express the orbits based on a single parameter that allows to select those that satisfy the kinematic condition. The aim of this paper is to reformulate the problem choosing as parameter the true anomaly of the bisector defined by the directions of the two position vectors. The algorithm applied is the SDG-code, developed by the Space Dynamics Group at UPM, which has already been assessed on the resolution of the Kepler equation proving its stability and reliability.

[View Full Paper]

* Ph.D. Student, Space Dynamics Group (SDG), E.T.S.I. Aeronáutica y del Espacio, Technical University of Madrid, Pza. Cardenal Cisneros 3, E- 28040, Madrid, Spain.
† Professor of Aerospace Engineering, Space Dynamics Group (SDG), E.T.S.I. Aeronáutica y del Espacio, Technical University of Madrid, Pza. Cardenal Cisneros 3, E- 28040, Madrid, Spain.

AAS 17-361

SOLVING THE KEPLER EQUATION WITH THE SDG-CODE

Virginia Raposo-Pulido[*] and Jesús Peláez[†]

A new code to solve the Kepler equation for elliptic and hyperbolic orbits has been developed. The motivation of the study is the determination of an appropriate seed to initialize the numerical method, considering the optimization already tested of the well-known Newton-Raphson method. To do that, we take advantage of the full potential of the symbolic manipulators. The final algorithm is stable, reliable and solves successfully the solution of the Kepler equation in the singular corner ($M \ll 1$ and $e \approx 1$). In most of the cases, the seed generated by the Space Dynamics Group at UPM (SDG-code) leads to reach machine error accuracy with the modified Newton-Raphson methods with no iterations or just one iteration. This approach improves the computational time compared with other methods currently in use. The advantage of our approach is its applicability to other problems as for example the Lambert problem for low thrust trajectories.

[View Full Paper]

[*] Ph.D. Student, Space Dynamics Group (SDG), E.T.S.I. Aeronáutica y del Espacio, Technical University of Madrid, Pza. Cardenal Cisneros 3, E- 28040, Madrid, Spain.

[†] Professor of Aerospace Engineering, Space Dynamics Group (SDG), E.T.S.I. Aeronáutica y del Espacio, Technical University of Madrid, Pza. Cardenal Cisneros 3, E- 28040, Madrid, Spain.

AAS 17-408

WIDE FIELD-OF-VIEW TIME DIFFERENCING ORBIT DETERMINATION METHOD

Nicholas Bijnens,* Franz Newland† and Jinjun Shan‡

With today's significant increase of interest in nanosatellite development, as well as the update frequency of the NORAD TLE data, the options for satellite orbit determination are often slim. The method proposed in this paper will allow a large field-of-view satellite, and potentially a small field-of-view satellite with sufficient attitude knowledge, to effectively use its own payload data to determine its orbital elements at any desired time instant, without the need for additional onboard equipment or processing. The only requirements are that the satellite has a way of detecting and locating a large number of known points on the surface of the body which it is orbiting and that timed visibility information is available. Not only will this provide future satellite missions with a much more cost-, space- and power-efficient method for instantaneous orbit determination but it also gives current satellite missions the ability to determine their orbit at any time, without the need to rely on external data. Some areas of interest include AIS, Automatic Dependent Surveillance-Broadcast (ADS-B), Internet of Things (IoT), Blueforce tracking and environmental sensor missions. To-date, using a modified SPSA algorithm has proven the approach to be viable and is able to estimate the satellite's orbit to well within acceptable error based on simulated input data. [View Full Paper]

* M.Sc. Candidate, Department of Earth and Space Science Engineering, 4700 Keele Street, York University, Toronto, Ontario, M3J 1P3, Canada.
† Assistant Lecturer, Department of Earth and Space Science Engineering, 4700 Keele Street, York University, Toronto, Ontario, M3J 1P3, Canada.
‡ Professor, Department of Earth and Space Science Engineering, 4700 Keele Street, York University, Toronto, Ontario, M3J 1P3, Canada.

AAS 17-421

HIGHER-ORDER DIFFERENTIAL CORRECTION SOLVER FOR PERTURBED LAMBERT PROBLEM

Mohammad Alhulayil,[*] Ahmad Bani Younes[†] and James Turner[‡]

This paper presents an extension of the classical 1*st* order shooting solver for lambert's problem to 4th order differential correction. The resulting Taylor expansion model requires 1*st* through 4*th* order state transition tensors (STTs) that relate the sensitivity of the terminal position errors with respect to the initial velocity vector. These STTs are generated using Computational differentiation (CD) tool integrated with high-order differential correction solver for lambert problem. The two body motion is perturbed using 200 × 200 spherical harmonic gravity model. [View Full Paper]

[*] Ph.D. Student, Aerospace Engineering, Khalifa University, Abu Dhabi, UAE, mohammad.alhulayil@kustar.ac.ae.
[†] Assistant Professor, Aerospace Engineering, Khalifa University, Abu Dhabi, UAE, ahmad.younes@kustar.ac.ae.
[‡] Research Professor, Aerospace Engineering Department, Texas A&M University, 3141 TAMU, College Station, Texas 77843-3141, U.S.A. E-mail: jamesdanielturner@hotmail.com.

A SPLITTING GAUSSIAN MIXTURE FORMULATION FOR A NONLINEAR MEASUREMENT UPDATE

Kirsten Tuggle,[*] Renato Zanetti[†] and Christopher D'Souza[‡]

Applications such as orbit determination and ground tracking necessitate accurate knowledge of state estimate uncertainty. Adaptive Gaussian mixture models are a favored approach with much work devoted to the prediction phase. Of the fewer splitting schemes provided for the filtering phase, nearly all choose to split components along the direction of maximum prior uncertainty. While this does address the goal of reducing uncertainty, it does not consider the role of the actual nonlinear measurement function in doing so. The proposed method offers a novel filtering step splitting scheme that addresses both contributors in a more computationally efficient manner than much of the literature.

[View Full Paper]

[*] Ph.D. Student, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, Austin, Texas 78712, U.S.A.

[†] Assistant Professor, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, Austin, Texas 78712, U.S.A.

[‡] Navigation Technical Discipline Lead, Aeroscience and Flight Mechanics Division, EG6, 2101 NASA Parkway. NASA Johnson Space Center, Houston, Texas 77058, U.S.A.

INDEX

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

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

It covers all articles that appear in the following:

Advances in the Astronautical Sciences (1957 - 1992)
Science and Technology Series (1964 -1992)
AAS History Series (1977 - 1992)
AAS Microfiche Series (1968 - 1992)
Journal of the Astronautical Sciences (1954 -September 1992)
Astronautical Sciences Review (1959 - 1962)

If you are in aerospace you will want this excellent reference tool which covers the first 35 years of the Space Age.

Numerical/Chronological/Author Index in three volumes,

Ordered as a set:

Library Binding (all three volumes) $120.00;
Soft Cover (all three volumes) $90.00.

Ordered by individual volume:

Volume I (1954 - 1978) Library Binding $40.00; Soft Cover $30.00;
Volume II (1979 - 1985/86) Library Binding $60.00; Soft Cover $45.00;
Volume III (1986 - 1992) Library Binding $70.00; Soft Cover $50.00.

Order from Univelt, Inc., P.O. Box 28130, San Diego, California 92198.
Web Site: http://www.univelt.com

NUMERICAL INDEX*

VOLUME 160 I, II, III & IV

ADVANCES IN THE ASTRONAUTICAL SCIENCES, SPACEFLIGHT MECHANICS 2017 (2017)

(27th AAS/AIAA Space Flight Mechanics Meeting, February 5–9, 2016, San Antonio, Texas, U.S.A.)

* Unless otherwise indicated all papers appear in Volume 160, *Advances in the Astronautical Sciences*. Part I, Part II, Part III and Part IV indicate in which part in the hard copy version of the proceedings that the paper appears.

AAS 17-348 to -350 Not Assigned

AAS 17-351 Not Available (Withdrawn)

AAS 17-352 An Analysis of the Convergence Newton's Iterations for Solving Elliptic Kepler's Equation, M. Calvo, A. Elipe, J. I. Montijano and L. Rández (Part III)

AAS 17-353 Rigid Body Consensus Under Relative Measurement Bias, Devyesh Tandon and Srikant Sukumar (Part IV)

AAS 17-354 Method of Equivalent Cross Section Area (MECSA) Used in the Analytical Formulation of Probability of Collision, Ken Chan (Part II)

AAS 17-355 Long-Term Analytical Propagation of Satellite Relative Motion in Perturbed Orbits, Tommaso Guffanti, Simone D'Amico and Michèle Lavagna (Part III)

AAS 17-356 Reachable Domain of Spacecraft with a Single Normal Impulse, Junhua Zhang, Jianping Yuan, Wei Wang, Jinglang Feng and Zhanxia Zhu (Part II)

AAS 17-357 Time-Delayed Feedback Control of Hovering and Orbiting About Asteroids, Haiyang Li and Hexi Baoyin (Part I)

AAS 17-358 Not Available (Withdrawn)

AAS 17-359 Spacecraft Forced Fly-Around Formation Design and Control Based on Relative Orbit Elements, Ran Zhang, Qichen Zhao and Chao Han (Part IV)

AAS 17-360 Perturbation in Orbital Elements of a High Elliptical Orbit of Satellite Constellations, Osama Mostafa, Koki Fujita and Toshiya Hanada (Part II)

AAS 17-361 Solving the Kepler Equation with the SDG-Code, Virginia Raposo-Pulido and Jesús Peláez (Part IV)

AAS 17-362 Not Assigned

AAS 17-363 Design of a Synthetic Population of Geostationary Space Debris by Statistical Means, Alexis Petit, Daniel Casanova, Morgane Dumont and Anne Lemaitre (Part IV)

AAS 17-364 to -367 Not Assigned

AAS 17-368 A Solution to the Three-Body Lambert Problem Based on Cubature Kalman Filter Parameter Estimation, Qichen Zhao, Hongli Zhang, Ran Zhang and Chao Han (Part IV)

AAS 17-369 Migration of the DSST Standalone to C/C++, Juan F. San-Juan, Rosario López, Ricardo Suanes, Iván Pérez, Srinivas J. Setty and Paul J. Cefola (Part III)

AAS 17-370 Landing on Small Bodies Trajectory Design, Robust Nonlinear Guidance and Control, Eric Joffre, Mattia Zamaro, Nuno Silva, Andrés Marcos, Pedro Simplício and Barbara Richardson (Part II)

AAS 17-371 From Simplified to Complex Small-Body Models: Sensitivity Analysis of Periodic Orbit Sets, Alex J. Pini, Benjamin F. Villac and Rodney L. Anderson (Part I)

AAS 17-372 Trajectory Planning of Approaching Non-Cooperative Targets Based on Gauss Pseudospectral Method, Shi Heng and Zhu Jihong (Part II)

AAS 17-373 The Eccentric Case of a Fast-Rotating, Gravity-Gradient-Perturbed Satellite Attitude Solution, Noble Hatten and Ryan P. Russell (Part III)

AAS 17-374 A New Multi-Target Tracking Algorithm for a Large Number of Orbiting Objects, E. D. Delande, J. Houssineau, J. Franco, C. Frueh and D. E. Clark (Part II)

AAS 17-375 Not Assigned

AAS 17-376 A Semianalytical Technique for Six-Degree-Of-Freedom Space Object Propagation, Noble Hatten and Ryan P. Russell (Part III)

AAS 17-400 Not Assigned

AAS 17-401 Optical Sensor Follow-Up Tasking on High Priority Uncorrelated Track, Timothy S. Murphy, Marcus J. Holzinger, K. Kim Luu and Chris Sabol (Part II)

AAS 17-402 Adaptive Filtering for Maneuver-Free Angles-Only Navigation in Eccentric Orbits, Joshua Sullivan and Simone D'Amico (Part I)

AAS 17-403 Not Assigned

AAS 17-404 Gravitational Potential Modeling of Near-Earth Contact Binaries, S. R. Wood, J. M. Pearl and D. L. Hitt (Part I)

AAS 17-405 to 407 Not Assigned

AAS 17-408 Wide Field-of-View Time Differencing Orbit Determination Method, Nicholas Bijnens, Franz Newland and Jinjun Shan (Part IV)

AAS 17-409 Expansion of the Gravitational Potential of a Polyhedral Body in Inertial Integrals, Stefano Casotto and Roberto Casotto (Part III)

AAS 17-410 Using Particle Swarm Optimization for Earth-Return Trajectories from Libration Point Orbits, Mollik Nayyar and David B. Spencer (Part I)

AAS 17-411 Safe Relative Motion Trajectory Planning for Satellite Inspection, Gregory R. Frey, Christopher D. Petersen, Frederick A. Leve, Anouck R. Girard and Ilya V. Kolmanovsky (Part I)

AAS 17-412 Nonlinear Gaussian Mixture Smoothing for Orbit Determination, Kyle J. DeMars (Part II)

AAS 17-413 Practical Demonstration of Track-to-Track Data Association Using the Bhattacharyya Divergence, Christopher W. T. Roscoe, Islam I. Hussein, Joseph D. Gerber, Jason Stauch, Tom Kelecy, Matthew P. Wilkins and Paul W. Schumacher, Jr. (Part II)

AAS 17-414 Not Assigned

AAS 17-415 Application of Sequential Monte Carlo Methods for Space Object Tracking, Islam I. Hussein, Waqar Zaidi, Weston Faber, Christopher W. T. Roscoe, Matthew P. Wilkins, Paul W. Schumacher, Jr. and Mark Bolden (Part II)

AAS 17-416 Multi-Tiered Approach to Constellation Maneuver Optimization for Low-Thrust Station-Keeping, Andris D. Jaunzemis, Christopher W. T. Roscoe and Marcus J. Holzinger (Part I)

AAS 17-417 Recursive Multi-Objective Optimization of Mars-Earth-Venus Trajectories, Kirk S. S. Barrow and Marcus J. Holzinger (Part II)

AAS 17-418 Convex Optimization for Proximity Maneuvering of a Spacecraft with a Robotic Manipulator, Josep Virgili-Llop, Costantinos Zagaris, Richard Zappulla II, Andrew Bradstreet and Marcello Romano (Part I)

AAS 17-419 Analysis of Spacecraft Planar Docking with Rotating Body in Close Proximity, Costantinos Zagaris and Marcello Romano (Part I)

AAS 17-420 Near-Optimal Real-Time Spacecraft Guidance and Control Using Harmonic Potential Functions and a Modified RRT*, Richard Zappulla II, Josep Virgili-Llop and Marcello Romano (Part IV)

AAS 17-421 Higher-Order Differential Correction Solver for Perturbed Lambert Problem, Mohammad Alhulayil, Ahmad Bani Younes and James Turner (Part IV)

AAS 17-422 Small Body Spin-State Determination Using Landed Transponders, Andrew S. French and Jay W. McMahon (Part I)

AAS 17-423 Not Assigned

AAS 17-465 Receding Horizon Drift Counteraction and its Application to Spacecraft Attitude Control, Robert A. E. Zidek, Christopher D. Petersen, Alberto Bemporad and Ilya V. Kolmanovsky (Part IV)

AAS 17-466 to -467 Not Assigned

AAS 17-468 A Simplified Model for Vibrating Mass Control Moment Gyroscope, Burak Akbulut, Ferhat Arberkli, Kivanc Azgin and Ozan Tekinalp (Part III)

AAS 17-469 Modelling Irregular Small Bodies Gravity Field Via Extreme Learning Machines, Roberto Furfaro, Richard Linares, Vishnu Reddy, Jules Simo and Lucille Le Corre (Part I)

AAS 17-470 Not Assigned

AAS 17-471 Not Available (Withdrawn)

AAS 17-472 Development of an Analytic Expression for Estimating the Time When the Uncertainty Becomes Non-Gaussian, Inkwan Park and Kyle T. Alfriend (Part III)

AAS 17-473 Exact Normalization of the Tesseral Harmonics, Bharat Mahajan, Srinivas R. Vadali and Kyle T. Alfriend

AAS 17-474 A Pursuit-Evasion Game in the Orbital Plane, Jhanani Selvakumar and Efstathios Bakolas (Part I)

AAS 17-475 Analytic Solution of Perturbed Relative Motion with Zonal and Tesseral Harmonics, Bharat Mahajan, Srinivas R. Vadali and Kyle T. Alfriend (Part I)

AAS 17-476 A Novel State Space Representation of Particle Swarm Optimization Dynamics, Michael Andrew Johnson and May-Win L. Thein (Part I)

AAS 17-477 Multiple Space Object Tracking Using Randomized Finite Set Statistics (R-FISST), W. Faber, S. Chakravorty and Islam I. Hussein (Part II)

AAS 17-478 Real-Time Attitude Control for Large-Angle Agile Maneuvers of a Spacecraft with Control Moment Gyros, Shota Kawajiri and Saburo Matunaga (Part III)

AAS 17-479 Iterative Five-Element Lyapunov Control for Low Thrust Rendezvous with Modified Chebyshev Picard Iteration, Nathan I. Budd, Julie L. Read, Robyn M. Woollands and John L. Junkins (Part IV)

AAS 17-480 Active Vibration Control of Gyroelastic Body with Optimal Placement of Actuators, Shiyuan Jia, Yinghong Jia and Shijie Xu (Part IV)

AAS 17-481 Optimal Trajectory Design and Control of a Planetary Exploration Rover, Ameya R. Godbole, V. N. V. Murali, Paul Quilen and Kamesh Subbarao (Part II)

AAS 17-482 Not Assigned

AAS 17-483 Electrostatically Charged Spacecraft Formation Estimation Using Linearized Relative Orbit Elements, Trevor Bennett and Hanspeter Schaub (Part IV)

AAS 17-484 Not Assigned

AAS 17-485 Non Linear K-Vector, Marcio A. A. Fialho and Daniele Mortari (Part III)

AAS 17-486 Not Assigned

AAS 17-487 Trajectory and Navigation Design for an Impactor Mission Concept, Andres Dono Perez, Roland Burton, Jan Stupl and David Mauro (Part IV)

AAS 17-488 Not Assigned

AAS 17-489 Optical Navigation Concept of Operations for the OSIRIS-REx Mission, Coralie D. Jackman, Derek S. Nelson, Leilah K. McCarthy, Tiffany J. Finley, Andrew J. Liounis, Kenneth M. Getzandanner, Peter G. Antreasian and Michael C. Moreau (Part IV)

AUTHOR INDEX